Modelling sediment and nutrient budgets in the Lake Burragerang catchment

P. Rustomji

Report to the Sydney Catchment Authority

CSIRO Land and Water Science Report 57/06
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Modelling sediment and nutrient budgets in the Lake Burragorang catchment.

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Acknowledgements

Sections of this report relating to SedNet and ANNEX methods have been modified from Read et al. (2003) and DeRose et al. (2003). Arthur Read (CSIRO) provided assistance in running the SedNet model. Gary Caitcheon, Brad Sherman and Scott Wilkinson contributed to the model development. Rebecca Bartley (CSIRO) and Penny Knights (SCA) are thanked for their comprehensive reviews of this report.
Executive Summary

This study has applied the SedNet catchment sediment and nutrient budget model to the Lake Burragorang catchment to provide predictions about the source areas and processes responsible for generating the sediment delivered to Lake Burragorang over the last few decades (circa 1980 – 2000). Five model scenarios have been evaluated for their capacity to match three independent data sets from the catchment including:

1. suspended sediment loads estimated at gauging stations,
2. geochemical tracer data measuring the relative sediment contributions at river confluences,
3. geochemical tracer data measuring the relative contribution of surface versus sub-soil sediment sources.

Of the five models, models A and B which retained the Revised Universal Soil Loss Equation predictions for hillslope erosion across the entire catchment performed relatively poorly. Models C, D and E, which for forested areas adopted an increased rate of sediment delivery (in line with gauging station sediment load estimates) performed better.

The model that most closely represented the observational data from the catchment (model E) had as its main feature a relatively high (40 t/km²/yr) rate of sediment yield from forested hillslopes for sub-catchments near the reservoir, along with reduced rates of contemporary sediment supply from gully erosion. Both of these characteristics were drawn from independent studies of the catchment. However, there is likely to be important intra-catchment variation in both hillslope and gully erosion processes that is not resolved in the current modelling and this represents an area in which future research could profitably focus upon.

The model E parameterisation predicts that 240 kt/yr of fine sediment is delivered to the reservoir. The vast majority of this sediment is predicted to be sourced from hillslope erosion in sub-catchments relatively close to the reservoir. Gully erosion is the next most significant sediment source. If the contributions from the majority-forested sub-catchments are disregarded, suspended sediment delivery to the reservoir is predicted to be dominated by the agricultural sub-catchments below Lyell Dam on the Coxs River and also from sub-catchments draining to the Wollondilly River between Paddys River and Guineacor Creek. Other notable source areas include much of the Tarlo River sub-catchment. The Mulwaree River, much of the upper Wingecarribee River and the Coxs River above Lyell Dam are predicted to contribute low rates of suspended sediment to the reservoir.
The nutrient budget predictions are strongly dominated by sediment-bound phosphorus and nitrogen input associated with the higher hillslope erosion rates predicted for the forested regions. Delivery to the reservoir of 2590 t/yr of nitrogen and 336 t/yr of phosphorus are predicted by the model. Inputs of nitrogen and phosphorus from urban areas, both from the dissolved fraction in runoff from urban areas and through point source inputs from sewage treatment plants (particularly those at Lithgow and Bowral) make notable contributions from the non-forested regions. For both nitrogen and phosphorus contributions to the reservoir, the agricultural sub-catchments below Lyell Dam on the Coxs River represent important source areas, as are parts of the Tarlo River sub-catchment and the Wollondilly River downstream of its confluence with the Mulwaree River. The Mulwaree River represents an area of low nutrient contribution to Lake Burragorang. The nutrient budget predictions have not been evaluated to the same degree as the suspended sediment budget predictions, hence they are more speculative.

The results presented here are model predictions based on the best available data. This study has demonstrated large variations in model predictions can result from differing model parameterisations and that increasing the amount of local data in the model calibration phase clearly increases the accuracy of the resulting predictions. Uncritically applying existing models of hillslope and gully erosion to the Lake Burragorang catchment can yield model predictions that bear little resemblance to reality. There is however an ongoing need for future data collection and research to test the major conclusions drawn from these predictions. Such large variations in model predictions (both in terms of spatial source areas and fluxes) resulting from differing model parameterisations reinforces the need for the use of local data to calibrate and test models such as SedNet.
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1 Background to the study

This report presents the results of applying the SedNet catchment scale sediment and nutrient budget model to predict the sources of sediment and nutrients delivered to Lake Burragorang from its catchment. It is one component of a collaborative research project between CSIRO Land and Water and the Sydney Catchment Authority investigating the sources of sediments and associated nutrients delivered to the Lake. Other components of this research project include:

- a spatial tracing study using the geochemical signatures of sediment from major sub-catchments delivering sediment to the reservoir (Caitcheon et al. 2006).
- erosion process tracing where fallout radionuclides are used to diagnose the relative contribution of surface and subsurface soils delivered to the reservoir, with the aim of differentiating the major erosion processes active in the catchment (Caitcheon et al. 2006).
- a study of floodplain deposition patterns within the catchment (Rustomji et al. 2006).
- estimation of suspended sediment loads at gauging stations.

This report follows a preliminary application of the SedNet model to the Lake Burragorang catchment by Read et al. (2003) that used default model parameterisations and national scale data. In the study reported here, a range of model parameterisations (based on additional research conducted in the catchment) that better reflect local catchment conditions are explored in terms of their capacity to match independent observational data sets. The predicted patterns of sediment and nutrient contribution from the various parameterisations are also discussed.
2 Introduction

This report describes the results of applying the SedNet catchment sediment and nutrient budget model to the Lake Burragorang catchment to provide predictions about the source areas and processes responsible for delivery of fine sediments to the reservoir. As many potential pollutants in freshwater systems, such as nutrients critical for cyanobacteria growth (Caitecheon et al. 1995; Harris 2001), pesticides (Kookana et al. 1998) and metals (White et al. 2006) are preferentially bound to fine sediment particles, knowledge of the spatial and temporal variations in suspended sediment flux within a catchment is critical to understanding the movement of these pollutants. Hence the focus of this report upon the catchment’s fine sediment (clay and silt particles; less than 63 µm) and nutrient budgets. The model approach adopted has been to represent as closely as possible contemporary catchment conditions, that is the catchment conditions prevailing over the last two to three decades. The most substantial implication of focussing upon this time period pertains to rates of sediment supply from gully erosion, which are known to have a strong temporal pattern related to gully formation; rates of which peaked in the 1800s (Olley and Wasson 2003).

Spatially-based catchment sediment budget models such as SedNet (Prosser et al. 2001) provide a means of predicting the linkages between (or contributions from) upstream sediment sources and downstream receiving water bodies. Models are needed to represent these effects because of the complexity of patterns of downstream sediment transport. Model’s such as SedNet can also provide predictions at a spatial scale finer than that obtainable by direct observational methods across a 9000 km² catchment area such as that of Lake Burragorang. When properly constrained, models such as SedNet also provide a means of predicting sediment sources areas and processes responsible for sediment generation. This in turn can then be used to target management actions aimed at reducing pollutant delivery to critical points in a river network.

In 2003, CSIRO Land and Water provided a preliminary assessment of the sources of sediment and nutrients delivered to Lake Burragorang (Read et al. 2003). This report by Read et al. (2003) represented an application of the SedNet model to the catchment using a combination of data provided by the Sydney Catchment Authority (such as gully erosion maps) and that derived from national scale mapping, along with a range of what were essentially “best guesses” for a number of important model parameters. Future refinements to a number of these model parameters were flagged as likely in response to subsequent research.

Over the course of this study, new information about the state of the catchment that has
enabled a substantial revision of the SedNet modelling and provides additional independent data to evaluate the accuracy of model predictions. This additional research includes:

1. the study of Rustomji (2006) of gully dimensions and gully sediment texture.
2. the study of Rustomji et al. (2006) into the temporal and spatial patterns of floodplain deposition and sediment storage.
3. new geochemical data pertaining to sediment source areas and erosion processes (Caitcheon et al. 2006).
4. evaluation of suspended sediment fluxes at the network of gauging stations within the catchment.

In this report, a number of different model parameterisations are compared in terms of their capacity to represent the observational data obtained for the catchment.

Figure 1 is a map of the main reporting sub-catchments whilst Figure 2 shows the main rivers, towns and gauging stations within the catchment.
Figure 1: Map of the main sub-catchments within the Lake Burragorang catchment.
Figure 2: Shaded relief map of the Lake Burragarang catchment showing major rivers, towns and gauging stations.
3 Methods and Data

3.1 The SedNet model

This report documents the results of applying the SedNet and Annex geographic information system-based sediment and nutrient budgeting models described by Prosser et al. (2001) and Young et al. (2001) to the Lake Burragorang catchment. These physical process based models construct sediment and nutrient budgets for river networks, enabling prediction of the major sources, storage sites and loads of these potential pollutants. SedNet divides a catchment's river network into a series of links each with its own sub-catchment (referred to below as a “SedNet sub-catchment”) and these river links and sub-catchments comprise the basic analysis unit of the model. A link is the stretch of river between adjacent stream junctions. Sediment and nutrient inputs to each link are estimated from the hillslope erosion, gully erosion and riverbank erosion processes within the link’s sub-catchment plus the contribution from any upstream tributaries. Sediment “losses” due to deposition of sediment upon floodplains and in reservoirs is also accounted for. Figure 3 shows a schematic representation of the major components of the SedNet suspended sediment model for each link.

3.2 River network definition

The river network and associated internal catchment areas were defined from the 25 m digital elevation model (DEM) provided by the Sydney Catchment Authority (SCA) to the CSIRO. The
river network was defined using a threshold catchment area of > 25 km$^2$. The physical stream network extends upstream of this limit in most areas and these areas are treated as part of the internal catchment area contributing material to the river link. First order links shorter than 1 km long were removed to simplify the stream network.

3.3 Hydrology

SedNet combines a number of hydrological parameters to calculate river sediment and nutrient budgets. These parameters, which need to be estimated for each river link are:

- The mean annual flow ($Q_a$);
- The mean annual sum of $Q^{1.4} (\cdot Q^{1.4})$ for calculating mean annual sediment transport capacity;
- The bank full discharge ($Q_{bf}$);
- A representative flood discharge for floodplain deposition (in this case median overbank flow, $Q_{ob}$)

Values for these variables were derived from the time series of daily flows for 16 unregulated gauging stations and 8 regulated stations in accordance with Wilkinson et al. (2006). The mean annual flow, $Q_a$, is estimated as the product of catchment area ($A$), rainfall ($P$) and a runoff coefficient ($R_c$). The first two of these terms can be derived from spatial data, requiring the runoff coefficient to be estimated for each SedNet link using equation 1:

\[
R_c = \left[ 1 + \left( \frac{E_0}{P} \right)^{a(E_0/P)+b} \right]^{1/[a(E_0/P)+b]} \tag{1}
\]

where the fitted parameters $a$ and $b$ equal 0.575 and 2.048 respectively and $E_0$ is the mean potential evapotranspiration for the upstream catchment, obtained from a gridded surface of this variable. Bankfull discharge, $Q_{bf}$, taken as the 1.58 year recurrence interval event on the annual maximum series, is estimated as a function of mean annual flow $Q_a$:

\[
Q_{bf} = 0.2774 \times Q_a^{0.8231} \tag{2}
\]

The median overbank flow, $Q_{ob}$ is also estimated as a function of $Q_a$

\[
Q_{ob} = 0.2390 \times Q_a^{0.8058} \tag{3}
\]
The parameter $Q^{1.4}$, required for calculations related to the bedload sediment budget (which is not discussed in this report), is calculated as:

$$Q^{1.4} = \sigma_d \times 365 \left( \frac{Q_a}{365} \right)^{1.4} \tag{4}$$

where

$$\sigma_d = \frac{1}{n} \sum_{i=1}^{n} \left( \frac{Q_i}{Q} \right)^{1.4} \tag{5}$$

Equation 4 requires $\sigma_d$ to be estimated for each link in the SedNet network using the following equation:

$$\sigma_d = -0.0005 \times e^{-2.859R} + 1 \tag{6}$$

Adjustments are made to $Q_a$, $Q^{1.4}$ and $Q_{ob}$ to account for changes in hydrology associated with river regulation.

### 3.4 Hillslope Erosion

Hillslope erosion is typically represented in SedNet using a sub-model based on the Revised Universal Soil Loss Equation (RUSLE) (RUSLE; Rennard et al. 1997; Lu et al. 2003) combined with a “hillslope sediment delivery ratio”, being the proportion of total hillslope erosion delivered to the channel. The RUSLE calculates mean annual soil loss ($Y$, tonnes/ha/y) as a product of six factors: rainfall erosivity ($R$), soil erodibility ($K$), hillslope length ($L$), hillslope gradient ($S$), ground cover ($C$) and land use practice ($P$):

$$Y = RKLSCP \tag{7}$$

The soil erodibility ($K$) and rainfall erosivity ($R$) grids used were identical to those used in the National Land and Water Resources Audit (NLWRA) as described by Lu et al. (2001). The cover factor has been recalculated to make use of high resolution (25 m cell size) land use data. Length and slope factors ($L,S$) for the catchment were derived directly from the 25 m digital elevation model of the catchment (Gallant 2001). The $L$ factor has been set to 1 for areas of woodlands, forests and pasture land (Lu et al. 2001). The $P$ factor represents soil conservation practices other than cover management. This factor was not included as mapping of the use of erosion control structures was not available.

A hillslope sediment delivery ratio (HSDR) of 5% has been applied to estimate sediment transfer from hillslopes to the stream network for non-forested areas. This value implies that
5% of the total soil erosion within a SedNet sub-catchment gets delivered to the stream network per year, with the remaining portion stored in various parts of the landscape. Sediment input from hillslope erosion is assumed to comprise fine sediment only and hence contribute only to the catchment’s suspended sediment budget.

The RUSLE model is comparatively well constrained and tested in agricultural settings (Lu et al. 2003), yet less well so for forested environments. To address this shortcoming, an alternative method of estimating sediment input to the stream network for forest lands is explored.

An analysis of suspended sediment fluxes at gauging stations in the Lake Burragorang catchment provided suspended sediment yields from forested catchment’s that could potentially be used to quantify sediment generation from forested environments via an alternative method to the RUSLE. Gauging stations 212016, 212280 (below gauging station 2122801) and 212260 in the Lake Burragorang catchment, for which sediment loads have been calculated have almost complete forest cover. Gully mapping indicates very few gullies are present within these sub-catchments. Whilst gullies may be difficult to see under forest vegetation and hence gully erosion in forested landscapes may be under-represented in the gully mapping, erosion process tracing of sediments deposited in the reservoir has reasonably high $^{137}$Cs activity equivalent to the $^{137}$Cs activities observed for surficial pasture and forest sediments. This indicates a strong contribution of hillslope sediments to the load deposited in the reservoir, estimated by Caitcheon et al. (2006) to be $63 \pm 18\%$. Consequently, the catchment sediment yields from stations 212016 and 212280 (below gauging station 2122801) could plausibly be used to estimate the sediment yield from hillslope erosion from forested catchments. Table 1 lists the area specific suspended sediment yields from these gauging stations.

The Kowmung River station is conspicuous on account of its comparatively high area specific sediment yield. It is also the steepest of the sub-catchments and on account of this steep-
ness, may not be representative of the other forested areas surrounding the reservoir. For this reason, data from this station is not included in estimation of forest hillslope sediment yields. If the mean area specific sediment yield for stations 212016 and 212280 is taken as being a first order approximation of the rate of sediment supply from forested hillslopes in the vicinity of Lake Burragorang, then a yield of 40 t/km²/yr is obtained.

The question of how representative these two stations used to derive this 40 t/km²/yr yield are of the broader Lake Burragorang catchment arises. Stations 212016 and 212280 are in the Sydney Basin geologic province and have a geology dominated by Permo-Triassic horizontally bedded sandstones. Their catchments are also moderately steep, with mean slopes of 19 and 20 degrees respectively. Consequently, it could be argued that they are more representative of the area in the immediate surroundings of the reservoir with similar geology, rainfall and hillslope morphology than they are of some of the more distal parts of the basin, particularly those sub-catchments on the drier and flatter Southern Tablelands dominated by Lachlan Fold belt meta-sediments and granites. However there are no exclusively forested sub-catchments with gauging stations or suspended sediment load data in these areas from which a representative sediment yield could be calculated.

Given the above observations, three models of hillslope sediment delivery to the river network have been explored:

1. Application of the RUSLE model with a 5% hillslope sediment delivery ratio
2. Application of the RUSLE model with a 5% hillslope sediment delivery ratio to non-forest areas and a uniform yield of 40 t/km²/yr for forested areas.
3. Application of the RUSLE model with a 5% hillslope sediment delivery ratio to non-forest areas and a uniform yield of 40 t/km²/yr for forested areas, with the exception of the area of the Southern Tablelands upstream of the confluence of the Mulwaree and Wollondilly River sub-catchments, where the RUSLE × 5% hillslope model will apply.

Thus for each SedNet sub-catchment, the total sediment input from hillslope erosion H (tonnes per year) is estimated as

\[
H = \sum_{i=1}^{n} h_i \frac{1}{n} \times A
\]

where \( n \) is the number of pixels in the hillslope erosion grid for each SedNet sub-catchment of area A (hectares) and \( h \) is the hillslope erosion rate for each pixel estimated either using the RUSLE model results multiplied by 0.05 (the 5% hillslope sediment delivery rate) or the forest erosion model with an effective hillslope sediment delivery rate of 1.
3.5 Gully erosion

Mapping of the gully network extent in the Burragorang catchment has been undertaken by the former New South Wales Department of Land and Water Conservation (DLWC; now the Department of Natural Resources - DNR). Sediment supply from gully erosion for each SedNet sub-catchment has been calculated as the product of mapped gully length in the sub-catchment, a representative cross-sectional area of 23 m$^2$ (Rustomji 2006) and average dry bulk soil density of 1.5 t/m$^3$, divided by a gully formation period of 150 years. This time period of 150 years is based on the increase in alluvial aggradation rates observed across both the Southern Tablelands and the Coxs River catchment after approximately AD 1850. This increase in alluvial aggradation was attributed by Rustomji et al. (2006) and Rustomji and Pietsch (in press) to the spread of European agricultural practices across these regions at this time which triggered widespread gully erosion. Finally, in keeping with the general observation that sediment yield from gully erosion varies strongly through time with most of the sediment eroded relatively soon after gully initiation, followed by a much longer, lower yielding phase (Olley and Wasson 2003; Wasson et al. 1998), contemporary yields from gully erosion are estimated using values of 20% and 35% of the long term average value on the basis of temporal changes in floodplain aggradation patterns in the catchment (Rustomji and Pietsch in press). This parameter is referred to as the gully production ratio.

The ratio of suspended to bedload sediment generated by gully erosion was noted by Rustomji (2006) to vary across the catchment depending on catchment geology, with gullies upon igneous (but non-basaltic) bedrock contributing a larger proportion (57% by weight) of coarse sediment (> 63 µm) compared to gullies developed on sedimentary and basaltic bedrock (50%). Consequently, Table 3.5 lists the percentage of coarse sediment generated from gully erosion for the four main geological classes found in the Lake Burragorang catchment. Note that one minus the proportion of coarse sediment equals the contribution of fine sediment to the suspended load budget of a river link.

---

3 METHODS AND DATA
Table 2: Percent coarse sediment (> 63 µm) by weight from gully erosion on different rock types.

<table>
<thead>
<tr>
<th>Rock type</th>
<th>% coarse</th>
</tr>
</thead>
<tbody>
<tr>
<td>Felsic volcanics (Bindook Porphyry)</td>
<td>0.57</td>
</tr>
<tr>
<td>Granites</td>
<td>0.57</td>
</tr>
<tr>
<td>Mafic volcanics (basalt)</td>
<td>0.50</td>
</tr>
<tr>
<td>Sedimentary rocks</td>
<td>0.50</td>
</tr>
</tbody>
</table>

3.6 Riverbank erosion

The mean annual rate of bank erosion $BE$ in units of metres of channel widening per year along a river link is estimated according to Hughes and Prosser (2003) as a function of stream power and the proportion of the reach length comprising potentially erodible banks:

$$BE = 0.0005 \rho g Q_{bf} S_x (1 - PR)(1 - e^{-0.015F})$$  \hspace{1cm} (9)

where $\rho$ is the density of water, $g$ is acceleration due to gravity, $Q_{bf}$ is bankfull discharge, $S$ is the river bed slope, $PR$ is the proportion of bank with intact native riparian vegetation, and $F$ is the floodplain width in metres. The model reduces the potential for erosion linearly with an increase in riparian vegetation. The exponential relationship with floodplain width reflects an exponential increase in the exposure of rock and other erosion resistant materials as floodplain extent decreases, such that bank erosion rates are reduced in steeper river reaches that typically have less alluvium adjacent to the channel. Bankfull discharge was taken to be the 1.58 year recurrence interval discharge on the annual maximum series (Wilkinson et al. 2004). Floodplain width was calculated from the 25 m digital elevation model for the catchment using the MR-VBF algorithm of Gallant and Dowling (2003). River bed slope was measured directly from the DEM. The proportion of riparian vegetation is derived from the Bureau of Rural Sciences land cover 95 dataset (25 m cell size; Barson et al., 2000). The estimated rate of channel widening is converted to units of tonnes of sediment contributed to the river reach by multiplying the lateral bank erosion rate by the bank height (assumed to be 1.3 m), the length of the river link and an assumed sediment density of 1.5 t/m$^3$. 

12 3.6 Riverbank erosion
3.7 Sediment Deposition

3.7.1 Floodplains

Sediment deposition upon floodplains is modelled according to the method described in Prosser et al. (2001) as a function of the residence time of flood water upon the floodplain and the sediment concentration of flood flows. Floodplain width was calculated from the 25 m DEM using a threshold value of the MR-VBF algorithm of Gallant and Dowling (2003) of 3.5. Suspended sediment in flood flow is assumed to be evenly distributed through the water column. As evident from Figure 4, the original floodplain width estimations used by Read et al. (2003) included floodplain width values of less than 10 m or greater than 1000 m for some SedNet links. These were deemed to be either inappropriately small or excessively large for the style of landscape within the catchment. Consequently, in this study floodplain widths have been constrained to fall between 10 and 1000 m.

3.7.2 Reservoirs

Sediment deposition in reservoirs is estimated as a function of an empirical rule based upon the mean annual inflow into the reservoir and the reservoir’s total storage capacity (Heinemann 1981). In the Lake Burragorang catchment, sediment deposition was modelled for six reservoirs upstream of Lake Burragorang listed in Table 3 but not in Lake Burragorang itself.
### Reservoirs in the Lake Burrarorang catchment for which sediment deposition has been modelled.

<table>
<thead>
<tr>
<th>Reservoir</th>
<th>Construction date</th>
<th>Capacity (ML)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sooley</td>
<td>1930</td>
<td>4550</td>
</tr>
<tr>
<td>Wingecarribee</td>
<td>1974</td>
<td>34200</td>
</tr>
<tr>
<td>Wallerawang</td>
<td>1978</td>
<td>4300</td>
</tr>
<tr>
<td>Pejar</td>
<td>1979</td>
<td>9000</td>
</tr>
<tr>
<td>Lyell</td>
<td>1982</td>
<td>33500</td>
</tr>
<tr>
<td>Narambulla</td>
<td>no data</td>
<td>3300</td>
</tr>
</tbody>
</table>
3.8 Contribution of Suspended Sediment to Lake Burragorang

The contribution that each SedNet sub-catchment makes to sediment delivery to Lake Burragorang can be calculated by the model using the “contributor” algorithm. The internal catchment area for each SedNet link delivers a mean annual load of suspended sediment \( (LF_x) \) to the river network. This is the sum of gully, hillslope and riverbank erosion sources within that sub-catchment. The sub-catchment delivery and tributary loads constitute the load of suspended sediment \( (TIF_x) \) received by each river link. Each link yields some fraction of that load \( (YF_x) \) with the rest being deposited upon floodplains and/or in reservoirs. The ratio of \( YF_x/TIF_x \) is the proportion of suspended sediment input 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 sub-catchment will pass through a number of links on route to the reservoir. The contribution of sediment \( CO_x \), from sub-catchment \( x \) to the reservoir is calculated as the product of the loading \( LF_x \) from the sub-catchment and the probability of that loading passing through each river link on the way to the reservoir:

\[
CO_x = LF_x \times \frac{YF_x}{TIF_x} \times \frac{YF_{x+1}}{TIF_{x+1}} \cdots \frac{YF_n}{TIF_n}
\]

where \( n \) is the number of links on the route to the outlet. Dividing this contribution by the internal catchment area expresses the contribution to outlet export \( CO_x \) as an erosion rate \((t/ha/\text{y})\).

3.9 The ANNEX model

The nutrient budget model (Annual Network Nutrient Export - ANNEX) predicts the average annual loads of phosphorous and nitrogen in each link in a river network in a similar way to SedNet, with which it is run in conjunction (see Young et al. 2001 for more details). The model considers only the physical (not biological) stores of nutrients in the river system and is also primarily concerned with the physical nutrient transport processes. It does, however, consider denitrification - a biological process resulting in loss of nitrogen gas to the atmosphere and phosphorous adsorption-desorption, a physical process influenced by biological activity.

The main nutrient sources considered are those associated with sediments derived from hillslope erosion, gully erosion, riverbank erosion; dissolved loads in runoff water and finally, point sources, which in this case comprise sewage treatment plants within the catchment. As with SedNet, the model then routes nutrient loads through the river network estimating the losses associated with floodplain and reservoir deposition and in-stream denitrification. A
The ANNEX model is given in Figure 5. Estimates of the nutrient concentration of each SedNet sub-catchment can be derived using the same procedure as for sediments.

Figure 5: ANNEX Schematic.
3.10 Total Nitrogen and Total Phosphorus

The total nitrogen and total phosphorus content of surface soils across the catchment was estimated using national scale total nitrogen and total phosphorus maps produced by Henderson et al. (2001) at 0.001 degrees resolution (approximately 1.1 km).

3.11 Point sources of nitrogen and phosphorus

Point source discharges of total nitrogen and total phosphorus from five sewage treatment plants in the catchment are listed in Table 4. These values have been derived from Department of Environment and Conservation (2005) and the National Pollution Inventory website (www.npi.gov.au) for the reporting year 2005.

<table>
<thead>
<tr>
<th>Plant</th>
<th>Easting</th>
<th>Northing</th>
<th>Total N (kg/yr)</th>
<th>Total P (kg/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lithgow</td>
<td>233913</td>
<td>6292392</td>
<td>17581</td>
<td>9371</td>
</tr>
<tr>
<td>Bowral</td>
<td>262306</td>
<td>6178480</td>
<td>28267</td>
<td>1000</td>
</tr>
<tr>
<td>Braemar</td>
<td>267805</td>
<td>6186802</td>
<td>4000</td>
<td>200</td>
</tr>
<tr>
<td>Goulburn</td>
<td>203459</td>
<td>6152827</td>
<td>2000</td>
<td>600</td>
</tr>
<tr>
<td>Moss Vale</td>
<td>256817</td>
<td>6173907</td>
<td>2000</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 4: Total nitrogen and total phosphorus discharges from sewage treatment plants in the Lake Burragorang catchment.

3.12 Dissolved nitrogen and phosphorus concentrations

The concentration of phosphorus and nitrogen in surface runoff has been estimated using a reclassified land use map generated by the Bureau of Rural Sciences (Barson et al. 2000) with 25 m pixels in conjunction with runoff concentrations calculated by DeRose et al. (2003) for equivalent land uses in the Goulburn- Broken catchment of Victoria. Table 5 lists the concentrations of dissolved nitrogen and phosphorus in runoff waters assigned to specific land uses in the Lake Burragorang catchment. It is worthwhile noting that these dissolved nutrient values are derived from Victoria and may not accurately represent dissolved nutrient generation rates in the Lake Burragorang catchment. At the time of writing, the Sydney Catchment Authority has research underway to derived local dissolved nutrient generation rates which, in future
<table>
<thead>
<tr>
<th>Value</th>
<th>Landuse</th>
<th>Soluble N (µg/L)</th>
<th>Soluble P (µg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Not classified</td>
<td>287</td>
<td>4</td>
</tr>
<tr>
<td>1</td>
<td>Pasture, Crop, non woody vegetation</td>
<td>510</td>
<td>8</td>
</tr>
<tr>
<td>2</td>
<td>Urban</td>
<td>3450</td>
<td>605</td>
</tr>
<tr>
<td>3</td>
<td>Bare ground</td>
<td>500</td>
<td>8</td>
</tr>
<tr>
<td>4</td>
<td>Water</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>Plantation forest</td>
<td>287</td>
<td>4</td>
</tr>
<tr>
<td>6</td>
<td>Orchard</td>
<td>2250</td>
<td>250</td>
</tr>
<tr>
<td>7</td>
<td>Native or exotic woody vegetation</td>
<td>287</td>
<td>4</td>
</tr>
</tbody>
</table>

Table 5: Dissolved nutrient concentrations associated with different land uses in the Lake Burragorang catchment, based on DeRose et al. (2003).

modelling efforts, may be more applicable than the values of DeRose et al. (2003) adopted here.
4 Results

The results section is comprised of two parts. The first describes the evaluation of model performance against a set of independent catchment data sets for four model parameterisations. The second section examines the various budget predictions for suspended sediments and nutrients.

4.1 Model Evaluation structure

Table 6 lists details of a series of SedNet parameterisations explored in this study for the Lake Burragorang catchment. Model A represents the model of Read et al. (2003) and serves as a reference against which improvements to model performance can be gauged. Model B involves adjustments to the gully erosion and floodplain width terms of the SedNet model but retains the RUSLE hillslope erosion model. Model C involves applying a sediment delivery rate of 40 t/km²/yr to any forested area within the catchment. Model D is the same as for model C except that the RUSLE hillslope erosion model has been retained in the Wollondilly and Mulwaree River sub-catchments above their confluence. Model E is the same as for model D but the gully production ratio term has been increased from 0.2 to 0.35.
<table>
<thead>
<tr>
<th>Model</th>
<th>Floodplain width</th>
<th><strong>Model Parameters</strong></th>
<th>Hillslope Erosion</th>
<th><strong>Kendall Correlation Coefficient</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>unconstrained</td>
<td>100 yr period 10 m² cross section production ratio = 1 50% fine sediment</td>
<td>RUSLE with 5% HSDR</td>
<td>0.43</td>
</tr>
<tr>
<td>B</td>
<td>10 m &lt; width &lt; 1000 m</td>
<td>150 yr period 23 m² cross section production ratio = 0.2 % fine sediment based on geology</td>
<td>RUSLE with 5% HSDR</td>
<td>0.43</td>
</tr>
<tr>
<td>C</td>
<td>as above</td>
<td>as above</td>
<td>40 t/km²/yr forest yield RUSLE elsewhere with 5% non-forest HSDR</td>
<td>0.71</td>
</tr>
<tr>
<td>D</td>
<td>as above</td>
<td>as above</td>
<td>40 t/km²/yr forest yield (except forests of upper Wollondilly River and Mulwaree River) RUSLE elsewhere with 5% non-forest HSDR</td>
<td>0.71</td>
</tr>
<tr>
<td>E</td>
<td>as above</td>
<td>as above but production ratio = 0.35</td>
<td>as above</td>
<td>0.64</td>
</tr>
</tbody>
</table>

Table 6: Summary of changes to the SedNet modelling of sediment sources within the Lake Burragorang catchment and correlation coefficients for comparisons with gauging station flux estimates. The $p$ values show the statistical significance of the correlations.
4.2 Evaluation of model performance

Evaluation of the SedNet predictions derived from models A to E are made against four independent measurements of catchment behaviour:

1. Total suspended sediment yield as estimated at eight gauging stations within the catchment (omitting stations 212016 and 212280 which were used to calibrate the model).
2. Area specific suspended sediment yields as estimated at eight gauging stations within the catchment.
3. Geochemical confluence tracing data.
4. Geochemical erosion process tracing data.

4.2.1 Total and Area specific suspended sediment yield

Total suspended sediment yields as estimated at eight gauging stations within the catchment for which suspended sediment rating curves could be constructed are used to examine the accuracy of the suspended sediment fluxes predicted by SedNet. Figure 6 shows the relationships between predictions of suspended sediment fluxes at SedNet links corresponding to gauging station locations and the equivalent mean annual suspended sediment fluxes estimated estimated using suspended sediment rating curves. The Kendall rank correlation parameter for each comparison is also reported in Table 6. This correlation coefficient represents the probability that any two pairs of data will be concordant (i.e. positively related) versus the probability that they will be discordant (i.e. negatively related) and essentially compares sample ranks. It falls within the range -1 to +1, with a value of zero representing no correlation. This correlation coefficient is arguably most appropriate for examining the area specific yields where the minimum desirable outcome is that the ranking of points should be as concordant as possible indicating that the model is at least accurately differentiating the high from low yielding regions. Whether or not this relationship is linear is arguably of secondary importance.

Examining the results in sequence, two main points emerge. Firstly, the correlation between observed and predicted total yields are better than for area specific yields. This is not surprising and simply indicates that the model can predict large fluxes at large catchment areas. Secondly, the predictions of Read et al. (2003), or Model A in Figure 6, using a “best-guess” model parameterisation are poorly related to the area specific yields. This changes little under the Model B scenario, indicating that changes to the sediment yield from adjusting the gully erosion and floodplain width variables provided little improvement to the overall predictions. Indeed
there remained virtually no correlation between the area specific yields under the Model B sce-
nario. A major increase in the correlation between observed and predicted mean annual loads
is obtained by implementing the uniform yield from forested catchments of 40 t/km$^2$/yr. Not only
do the totals yield predictions agree much better, but there is a statistically significant positive
correlation for the area specific yield. The model D parameterisation made no difference to
the correlation coefficients for either total or area specific sediment yields. Model E caused a
minor regression in the correlation coefficient for total yield (due to a swap in the rankings of
stations 212271 and 212260) but the area specific yield correlation remained unchanged and
both correlations were statistically significant.

As a means of summarising the changes in model performance, Figure 7 shows the “dis-
crepancy ratio’ between SedNet predictions and the mean annual suspended sediment fluxes
estimated at the eight non-calibration gauging stations using sediment rating curves. This ratio,
$D_r$, is calculated as:

$$D_r = 10^{\log(\text{observed}) - \log(\text{predicted})}$$

(11)

Note that the vertical bars around the difference part of the equation mean the absolute
value of this difference was used. $D_r$ equates to the factor by which the modelled and observed
results agree (either higher or lower) and a value of 1 indicates perfect agreement. A value
of 2 means that the predictions agree within the observed values within a factor of two (either
higher or lower) whilst a value of 10 means the predicted values differ from the observed values
by an order of magnitude. The gauging stations have been ranked by discrepancy ratio and
their ranks normalised by the number of stations. From Figure 7 it is clear that the changes
made to the SedNet modelling have reduced the discrepancy ratio from values exceeding 90
in the preliminary model results of Read et al. (2003) to a maximum discrepancy ratio of 6.5
under Model's C, D and E. Moreover, under any of these three parameterisations, 80% of
the predictions at the gauging stations have a discrepancy ratio less than or equal to 2.8.
Considering that the total yield estimates vary over more than two orders of magnitude across
the catchment, this represents a major improvement in model performance. As noted above,
the most substantial improvement in the overall discrepancy ratio distribution was a result of
implementing the 40 t/km$^2$/yr yield for forested areas (Model B to Model C). Models C, D and
E are however not fully representing the range of area specific sediment yields observed at
the gauging stations. Low yielding sub-catchments are being over predicted and high yielding
sub-catchments are being under predicted.

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4.2 Evaluation of model performance
Figure 6: SedNet modelling results compared to total and area specific suspended sediment yields estimated at 8 gauging stations within the Lake Burragerang catchment. Each row of the Figure represents a sequential change to the model parameterisation as outlined in Table 6.
Figure 7: Observed versus predicted discrepancy ratio for total mean annual suspended sediment yield at ten gauging stations sites in the Lake Burragorang catchment for four model parameterisations.
4.2.2 Geochemical confluence tracing data

Using the geochemistry of fine sediment samples collected from upstream and downstream of major stream confluences (Caitcheon et al. 2006), the relative proportions of sediment contributed from the tributaries to a downstream river link can be computed. These proportions can then be compared with equivalent predictions produced by the SedNet model. Figure 8 shows the observed versus predicted confluence tracing results for the various iterations of the SedNet model, as described in Table 6.

For the Mulwaree–Wollondilly River confluence, the SedNet model under parameterisation C is performing reasonably, with the predictions consistent with the tracer data given their uncertainties. However, the model is predicting the Wollondilly River to be the dominant source of sediment downstream of this confluence and such a scenario is at the margins of the empirical data distribution. Model parameterisations A, B, D and E are incongruent with the geochemical tracing observations, but model A is clearly performing the worst of these.

For the Wollondilly–Tarlo River confluence, all five SedNet predictions are consistent with the observed data, falling within the uncertainty of the observed data points. More significantly though, the changes from the Read et al. (2003) modelling (models B to E) have reduced the discrepancy between observed and predicted percentage contribution. The major improvement in model performance at this confluence was associated with the Model B changes.

For the Wollondilly–Wingecarribee–Guineacor confluence, it is clear that the preliminary modelling was entirely inconsistent with the tracer data with a very strong predicted contribution from the Wollondilly River at the expense of the two other tributaries. Model B reduced the discrepancy but still not to the point of agreement with any of the data. Under the model C parameterisation with the 40 t/km\(^2\)/yr forest yield, the Wingecarribee contribution is consistent with the contribution estimated from the tracer data, though over prediction still occurs for the Wollondilly River. Model D rectifies this to a very minor degree whilst model E represents a small regression in model performance. In essence, models C to E appear to be underestimating the sediment yields from Guineacor Creek at the expense of the Wollondilly River. Whilst the agreement with the tracer data is weak, it is clear that revising the hillslope sediment yields to 40 t/km\(^2\)/yr from the forested lands substantially improved the agreement between observed and predicted data. It is possible that further increases in forest hillslope sediment yield for the Wingecarribee River and Guineacor Creek sub-catchments beyond 40 t/km\(^2\)/yr, perhaps to values closer to the 155 \(\pm 85 - 41\) t/km\(^2\)/yr observed for the Kowmung River would further improve the model’s performance at this confluence.

4 RESULTS
Figure 8: Comparison of confluence tracing results and equivalent SedNet predictions. The observed data are shown by the black dots with uncertainties represented by the horizontal bars. The various iterations of the SedNet model, as described in Table 6 are plotted as open triangles.
4.2.3 Geochemical erosion process tracing data

Fallout radionuclides have been used by Caitcheon et al. (2006) to determine the percentage of fine sediment generated from hillslope erosion versus the proportion generated by erosion of subsoils (gully erosion and river bank erosion) using a two-part mixing model. This mixing model can be expressed as:

\[ x = \frac{r - g}{h - g} \times 100 \] (12)

where \( x \) is the percentage of sampled sediment contributed from surficial \(^{137}\text{Cs}\) labelled sediments, \( r \) is the \(^{137}\text{Cs}\) activity (Bq/kg) of the river sediment sample, \( g \) is a representative \(^{137}\text{Cs}\) activity for gully samples and \( h \) is a representative \(^{137}\text{Cs}\) activity for hillslope samples. In this case, \( h \) is estimated as the mean of a representative value of surficial pasture soils and a representative value of surficial forest soils. A critical issue that thus arises is the selection of representative values of \( h \) and \( g \) as from Equation 12, it can be seen that larger values of \( h \) will give lower percentage contributions of surficial soils, \( x \). Caitcheon et al. (2006) used the mean \(^{137}\text{Cs}\) activities of both pasture (denoted \( p \)) and forest (denoted \( f \)) samples to calculate \( h \). However, from Figure 9 it is evident that the distribution of data points for forest and pasture landuses in particular are strongly positively skewed, with both having a high activity outlying data point. The appropriateness of using a mean value to represent such distributions is debatable and doing so has the effect of increasing \( h \) relative to \( g \) and thus decreasing the percentage hillslope erosion contribution of a river sample \( r \).

An alternative model would be to adopt the median values of the \(^{137}\text{Cs}\) activity for all three end members and use these median values in the mixing model. This has the effect of increasing the contribution of hillslope derived sediments in the river sediment samples, as shown in Table 7. One disadvantage of taking the median end-member approach is that a greater number of river sediment samples have \(^{137}\text{Cs}\) activities that exceed the calculated hillslope end member and give apparent hillslope contributions greater than 100\%. Whilst values greater than 100\% are not sensible, they are essentially an artefact of representing the distribution of hillslope sediment sources, which range from 0.5 to 43 Bq/kg with single number. At the very least though these \( > 100 \% \) samples indicate a strong contribution from hillslope sediments.

Table 8 lists the percentage of hillslope derived fine sediment predicted by SedNet along with the equivalent values estimated using the mean and median end-member mixing models, as described above. From these data the discrepancy between the observed and predicted data is represented by the “absolute error”, calculated as the absolute value of the observed
minus predicted percentage contribution from hillslope erosion in units of percentage points. Lower values represent a better agreement between observed and predicted data with a value of 0 percentage points indicating perfect agreement. Figure 10 shows the overall changes in model performance under models A to E.

**Figure 9:** $^{137}$Cs activity for forest, pasture and gully sediments from the Lake Burragorang catchment. Individual samples are shown as dots whilst the vertical bars above show the mean and median value of each set of samples.

4.2 Evaluation of model performance
<table>
<thead>
<tr>
<th>River Sample</th>
<th>Mean End-member Model</th>
<th>Median End-member Model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>r (Bq/kg)</td>
<td>g (Bq/kg)</td>
</tr>
<tr>
<td>Wollondilly u/s Mulwaree</td>
<td>2.03 0.31</td>
<td>0.9 9 15.4 12.2 10</td>
</tr>
<tr>
<td>Wollondilly d/s Mulwaree</td>
<td>3.3 0.31</td>
<td>0.9 9 15.4 12.2 21</td>
</tr>
<tr>
<td>Mulwaree u/s Wollondilly</td>
<td>3.87 0.22</td>
<td>0.9 9 15.4 12.2 26</td>
</tr>
<tr>
<td>Wollondilly u/s Tarlo</td>
<td>4.3 0.22</td>
<td>0.9 9 15.4 12.2 30</td>
</tr>
<tr>
<td>Tarlo u/s Wollondilly</td>
<td>6.86 0.36</td>
<td>0.9 9 15.4 12.2 53</td>
</tr>
<tr>
<td>Wingecarribee u/s Wollondilly</td>
<td>18.17 0.36</td>
<td>0.9 9 15.4 12.2 153</td>
</tr>
<tr>
<td>Wollondilly d/s Guineacor</td>
<td>11.42 0.26</td>
<td>0.9 9 15.4 12.2 93</td>
</tr>
<tr>
<td>Wollondilly d/s Tarlo u/s</td>
<td>4.75 0.41</td>
<td>0.9 9 15.4 12.2 34</td>
</tr>
<tr>
<td>Wingecarribee u/s Guineacor</td>
<td>11.72 0.28</td>
<td>0.9 9 15.4 12.2 96</td>
</tr>
<tr>
<td>Wollondilly Arm of Lake Burrarorang</td>
<td>8.36 2.03</td>
<td>0.9 9 15.4 12.2 66</td>
</tr>
</tbody>
</table>

**Table 7:** Variations in percentage sediment sourced from hillslope erosion from different specification of gully and hillslope end members in the two-part mixing model. Column headings are described in the text.
Table 8: Erosion process tracing results and comparison with SedNet predictions.

<table>
<thead>
<tr>
<th>River reach</th>
<th>Mean end member model</th>
<th>Median end member model</th>
<th>Model A</th>
<th>Model B</th>
<th>Model C</th>
<th>Model D</th>
<th>Model E</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wollondilly upstream of Mulwaree</td>
<td>10</td>
<td>17</td>
<td>23</td>
<td>36</td>
<td>42</td>
<td>36</td>
<td>25</td>
</tr>
<tr>
<td>Wollondilly downstream of Mulwaree</td>
<td>21</td>
<td>29</td>
<td>15</td>
<td>38</td>
<td>50</td>
<td>40</td>
<td>28</td>
</tr>
<tr>
<td>Lower Mulwaree</td>
<td>26</td>
<td>35</td>
<td>19</td>
<td>44</td>
<td>62</td>
<td>44</td>
<td>32</td>
</tr>
<tr>
<td>Wollondilly upstream of Tarlo</td>
<td>30</td>
<td>40</td>
<td>17</td>
<td>41</td>
<td>61</td>
<td>59</td>
<td>46</td>
</tr>
<tr>
<td>Lower Tarlo</td>
<td>53</td>
<td>66</td>
<td>23</td>
<td>50</td>
<td>69</td>
<td>69</td>
<td>66</td>
</tr>
<tr>
<td>Lower Wingecarribee</td>
<td>100</td>
<td>100</td>
<td>51</td>
<td>75</td>
<td>95</td>
<td>95</td>
<td>92</td>
</tr>
<tr>
<td>Wollondilly downstream of Guineacor</td>
<td>93</td>
<td>100</td>
<td>23</td>
<td>50</td>
<td>72</td>
<td>72</td>
<td>61</td>
</tr>
<tr>
<td>Wollondilly between Tarlo and Wingecarribe</td>
<td>34</td>
<td>44</td>
<td>20</td>
<td>45</td>
<td>64</td>
<td>63</td>
<td>51</td>
</tr>
<tr>
<td>Lower Guineacor</td>
<td>96</td>
<td>100</td>
<td>36</td>
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</table>

Figure 10: Distribution of erosion process tracing discrepancies. The discrepancies are given as the magnitude (in percentage points) of the difference between the observed tracer-based and predicted percentages for the mean end member mixing model (left) and median end member mixing model (right).
It is clear from Figure 10 that the Model A and B parameterisations performed relatively poorly against both representations of the tracer data, with the percentage sediment predicted to be sourced from hillslope erosion in error by over 50 percentage points for some stations. Of the remaining three model parameterisations, model E matches the tracer data the closest overall and shows a notable improvement over models C and D. This strongly suggests that the gully production ratio of 0.35 implemented in model E is more appropriate for the Lake Burragorang catchment (or at least the Wollondilly River sub-catchment) than the value of 0.2 adopted in models B to D. Models C to E are also reasonably consistent with the proportion of hillslope sediment deposited in the Wollondilly arm of Lake Burragorang (estimated to be 66 to 81% using data from Caitcheon et al. 2006). Models A and B had 23% and 49% hillslope contributions at the reservoir respectively, neither of which are consistent with these observations drawn from sediment deposited in the reservoir.

4.3 Inter-comparison of model predictions

Clearly there are a range of potential model parameterisations that could be applied to the Lake Burragorang catchment to predict sediment sources. There is clear evidence that models A and B have a relatively poor agreement with all or most of the empirical data from the catchment. There is however ambiguity about whether models C, D or E represents the closest match to the observational data. This ambiguity stems in part from subjective assessments of which aspect of the budget is considered the most critical: is it the magnitude of the fluxes, the correct prediction of the relative contribution of surface versus subsoil sources or the correct prediction of the relative loads at river junctions, for example?

In such situations a comparison of the basin wide predictions of sediment contribution can provide a useful perspective. If the spatial pattern of sediment sources are insensitive to these parameterisations then, for operational purposes, the differences in model performance may not be of consequence. Figure 11 shows the predicted patterns of suspended sediment contribution to Lake Burragorang from SedNet parameterisations A, B, D and E and Figure 12 shows the same data but with mainly forested sub-catchments excluded. Note that in the classification scheme adopted in these figures, the spatial pattern of sediment contribution of models C and D are indistinguishable. Model A shows high contribution rates from the middle Cox’s River sub-catchment, the middle reaches of the Wollondilly River and parts of the upper Wollondilly River. This reflects the high rates of sediment input from gully erosion in this model and generally low rates predicted for forest environments by the RUSLE. Model B, with a reduced gully production ratio and longer formation epoch (offset to some degree by an increased gully
cross sectional area) has reduced the contribution rates from the high yielding areas of Model A, but the overall spatial pattern of sediment sources remains similar. The forested areas near the Lake are universally predicted to be contributing at low rates. Implementing the 40 t/km²/yr sediment yield rate from forested areas other than in the Upper Wollondilly and Mulwaree River sub-catchments (model D) substantially increases the predicted contribution rate from sub-catchments near the reservoir to the point where the forested catchments are predicted to contribute fine sediment at a higher rate than the majority of catchments in the Upper Wollondilly River and Wingecarribee River sub-catchments, for example. The lack of differentiation of the contribution rate from the forested sub-catchments near the reservoir stems from the uniform rate of hillslope sediment input in these environments. Increasing the gully production ratio to 0.35 (model E) increased the contribution rate from the middle reaches of the Wollondilly River, the Tarlo River, parts of the Coxs River and Guineacor Creek sub-catchments where gully erosion has occurred.
Figure 11: Contribution rate of fine sediment to Lake Burragorang under SedNet parameterisations A to E.
Figure 12: Contribution rate of fine sediment to Lake Burragorang under SedNet parameterisations A to E. Green sub-catchments are mostly forested sub-catchments.
Table 9 lists summary statistics of the suspended sediment budgets for the Lake Burragorang catchment for the five model parameterisations. The model A budget has input from gully erosion being the dominant input term. The total rate of sediment input to the river network under model B is roughly 50% that of model A and sediment storage on floodplains has been more than halved. Model C, with the 40 t/km$^2$/yr sediment yield rate from forested environments has a five fold increase in hillslope sediment input relative to models A and B such that hillslope sediment input is predicted to be the dominant sediment source within the catchment. Total sediment delivery to the reservoir is estimated to be $\sim$ 225 kt/yr under model C. Model D has a 2.5% decrease in hillslope sediment input (relative to model C). This decline is attributable to lower rates of predicted hillslope input in the catchments above the Wollondilly-Mulwaree River confluence from applying the RUSLE model relative to the uniform 40 t/km$^2$/yr forest input rate of model C. Net delivery to the reservoir for model D is within 1% of model C. Model E has a much larger rate of sediment input from gully erosion than models B to D and the highest rate of total sediment input to the river network and delivery to the reservoir.

Estimates of the suspended sediment yield to Lake Burrarorang by Rustomji and Wilkinson (in preparation) from gauged tributaries suggests an annual delivery rate of $466^{+428}_{-189}$ kt/year, with $251^{+264}_{-49}$ coming from the Wollondilly River alone. Models A and B are predicting substantially lower rates of delivery to the reservoir relative than these gauging station-derived loads. Models C, D and E are still below the gauging station based load estimates but closer to the lower extent of the 95% confidence interval value (277 kt/yr) for the total load estimates based on the gauging station data. It is clear from Figure 6 that the total yields from the lower most gauging stations on the Wollondilly, Coxs and Kowmung Rivers are all being under-predicted by models C to E.

### 4.4 Model evaluation summary

This section of the report has explored, through a number of parameterisations of the SedNet model, variations in the predicted magnitude and spatial pattern of sediment transport in the Lake Burragorang catchment and compared these predictions to a range of observational data including geochemical tracing of river confluence contributions and erosion processes and finally, estimation of suspended sediment loads at eight gauging stations within the catchment. Variations in model performance were assessed relative to a “default” model parameterisation constrained by relatively little local data.

The preliminary model predictions (model A) derived using default model parameters and minimal local calibration agreed the least with the majority of the observational data from the
Table 9: Comparison of suspended sediment budgets for SedNet parameterisations A to E. Units are kilotonnes per year.

catchment. Model B, whilst better than model A in a number of tests still performed relatively poorly. Models C, D and E represent a substantial improvement in predictive accuracy when compared to the suspended sediment loads estimated at the network of river gauging stations in the catchment. Model E shows the best agreement with the erosion process tracer data and is comparable to models C and D in the confluence tracing comparison and the agreement with the gauging station based load estimates.

Local calibration clearly improved model performance and resulted in the maximum discrepancy in observed versus predicted sediment loads falling from a factor of 93 to less than 6 and the predicted suspended sediment loads at most (80%) gauging stations agree with the flux estimates produced using suspended sediment rating curves by a factor of \( \leq 2.8 \). Given that the range of mean annual suspended sediment flux estimates at the gauging stations vary by more than a factor of 100, this remaining discrepancy is comparatively small. Substantial improvements have also been made in the prediction of the relative ranking of high and low yielding sub-catchments as judged by the improved correlations between area specific sediment yields.

The agreement between SedNet predictions and the spatial (confluence) tracing and ero-
sion process tracing observations was improved in comparison to the preliminary model results, particularly regarding the erosion process predictions for sediments deposited in the reservoir. However, accurately representing confluence proportions from the upper Southern Tablelands has been less successful. This is most likely because the most substantial variation explored in this comparative exercise has been to alter the rate of sediment supply from forested hillslope erosion. The impetus for this change was sediment yield data from two Sydney Basin sandstone catchments in close proximity to the reservoir. The lack of agreement between model predictions and observational data when varying the forest sediment yields in this manner for the Southern Tablelands river reaches suggests that the forest yields estimated from the two gauging stations near the reservoir may not be appropriate for use in the drier environments of the southern Tablelands with their differing geomorphology and geology. There is some evidence that retaining the RUSLE model for predicting forest erosion rates for the Mulwaree River catchment and the Wollondilly River sub-catchment above its confluence with the Mulwaree improves the predictions of the proportion of sediment derived from hillslope erosion, however there is less evidence to support this when considering the confluence tracing results. In any case this change makes negligible difference to the catchment's sediment budget (as is described below). A gully production ratio of 0.35, in conjunction with the model D hillslope sediment yield model represents the optimal prediction of erosion process dominance in the catchment.

These observations do suggest that model E is the representation of the Lake Burragorang catchment sediment budget most consistent with the available data from the catchment. It thus represents the best set of model predictions that can be derived from the presently available data. The following sections examine in more detail the sediment and nutrient budget predictions from the model E parameterisation, making reference where appropriate to other model predictions.

4.5 Spatial distribution of sediment sources

Figures 13, 14 and 15 show the spatial pattern of sediment input to the river network from gully, hillslope and riverbank erosion. Note that the classes used to depict the rates of supply vary between the figures.

The majority of the Wollondilly River catchment (apart from the Wingecarribee tributary) and the Upper Coxs River catchment are predicted to contribute sediment to the river network from gully erosion at moderate to high rates. Within these sub-catchments there are a number of localised areas of relatively higher levels of sediment input from gully erosion, with area
specific sediment yields in the range 0.25 to 0.51 t/ha/yr. However, whether these high yielding sub-catchments should be the focus of treatment efforts should be evaluated in respect to the contributions these areas make in the overall catchment sediment budget.

The pattern of sediment input from hillslope erosion is strongly dominated by the 40 t/km²/yr sediment yield (equivalent to 0.4 tonnes per hectare per year) from forested areas (excluding the Upper Wollondilly and Mulwaree River sub-catchments). An extensive area surrounding the reservoir is predicted to supply sediment to the river network at this rate. These predicted rates of sediment input from hillslope erosion are comparable in magnitude to the rate of sediment input from the most intense areas of gully erosion.

Whilst total sediment yields for the Southern Tablelands in the post-European settlement period are generally known to be dominated by gully erosion (Olley and Wasson 2003), the conclusion reached above that sediment yields from predominantly un-gullied forested hillslopes are comparable to those of gullied agricultural areas of the catchment would seem to be incongruous. It is important to note however that the scenario being modelled here attempts to represent the prevailing conditions of the last few decades, not the average of the total post-European settlement period. Hence, contemporary rates of sediment supply from gully erosion have been scaled to be only 35% of the long term rate in model E to reflect relatively low rates of contemporary sediment supply from gully erosion (Olley and Wasson 2003; Rustomji et al. 2006).

Relatively low rates of river bank erosion are predicted for the Upper Wollondilly River and Mulwaree River sub-catchments as well as for the upper portions of the the Wollondilly River and Tarlo River sub-catchments. These low rates of bank erosion reflect the low discharge and slope characteristics of these environments that result in low rates of stream power. Bank erosion rates are predicted to be higher along the steeper reaches of the Wollondilly River (as it descends into its gorge reach) and along the steeper reaches of the Coxs and Kowmung Rivers. In reality, there is little evidence to either support or reject the accuracy of these predictions, either with regards to their magnitude or spatial pattern. In addition, bank erosion predictions in the Wingecarribee catchment may be inaccurate on account of the substantial augmentation of the natural river flow that occurs in this catchment as a result of inter-basin water transfers from the Shoalhaven River catchment. However, at less than 2% of total sediment input to the river network (see Table 10), river bank erosion is currently predicted to be a very small component of the catchment’s overall sediment budget. Hence, unless bank erosion rates are currently being severely underestimated (for which there is neither strong field or anecdotal evidence) these uncertainties are ultimately of little importance. Given the uncertainties in

4 RESULTS
these rates and that localised bank erosion at scales not represented by SedNet for example can still occur, the use of better data (where available) to manage bank erosion hazard is recommended.
Figure 13: Suspended sediment input to the river network from gully erosion.
Figure 14: Suspended sediment input to the river network from hillslope erosion.
Sediment input (Bank erosion)

(t/ha/yr)
0.00- 0.18
0.18 - 0.50
(t/m[active]/yr)
0 - 10
10 - 30
30 - 60
60 - 120
120 - 270

Figure 15: Suspended sediment input to the river network from riverbank erosion. Note that rates are given as tonnes per metre of “active” bank per year, where the “active” bank is the length of bank capable of eroding (ie. predicted to be alluvial and with low riparian vegetation).
4.6 Suspended sediment budget for the Lake Burragorang catchment

Table 10 lists the major components of the suspended sediment budget for the Lake Burragorang catchment predicted by SedNet under the model E parameterisation. The spatial pattern of suspended sediment contribution is shown in Figure 12E. The predicted mean annual supply of fine sediment to the river network is estimated to be 290 kt/yr, of which 220 kt/yr is predicted to be sourced from hillslope erosion, 61 kt/yr from gully erosion and 7 kt/yr from river bank erosion. In most sub-catchments, sediment input from hillslope erosion is predicted to be substantially greater than input from either river bank or gully erosion. Gully erosion is however predicted to be the dominant sediment source in the Upper Wollondilly River and Mulwaree River sub-catchments.

Approximately 18% of the sediment delivered to the drainage network is predicted to be stored in floodplain deposits (37 kt/yr) and reservoirs (16 kt/yr) upstream of Lake Burragorang. The majority of the reservoir deposition upstream of Lake Burragorang is predicted to occur in reservoirs in the upper Coxs River sub-catchment (note that sediment deposition within Lake Burragorang itself has not been included in the budget presented in Table 10). It is worthwhile noting that apart from some localised variations in the partitioning of sediment sources into hillslope and gully components, the main characteristics of the budget presented in Table 10 for model E are similar to those of models C and D.
<table>
<thead>
<tr>
<th>Sub-catchment</th>
<th>Sediment Inputs (t/yr)</th>
<th>Sediment Losses (t/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Hillslope erosion</td>
<td>Gully erosion</td>
</tr>
<tr>
<td>1 Kowmung R</td>
<td>25000</td>
<td>67</td>
</tr>
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<td>0</td>
</tr>
<tr>
<td>4 Lower Coxs R</td>
<td>9800</td>
<td>50</td>
</tr>
<tr>
<td>5 Mid Coxs R</td>
<td>33000</td>
<td>4400</td>
</tr>
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<td>3700</td>
<td>7300</td>
</tr>
<tr>
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<td>15000</td>
<td>320</td>
</tr>
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<td>8 Werribberi Ck</td>
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<td>0</td>
</tr>
<tr>
<td>9 Upper Coxs R</td>
<td>9600</td>
<td>1700</td>
</tr>
<tr>
<td>10 Upper Wollondilly R</td>
<td>6200</td>
<td>16000</td>
</tr>
<tr>
<td>11 Wingecarribee R</td>
<td>13000</td>
<td>830</td>
</tr>
<tr>
<td>12 Wollondilly R</td>
<td>67000</td>
<td>31000</td>
</tr>
</tbody>
</table>

Sub-total | 220000 | 61000 | 6900 | 290000 | -37000 | -16000 | -53000 |

Net supply to reservoir (t/yr) | 290000 | + | ( -53000 ) | = 237000 |

Table 10: Summary of the fine sediment budget for the Lake Burragorang catchment, disaggregated by sub-catchment and erosion process. Note that values have been rounded to two significant digits. Sediment deposition within Lake Burragorang itself has not been calculated in this study and hence the reservoir deposition values in this table do not include this.
Having established the pattern of suspended sediment sources in the Lake Burragorang catchment, we now consider the modelling of the catchments nutrient budgets. Figure 18 is a map of total nitrogen input to the SedNet river network from both diffuse and point sources. As the nitrogen loadings are strongly dominated by input from hillslope erosion (see Table 11), it is no surprise that the areas of high total nitrogen input (> 4 kg/ha/yr) are areas near the reservoir for which the highest hillslope erosion rates were predicted under the 40 t/km²/yr forest input rate, modulated partially by the soil nitrogen content (Figure 16). Nitrogen input to the stream network from the Southern Tablelands is generally lower, typically 4 t/ha/yr or less. Nitrogen input from urban areas around Bowral, Moss Vale and Mittagong cause local increases in area specific input rates for these SedNet sub-catchments of the Widgecarrribee River.

Dissolved nitrogen input, shown in Figures 20 and 21 (derived using a re-classification of landuse mapping) shows the urban areas to be noteworthy nitrogen sources. This is due to the dissolved nitrogen concentration of 3450 µg/l assigned to runoff from urban areas, which is five to ten times greater than that associated with grazing or forested lands.

Figure 19 is a map of total phosphorus input to the SedNet river network from both diffuse and point sources. Moderate to high rates of total phosphorus input (> 0.8 t/ha/yr) occur around the steep forested areas near the reservoir for which the highest hillslope erosion rates were predicted. This is in accordance with the budget presented in Table 12 showing the catchment’s phosphorus budget to be dominated by particulate phosphorus derived from hillslope erosion. Very high rates of total phosphorus generation are predicted for the northern end of the Upper Coxs River sub-catchment and these are associated with high phosphorus content in the local soils (Figure 17). The phosphorus contribution from the Lithgow sewage treatment plant (9.4 t/yr) also represents a notable input to the Upper Coxs River sub-catchment.

Dissolved phosphorus input, shown in Figures 22 and 23, is strongly dominated by the sub-catchments that have substantial urban areas (ie. contain the towns of Goulburn, Moss Vale, Mittagong, Bowral and Lithgow). Runoff from urban areas has been assigned a dissolved phosphorus concentration of 605 µg/l. This value is 75 to 150 times the runoff concentration assigned to grazing or forested lands respectively. Hence, despite their restricted spatial extent, the relatively high dissolved phosphorus concentrations urban areas means that they dominate the spatial pattern of dissolved phosphorus input.
Figure 16: Soil nitrogen content for SedNet sub-catchments.
Soil phosphorus content (g/kg)

0.07 - 0.34
0.35 - 0.61
0.62 - 0.88
0.89 - 1.14
1.15 - 1.41

Figure 17: Soil phosphorus content for SedNet sub-catchments.
Total nitrogen input (diffuse and point sources) (kg/ha/yr) (kg/yr)

- 0.2 - 2.0  □ 1,000
- 2.0 - 4.0  □ 2,500
- 4.0 - 6.0  □ 5,000
- 6.0 - 10.0 □ 7,500
- 10.0 - 16.0 □ 10,000

Figure 18: Total nitrogen input for each SedNet link normalised by internal catchment area. Sewage treatment plants are shown by the square point markers whose size varies in proportion to their total nitrogen input.
Figure 19: Total phosphorus input for each SedNet link normalised by internal catchment area. Sewage treatment plants are shown by the square point markers whose size varies in proportion to their total phosphorus input.
Figure 20: Dissolved nitrogen input to the SedNet network normalised by internal catchment area. The major towns within the catchment contributing dissolved nitrogen loadings are shown as black circles.
Figure 21: Dissolved nitrogen input to the SedNet network expressed as a concentration of internal catchment runoff. The major towns within the catchment contributing dissolved nitrogen loadings are shown as black circles.
Figure 22: Dissolved phosphorus input to the SedNet network normalised by internal catchment area. The major towns within the catchment contributing dissolved phosphorus loadings are shown as black circles.
Figure 23: Dissolved phosphorus input to the SedNet network expressed as a concentration of internal catchment runoff. The major towns within the catchment contributing dissolved phosphorus loadings are shown as black circles.
4.8 Nutrient budgets for the Lake Burragorang catchment

4.8.1 Nitrogen

The predicted nitrogen budget for the Lake Burragorang catchment generated by the model E parameterisation of SedNet is listed in Table 11. Input of nitrogen to the stream network is predicted to be strongly dominated by sediment-attached nitrogen delivered by hillslope erosion, with 2300 t/yr being delivered by this process. This represents 79% of the total nitrogen loading (2900 t/yr) delivered to the stream network. The mid Coxs River, Wollondilly River, Kowmung River and Lake Burragorang sub-catchments are all high contributors of particulate nitrogen derived from hillslope erosion. This high particulate nitrogen loading is related to the relatively high hillslope erosion rates incorporated under the model E scenario, lower rates of particulate input are predicted from models A and B for example that retained the RUSLE predictions across the entire catchment.

Dissolved nitrogen input is predicted to be the next most significant input term, providing an input of 460 t/year. Particulate nitrogen sourced from gully erosion in the Wollondilly River and Upper Wollondilly River sub-catchments are the dominant terms in the 130 t/yr of nitrogen derived from gully erosion. Point sources (discharges from sewage treatment plants) account for 54 t/yr of nitrogen loading, with a high contribution from the Bowral (28 t/yr) and Moss Vale (2 t/yr) sewage treatment plants. 18 t/yr comes from the Lithgow sewage treatment plant.

Predicted nitrogen losses due to storage on floodplains, in reservoirs and through denitrification together account for ∼11% (310 t/yr) of the total nitrogen input, with the majority of this associated with floodplain deposition (200 t/yr) and reservoir deposition (100 t/yr). Denitrification is estimated to be a relatively minor component of the budget. Overall, ∼2600 tonnes of nitrogen are predicted to be delivered to the reservoir per year. This predicted delivery rate of nitrogen under model E is essentially indistinguishable from that predicted under either models C or D.
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<td><strong>Sub-total</strong></td>
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<td><strong>130</strong></td>
<td><strong>14</strong></td>
<td><strong>460</strong></td>
<td><strong>54</strong></td>
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<th>Floodplain deposition</th>
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<td>−15</td>
<td>−2.5</td>
<td>−2.3</td>
<td>−20</td>
</tr>
<tr>
<td>12 Wollondilly R</td>
<td>−79</td>
<td>−8.6</td>
<td>−1.4</td>
<td>−89</td>
</tr>
<tr>
<td><strong>Sub-total</strong></td>
<td><strong>−200</strong></td>
<td><strong>−100</strong></td>
<td><strong>−13</strong></td>
<td><strong>−310</strong></td>
</tr>
</tbody>
</table>

| Net supply to reservoir (t/yr) | 2900 | + | ( - 310 ) | = 2590 |

**Table 11**: Summary nitrogen budget for the Lake Burragorang catchment, dis-aggregated by sub-catchment and process. Note that values have been rounded to two significant digits. Negative values represent material lost from fluvial transport through deposition or denitrification. Particulate nitrogen deposition within Lake Burragorang itself has not been calculated in this study and hence the reservoir deposition values in this table do not include this.
4.8.2 Phosphorus

The phosphorus budget for the Lake Burragorang catchment predicted by SedNet under the model E parameterisation is listed in Table 12. Input of phosphorus to the reservoir is predicted to be strongly dominated by particulate phosphorus attached to sediment delivered to the stream network from hillslope erosion, with 360 t/yr being delivered by this process. This represents 90% of the total phosphorus loading (400 t/yr) delivered to the stream network. The mid Coxs River, Wollondilly River, Kowmung River and Lake Burragorang sub-catchments are all high contributors of particulate phosphorus derived from hillslope erosion. Phosphorus liberated by gully erosion is the next most significant source contributing 32 t/yr. Most (78%) of this gully-generated phosphorus comes from the Wollondilly River and Upper Wollondilly River sub-catchments.

Point sources inputs (discharges from sewage treatment plants in this case) are predicted to account for 11 t/yr of phosphorus loading, with this value dominated by the 9.4 t/yr input from the Lithgow sewage treatment plant. Dissolved phosphorus input is predicted to provide 11 t/yr of phosphorus loading, of which the largest component (3 t/yr) comes from the Wingecarribee sub-catchment.

Predicted phosphorus losses due to storage in floodplains and in reservoirs accounts for approximately 20% (74 t/yr) of the total phosphorus input. Phosphorus storage upon floodplains (41 t/yr) and in reservoirs (33 t/yr) is approximately equal. Overall, 336 tonnes of phosphorus are predicted to be delivered to the reservoir per year.

Under the model C and D parameterisations, the predicted phosphorus load to the reservoir was 334 and 331 tonnes per year respectively. Similar to the nitrogen budget, these rates of delivery are essentially indistinguishable from the 336 tonnes per estimated under model E.
<table>
<thead>
<tr>
<th>Sub-catchment</th>
<th>Phosphorus Inputs (t/yr)</th>
<th>Phosphorus Losses (t/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Hillslope erosion</td>
<td>Gully erosion</td>
</tr>
<tr>
<td>1 Kowmung R</td>
<td>41</td>
<td>0.033</td>
</tr>
<tr>
<td>2 Lake Burragorang</td>
<td>49</td>
<td>0.019</td>
</tr>
<tr>
<td>3 Little R</td>
<td>5.1</td>
<td>0</td>
</tr>
<tr>
<td>4 Lower Coxs R</td>
<td>16</td>
<td>0.025</td>
</tr>
<tr>
<td>5 Mid Coxs R</td>
<td>64</td>
<td>2.5</td>
</tr>
<tr>
<td>6 Mulwaree R</td>
<td>7.8</td>
<td>3.5</td>
</tr>
<tr>
<td>7 Nattai R</td>
<td>10</td>
<td>0.16</td>
</tr>
<tr>
<td>8 Wermiberry Ck</td>
<td>7.5</td>
<td>0</td>
</tr>
<tr>
<td>9 Upper Coxs R</td>
<td>17</td>
<td>0.9</td>
</tr>
<tr>
<td>10 Upper Wollondilly R</td>
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<td>8.6</td>
</tr>
<tr>
<td>11 Wingecarribee R</td>
<td>14</td>
<td>0.45</td>
</tr>
<tr>
<td>12 Wollondilly R</td>
<td>110</td>
<td>16</td>
</tr>
<tr>
<td>Sub-total</td>
<td>360</td>
<td>32</td>
</tr>
</tbody>
</table>

| Net supply to reservoir (t/yr) | 410 | + | (−74) | = 336 |

**Table 12:** Summary phosphorus budget for the Lake Burragorang catchment, dis-aggregated by sub-catchment and process. Note that values have been rounded to two significant digits. Negative values represent material lost (through deposition) to downstream transport. Particulate phosphorus deposition within Lake Burragorang itself has not been calculated in this study and hence the reservoir deposition values in this table do not include this.
4.9  Spatial pattern of nutrient contribution to Lake Burragorang

Figure 24 shows the rate of contribution of both nitrogen and phosphorus to Lake Burragorang under the model E parameterisation.

4.9.1  Nitrogen

Predicted high rates of contribution of total nitrogen to Lake Burragorang occur along the western side of the mid-Coxs River sub-catchment plus much of the Kowmung, Nattai, Little River and Lake Burragorang sub-catchments. An area of high nitrogen contribution is predicted in the upper Wingecarribee River sub-catchment associated with high rates of dissolved and point source nitrogen input associated with urban areas. Low rates of nitrogen contribution are predicted for the upper Wollondilly and Mulwaree River sub-catchments.

4.9.2  Phosphorus

The pattern of phosphorus contribution to Lake Burragorang is slightly more focused than that of nitrogen. The highest rates of phosphorus contribution are located in the vicinity of the confluence of the Coxs and Wollondilly arms of Lake Burragorang. Moderately high levels of phosphorus contribution are also predicted for the mainly forested sub-catchments of the mid-Coxs River and lower Kowmung River. A zone of high phosphorus contribution is also predicted adjacent to the Wollondilly River between Guineacor Creek and the reservoir. Most of the Wingecarribee River sub-catchment (apart from the urban areas), the Mulwaree and Upper Wollondilly River sub-catchments are predicted to contribute phosphorus to the reservoir at a relatively low rate.
Figure 24: Predicted contribution of total nitrogen and total phosphorus from each SedNet sub-catchment to Lake Burragorang under the model E parameterisation.
5 Discussion

Five parameterisations of the SedNet model have been explored in this study, each evaluated against three independent data sets. The preliminary model predictions, model A, derived using default model parameters and minimal local calibration agreed the least with the majority of the observational data from the catchment. Models C, D and E represent a substantial improvement in model accuracy particularly when compared to the suspended sediment loads estimated at the network of river gauging stations in the catchment, though there are subtle differences in their performance in different areas of the Lake Burragorang catchment. For example, model C, with its uniformly high rate of sediment input from forested areas provided a much better representation of total load and erosion process dominance in many of the steeper, forested catchment, but simultaneously over predicted the proportion of hillslope derived sediment contributed to the drainage network in the upper Southern Tablelands region. Model D, by retaining the RUSLE predictions for forest hillslope erosion improved on this aspect as did increasing the gully production ratio in model E. Under model E there is still an unresolved issue of the SedNet model not accurately representing the range of area specific sediment yields within the catchment. The general pattern under models C to E is of a mild over prediction of area-specific suspended sediment yield for the low yielding areas, such as the upper Wollondilly and Mulwaree Rivers, yet an under prediction of suspended sediment yields at the lower end of the main rivers flowing through deep gorges. This includes the Kowmung, Coxs and lower Wollondilly Rivers.

Both in this study and that of Caitcheon et al. (2006), the dominance of hillslope erosion as a sediment source in the Lake Burragorang catchment has been established. What the current modelling highlights is that our current capacity to accurately represent forest sediment yields via the RUSLE model is low. It can be improved using observed sediment yields from forested gauging stations, which incidentally are substantially higher than had been predicted by the RUSLE model with a 5% hillslope sediment delivery ratio. At present though there is only a limited basis to distinguish areas of high hillslope forest yield from areas of low hillslope forest yield. Improving this aspect of the modelling would arguably lead to an improved capacity to accurately model area specific sediment yields in the Lake Burragorang catchment.

The geological, landscape and rainfall characteristics for much of the Southern Tablelands portion of the Wollondilly River catchment differ strongly from the Sydney Basin sandstone catchments used to derive the 40 t/km$^2$/yr forest sediment yield estimate and it may be that another value or set of values are more appropriate for areas such as the Upper Wollondilly
and Mulwaree River sub-catchments - at present the best that can be done is to retain the RUSLE modelling for the flatter and drier upper parts of the Wollondilly River.

Models A and B predict main sediment contributing sub-catchments to occur amidst the Southern Tablelands and the mid-Coxs River. The mainly forested areas are generally predicted to contribute at a relatively low rate. These predictions reflect generally low rates of predicted hillslope erosion for forested areas and relatively high rates of sediment supply from gully erosion. Models C and D predict similar spatial patterns of sediment contribution to Lake Burragorang. A relatively even rate of sediment contribution is predicted for much of the catchment, reflecting the uniform rate of sediment input adopted for all (model C) or most (model D) of the forested areas of the catchment. Relatively low contribution rates are predicted from the upper Wingecarribee River, the Mulwaree and Wollondilly Rivers above their confluence and the Coxs River above Lyell Dam. The contrast with models A and B is strong and essentially represents an inversion of the main sediment source areas and an inversion of the main erosion process responsible for generation of sediment delivered to the reservoir. Models C and D are however more consistent with much of the empirical data from the catchment. As noted above, important internal differentiation in sediment input rates from hillslope erosion almost certainly exist within the forested areas of Lake Burragorang and the higher area specific yields from the Kowmung River for example suggests that this could well be the case.

Model E, with its increased gully production ratio relative to models B to D starts to re-emphasise the significance of gully erosion as a secondary sediment source. Sub-catchments with a mixture of forest and gullied areas emerge in this model as areas of relatively high contribution rate and are clustered along the main stem of the Wollondilly River principally below its confluence with Paddys River and also occur amidst sections of the Tarlo River, Guineacor Creek and Coxs River sub-catchments.

Comparison of the SedNet modelling with the tracer data has been an important component of this study. However, it is worthwhile to consider the representativeness of this tracer data in comparison to longer term mean annual load estimates predicted by SedNet. The tracer data are based on a one-off collection of aggregated river sediment samples collected at various points in the drainage network. It is possible in the case of the confluence tracing results for example, that the tracer data may represent the effects of recent floods and may not be representative of the longer term pattern of sediment transport. As an example, it can be seen that the tracer data predict a broadly even contribution of sediment from the Wollondilly, Wingecarribee and Guineacor Creek tributaries despite vastly different catchment areas and the SedNet modelling struggled to represent this balance. Whilst the tracer data from this
confluence may be an accurate picture of the long term relative supply rate, this may just as easily not be the case. Potentially the rainfall that triggered the last major flood in these rivers and which deposited the sampled sediment may have preferentially fallen over the Guineacor Creek and Wingecarribee River catchments with relatively little falling on the Wollondilly River catchment. Hence, the contribution of the Wollondilly River may be underestimated at the expense of these smaller tributaries purely because of the nature of the last rainfall event. This is an issue inherent in all once-off sediment sampling and suggests that whilst the tracer data represent an important empirical data set, their sensitivity to recent rainfall and flood events may mean they are not always representative of the longer term pattern of sediment transport in the catchment.

5.1 Suspended sediment yields - comparison with other data

One of the greatest impacts upon the SedNet predictions presented in this study has been the application of a hillslope suspended sediment yield of 40 t/km²/yr for most or all of the forested area within the catchment. This value has been derived from mean annual suspended sediment fluxes estimated at two gauging stations within the Lake Burragorang catchment and predicts comparatively high sediment yields from forested areas relative to the RUSLE model with a 5% hillslope sediment delivery ratio. Given the leverage this has upon the predictions of models C, D and E, it is important to examine the veracity of the estimated suspended sediment fluxes at both the gauging stations and for the SedNet river links themselves. One method to do this is to compare the area specific sediment yields obtained by these two methods with other empirical data. In this case, a data set of sediment yields from Australian catchments compiled by Wasson (1994) and an estimate of reservoir sedimentation from Lake Burragorang itself obtained by Fredericks (1994) serve as the reference data and the comparison of these data sets is shown in Figure 25.

Three main features are apparent from this comparison. The first point to note is that an area specific sediment yield of 40 t/km²/yr falls within the middle to upper range of sediment yields observed from other Australian catchments. The yields at some gauging stations such as 212260, 212250 and 212270 (Kowmung River, Coxs River and lower Wollondilly River stations respectively) certainly have high area specific yields by Australian standards, though not excessively so. Secondly, the model E SedNet predictions are consistent with other observed catchment sediment yields from Australia. As noted above, the model predictions may in fact be under-predicting the suspended sediment yield from some of these higher yielding sub-catchments (such as at the Kowmung and Lower Wollondilly River gauging stations). Thirdly,
the sediment yield obtained by Fredericks (1994) appears as an anomalously high area specific yield in relation to the fluxes estimated at the gauging stations, the data of Wasson (1994) and also the SedNet predictions of this study. Fredericks’ estimated an annual supply rate of sediment of $2 \times 10^6$ t/yr. Whilst this included a bedload component, this value was still substantially larger than the $2.4 \times 10^5$ t/yr estimated by SedNet in this study and the $5 \times 10^5$ t/yr estimate derived from the gauging station data.

Thus, whilst the dominance of hillslope erosion from forested environments in the Lake Burragorang catchment in the catchment’s sediment and nutrient budgets may be unexpected, the sediment yields estimated in the model are consistent with other Australian data and cannot be discounted on the basis of their magnitude alone. Indeed, the possibility of high area specific sediment yields being generated from the forested parts of the catchment had been noted by Fredericks (1994) as an explanation of the high area specific sediment yields he estimated. Area specific suspended sediment yields of approximately 250 t/km$^2$/yr have been measured by McJannet et al. (2005) from the forested part of the Daintree River’s catchment in northern Queensland. Whilst being from a very different environment to the Lake Burragorang catchment, this result does serve to reinforce the notion that forested environments can yield relatively large amounts of sediment and that a priori assumptions that forested areas are inherently low yielding environments may be incorrect.

This study highlights the important role that a new data set of direct and detailed observations of sediment accumulation in the two arms of Lake Burragorang and below some minor tributaries could play in testing and constraining the modelled sediment fluxes to the reservoir. This information would provide independent data to evaluate the fluxes from the major tributaries and the sediment geochemistry may possibly be used to look at changes in sediment sources over time.

The empirical forest hillslope erosion model is obviously crude and, thus far, limited capacity to reliably differentiate high and low yielding forest areas for individual SedNet sub-catchments exists. The predicted importance of hillslope erosion from the steep forested lands of the catchment in the catchment’s overall sediment budget implies that better definition of such sediment yields may be an area worthy of future research. It is important to note that estimates of annual suspended sediment fluxes calculated at the ten gauging stations within the catchment (not shown) vary by several orders of magnitude from year to year (but also have a longer duration inter-annual trend), reflecting the highly variable hydrologic regime of the catchment.
Figure 25: Comparison of area specific sediment yields obtained in this study with data from Wasson (1994), Fredericks (1994) and suspended sediment fluxes estimated at 11 gauging stations within the catchment. Note that vertical bars denote a 95% confidence interval for the gauging stations flux estimates. Additionally, area specific sediment yields for nested gauging stations are reported as (a) the area specific yield of the total catchment (total yield) and also as (b) the marginal yield, being the extra sediment yield from the catchment area below any downstream gauging stations.
One of the other important components of the model predictions presented here is the choice to scale sediment generation from gully erosion to be 35% of the long term average rate (i.e. adopting a gully production ratio of 35%). This value is based on observed changes in sediment storage in parts of the catchment affected by gully erosion (Rustomji and Pietsch in press; Rustomji et al. 2006). However, future research could focus on better definition of the regional variation of this parameter and the controls upon it. The model results are however only marginally sensitive to the value of this parameter. A 7% increase in total yield to the reservoir was obtained by increasing the gully production from 0.2 to 0.35, an increase of 175%. As the gully erosion model is strictly linear (Prosser et al. 2001), changes in the percentage selected translate linearly into changes in sediment input from gully erosion, but the pattern of deposition upstream of the reservoir attenuates much of this additional sediment input.

The possibility exists that the predicted reservoir storage rates may be inaccurate due to sediment laden reservoir spills not being accounted for in the current algorithm. However, the catchment wide reservoir deposition rate of 15,600 t/yr (excluding deposition in Lake Burrage-rang itself) is a minor component of the 293,000 t/yr estimated total supply rate and comprises about half the total sediment “losses”, with the other major sediment loss being to floodplain deposition. Thus errors in this term will have limited impact on the overall sediment budget.
6 Conclusions

This study has applied the SedNet catchment sediment and nutrient budget model to the Lake Burragorang catchment to provide predictions of the source areas and processes responsible for generating the sediment delivered to Lake Burragorang over the last few decades (circa 1980 – 2000). Five model scenarios have been evaluated for their capacity to match three independent data sets from the catchment including:

1. suspended sediment loads estimated at gauging stations,
2. geochemical tracer data measuring the relative sediment contributions at river confluences,
3. geochemical tracer data measuring the relative contribution of surface versus sub-soil sediment sources.

It is clear from this evaluation that the capacity of the five model parameterisations (A to E) to match the observational data was not equal. The model that arguably most closely represented the observational data from the catchment (model E) had as its main feature a relatively high (40 t/km²/yr) rate of sediment supply from forested hillslopes (except those above the Wollondilly/Mulwaree River confluence), along with reduced rates of contemporary sediment supply from gully erosion (relative to the long term average rate). Both of these characteristics were drawn from independent studies of the catchment.

The model A parameterisation (with minimal local parameterisation) performed poorly in all evaluation metrics. The model B parameterisation performed poorly in relation to the suspended sediment flux estimates (distributed evenly across the catchment) but better against the tracer data, which were drawn from the Wollondilly River catchment. Thus it can be concluded that whilst model B represents some aspects of the Wollondilly River catchment as well as some other model parameterisations, it performs less well when applied elsewhere in the Lake's catchment and this under-performance appears to be related to an underestimation of suspended sediment input from hillslope erosion in forested areas (and perhaps other steep areas). Increasing sediment supply from hillslope erosion in forested areas (models C, D and E) resulted in a large improvement in the prediction of the sediment fluxes across the catchment and also in the prediction of the dominant erosion process responsible for generating the sediment delivered to the reservoir.

The model E parameterisation which overall most closely matched the observational data predicts that 240 kt/yr of fine sediment is delivered to the reservoir. The vast majority of this
sediment is predicted to be sourced from hillslope erosion in areas relatively close to the reservoir. Gully erosion is the next most significant sediment source. If the contributions from the majority-forested sub-catchments are disregarded, suspended sediment delivery to the reservoir is predicted to be dominated by the agricultural sub-catchments below Lyell Dam on the Coxs River and also from sub-catchments draining to the Wollondilly River between Paddys River and Guineacor Creek. Other notable source areas include much of the Tarlo River sub-catchment. The Mulwaree River, much of the upper Wingecarribee River and the Coxs River above Lyell Dam are predicted to contribute low rates of suspended sediment to the reservoir.

The nutrient budget predictions are strongly dominated by sediment-bound phosphorus and nitrogen input associated with the higher hillslope erosion rates predicted for the forested regions. Hence, whilst they have not been independently evaluated to the degree that the suspended sediment modelling has been, the dominance of particulate nutrients implies that improving the catchment’s sediment budget will also improve the nutrient predictions.

Delivery to the reservoir of 2590 t/yr of nitrogen and 336 t/yr of phosphorus are predicted by model E. Inputs of nitrogen and phosphorus from urban areas, both from the dissolved fraction in runoff from urban areas and through point source inputs from sewage treatment plants (particularly those at Lithgow and Bowral) make notable contributions from the non-forested regions. For both nitrogen and phosphorus contributions to the reservoir, the agricultural sub-catchments below Lyell Dam on the Coxs River represent important source areas, as are parts of the Tarlo River sub-catchment and the Wollondilly River downstream of its confluence with the Mulwaree River. The Mulwaree River represents an area of low nutrient contribution to Lake Burragorang.

The catchment sediment and nutrient budgets presented here are model predictions based on the best available data. There is however an ongoing need for future data collection and research to test the major conclusions drawn from these predictions. Moreover, this study has demonstrated large variations in model predictions can result from differing model parameterisations and that increasing the amount of local data in the model calibration phase clearly increases the accuracy of the resulting predictions. Uncritically applying existing models of hillslope and gully erosion to the Lake Burragorang catchment can yield model predictions that bear little resemblance to reality. At the very least, this study has identified that models such as the RUSLE may not be appropriate for use in areas far beyond their calibration realm and this arguably includes the steep forested lands that make up a sizable proportion of the Lake Burragorang catchment.
References


REFERENCES


