Suspended Sediment and Bedload Budgets for the Western Port Bay Basin

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**Background**

In February 2000 a three year study commenced that sought to detect the sources of sediment to Western Port Bay, as well as the redistribution of sediment within the Bay itself. This was funded by CSIRO Land & Water, Melbourne Water and EPA Victoria. The project was divided into three broad phases:

1) sediment accumulation and redistribution in the Bay;

2) modelling of sediment sources and transport; and

3) tracer based assessment of catchment sources.

The first phase dealing with sediment distribution within Western Port Bay has been published as a CSIRO technical report (47/01) by Hancock et al., 2001.

This report encompasses the work of Phase 2 of the project.

**Introduction**

A significant aspect of achieving ecologically sustainable land management is to ensure that the downstream impacts of land uses on streams are minimised. An essential part of minimising impact is to reduce the delivery of sediments from land to streams.

To put a particular land use or sub-catchment in context with the regional catchments in which it occurs requires us to conceptualise the critical sources, transport pathways and sinks of sediment in a catchment. We need to identify where sediment is derived from, where it is stored within the catchment, and how much is delivered downstream to rivers and the sea. To quantify sources, stores and delivery is to construct a sediment budget for a catchment or any part of a catchment. This is a critical step to conceptualise the context of land use in a large regional catchment and to focus more detailed studies on the areas of greatest potential impact.

Most catchments are complex systems, often with considerable variation in land use pressures, and diverse topography, soils, rainfall and vegetation cover. Thus before changing any particular management or even undertaking remediation measures we need to determine the spatial pattern of sediment transport.
Some parts of the landscape are inherently more at risk of increased erosion and sediment transport than others. It is important to identify these areas for priority management to ensure a sustainable future. For example, some landscapes have inherently poor soil that is prone to gully erosion if vegetation cover is reduced. Other factors that contribute to inherent risk of sediment and nutrient delivery to streams include steep slopes, high channel density, and high rainfall erosivity.

Sediment is derived chiefly from three types of processes:

- runoff on the land, termed surface wash and rill erosion or alternatively hillslope erosion;
- erosion of gullies formed as a result of land clearing or grazing; and
- erosion of the banks of streams and rivers.

In many cases one process far dominates the other in terms of delivering sediment to streams. The predominant process can vary from one part of a catchment to another. Management aimed at reducing sediment transport will need to target each process differently. For example, stream bank and gully erosion is best targeted by managing stock access to streams, protecting vegetation cover in areas prone to future gully erosion, revegetating bare banks and reducing sub-surface seepage in areas with erodible sub-soils. Surface wash erosion is best managed by promoting consistent groundcover, maintaining soil structure, promoting nutrient uptake and promoting deposition of eroded sediment before it reaches the stream. Consequently, it is quite important to identify the predominant sediment delivery process before undertaking catchment remediation or making recommendations for changed land use practice.

Sediment delivered to streams has several potential downstream impacts. High loads of suspended sediment, the silts and clays that are carried in the flow, degrade water quality in streams, reservoirs and estuaries. This is a result of both the sediment itself and the nutrients that the sediment carries. High concentrations of suspended sediment reduce stream clarity; inhibit respiration and feeding of stream biota; diminish light needed for plant photosynthesis; make water unsuitable for irrigation and require treatment of water for human use. The suspended sediment is also deposited in low energy environments. The main depositional environment for suspended sediment generated with the Western Port Bay basin is the in-shore marine environment of the Bay itself. Accelerated deposition in this area can smother aquatic
habitats and can increase turbidity through resuspension of the sediment. Not all suspended sediment delivered to streams is exported to the coast. Much of it is deposited along the way on floodplains, providing fertile alluvial soils, or it is deposited in reservoirs. The extent of this deposition is highly variable from one river reach to another. Deposition potential must be considered when trying to relate catchment land use to downstream loads of sediment.

The formation of gullies and accelerated erosion of stream banks can supply large amounts of sand and gravel to streams. These are transported as bedload, being rolled, and bounced along the bed of streams. Where streams are unable to transmit the load of sand and gravel downstream, it is deposited, burying the bed, and in extreme examples forming sheets of sand and fine gravel referred to as sand slugs (Rutherfurd, 2000). Sand slugs are poor aquatic habitat. They can prevent fish passage, they fill pools and other refugia, and are unstable substrate for benthic organisms (Jeffers, 1998).

**Western Port Bay**

The major contributory catchments of Western Port Bay are arranged radially around the Bay. There are also numerous other smaller streams that drain into the Bay. This report only considers the five major streams: Cardinia Creek, Bunyip River, Yallock Creek, Lang Lang River and the Bass River. These waterways drain into the east arm of Western Port Bay, which was identified by EPA as the primary zone of elevated turbidity in the Bay (EPA, 2000). Individual suspended sediment and bedload budgets are calculated for each of these.

Reconnaissance level sediment budgets for the streams of the Western Port Bay basin will provide an understanding of the critical processes of sediment transport that can lead to downstream impact. The budget will also identify sub-catchments with the greatest potential for downstream impact on aquatic ecosystems. These are the first steps toward better targeting of remedial and land conservation measures.
Methods

A practical framework to assess the patterns of sediment transport across a large complex area such as Western Port Bay is a spatial modelling framework. There are few direct measurements of sediment transport in regional catchments, and it is unrealistic to initiate sampling programs of river sediment loads and expect meaningful results within a decade. Furthermore, collation and integration of existing data has to be put within an overall assessment framework, and a large-scale spatial model of sediment transport is the most effective use of that data.

The modelling framework used in this study was the SedNet model (the Sediment River Network model). SedNet consists of a suite of ARCINFO scripts (coded in Arc Macro Language (AML)). The scripts are used to define river networks and their sub-catchments (from digital elevation models (DEMs)), process required input data, calculate the sediment budget for each link and compile the results. Details of the model and its application to regional catchments in Australia are described in Prosser et al., (2001a). That document describes all the equations and input data used. Here we give a brief descriptive summary of the approach.

The assessment of sediment transport is divided into three aspects: hillslope erosion as a source of sediment, gully erosion as a source of sediment, and river channels as a further source, receiver and propagator of the sediment. The methods used in each aspect of the spatial model are outlined below in brief. They were developed for the National Land and Water Resources Audit project on sediment budgets and reference is made to supporting technical documentation which contains details of the approach.

Hillslope erosion

Hillslope erosion from sheet and rill erosion processes was estimated using the Revised Universal Soil Loss Equation (RUSLE; Renard et al., 1997) as applied in the NLWRA (Lu et al., 2001). The RUSLE calculates mean annual soil loss \( Y \), tonnes ha\(^{-1}\) y\(^{-1}\) 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 \( P \):

**Equation 1**

\[
Y = RKLSCP
\]
The precise form of each factor is based on soil loss measurements on hillslope plots, mainly in the USA. Limited local calibration of the RUSLE factors, particularly the $C$ factor, have been undertaken in some catchments using plot scale measurements of erosion (Melvor et al., 1995; Scanlan et al., 1996).

*Gully erosion*

The spatial pattern of gullies in the Western Port Bay basin was derived primarily from mapping of gullies from aerial photographs. Aerial photographs were available for most of the study area and therefore it was possible to directly map most gullies (Figure 1).

![Map of gullies distribution](image)

**Figure 1** Distribution of gullies as mapped from aerial photographs

However, for the northern and south-eastern parts of the basin no aerial photographs were available (Figure 1) so the distribution of gullies was modelled using the mapped gullies and various predictive environmental variables. The methodology used to model these unmapped areas was similar to that used in the gully modelling carried
out for the NLWRA (see Hughes, *et al.*, 2001). In order to determine volumes of sediment being generated by gullies the measured and modelled gully data were converted into a gully density by averaging the gully data over a 10 km x 10 km grid. For each individual grid cell the entire length of gullies was measured (in kilometres) and then divided by the total area (in kilometres$^2$) of the grid cell. This gave a gully density measured as length of gully per unit area (km/km$^2$).

_River bank erosion_

The supply of sediment from riverbank erosion was calculated from the results of a global review of river bank migration data (Rutherfurd, 2000). The best predictor of bank erosion rate ($BE; \text{m y}^{-1}$) was found to be bankfull discharge ($Q_{1.58}; \text{m}^3 \text{s}^{-1}$) equivalent to a 1.58 year occurrence interval flow. To take account of the low natural rates of bank erosion that have been observed in Australian rivers with intact riparian vegetation (Brooks, 1999), a riparian vegetation condition factor was also included ($PR_x$):

**Equation 2**

$$BE = 0.008 \times (1 - PR) \times Q_{1.58}^{0.60}$$

The condition of riparian vegetation was taken from a land cover map (100 metre resolution) of Australia produced by Bureau of Resource Sciences (Barson, *et al.*, 2001). The 100 m resolution fails to identify narrow bands of remnant riparian vegetation in cleared areas. It also fails to identify narrow valleys of cleared land penetrating otherwise uncleared land. Therefore it is a crude measure of riparian vegetation, however, it was the best available data.

_Sediment delivery through the river network_

Hillslope, gully, and stream bank erosion, together supply sediment to the stream network (the network of creeks and rivers in a catchment). The sediment supplied to a reach of river is then either deposited within the river, and its surrounding floodplain, or is transmitted to the next reach downstream. There also may be substantial deposition in reservoirs.
The supply of sediment, its deposition and delivery downstream can be quantified within a river sediment budget. We calculated budgets for two types of sediment: suspended sediment and bedload and these were calculated for the five major watersheds that drain into the Bay: Cardinia Creek, Bunyip River, Yallock Creek, Lang Lang River and the Bass River.

For this project, suspended sediment is characterised as fine textured sediment carried at relatively uniform concentration through the water column during large flows. The main process for net deposition of suspended sediment is overbank deposition on floodplains (e.g., Walling et al., 1992). The sediment budget is reported as mean annual values calculated with respect to current land use.

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

The basic unit of calculation for constructing the sediment budgets is a link in a river network. A link is the stretch of river between any two stream junctions (or nodes; Figure 2). Each link has an internal sub-catchment, from which sediment is delivered to the river network by hillslope and gully erosion processes. The internal catchment area is the catchment area added to the link between its upper and lower nodes (Figure 2). For the purpose of the model, the internal catchment area of first order streams is
the entire catchment area of the river link. Additional sediment is supplied from bank erosion along the link and from any tributaries to the link.

![Figure 2](image_url) A river network showing links, nodes, Shreve magnitude of each link (Shreve, 1966) and internal catchment area of a magnitude one and a magnitude four link.

A branching network of river links joined by nodes was defined from a 50 metre resolution DEM of the Western Port Bay basin. The river network was defined as beginning at a catchment area of 10 km². This area was selected to limit the number of links across the assessment area, while providing a good representation of the channel network. The physical stream network extends upstream of the limit in most areas and these areas are treated as part of the internal catchment area contributing material to the river link.

**Bedload sediment budgets**

A sediment budget for bedload was calculated for each river link (x) in the network, working from the top of each watershed to the Bay (Figure 3). The aim was to define those links subject to net deposition because the historical supply of bedload has
exceeded sediment transport capacity. The mean annual load supplied to the outlet of the link at any time is compared with the mean annual sediment transport capacity at that point. If the load is in excess of capacity, the excess is deposited and the yield to the link immediately downstream equals the sediment transport capacity. If the loading to the outlet is less than the sediment transport capacity there is no net deposition and the yield downstream equals the loading to the outlet.

Figure 3 Conceptual diagram of the bedload sediment budget for a river link. STC is the sediment transport capacity of the river link, determined by Equation 3

Bedload is supplied to a river link from tributary links and from gully and riverbank erosion in the internal catchment area of the link. Half the sediment derived from riverbank and gully erosion contributed to the bedload budget and the other half contributed to the suspended load budget. This reflects observed sediment budgets (e.g., Dietrich and Dunne, 1978) and the particle size of bank materials.

Gully density was converted to a mean annual mass of sediment derived from gully erosion by assuming development of gullies over 100 years and a mean gully cross-sectional area of 10 m². Similarly, bank retreat was converted to a mean annual mass of sediment supplied by bank erosion by multiplying Equation 4 by bank height, channel length, and a dry bulk density of 1.5 t m⁻³.
Once calculated, the total supply of bedload to a river link is compared to sediment transport capacity ($STC_x$). Sediment transport capacity is a function of the river width ($w_x$), slope ($S_x$), discharge ($Q_x$), particle size of sediment and hydraulic roughness of the channel. Yang (1973) found strong relationships between unit stream power and $STC$. Using Yang’s (1973) equation, and an average value for Mannings roughness coefficient of 0.025, we predicted sediment transport capacity in a river link ($t \ y^{-1}$) from:

$$Equation \ 3$$

$$STC_x = \frac{865 S_x^{1.3} \sum Q_x^{1.4}}{\omega W_x^{0.4}}$$

where $\omega$ is the settling velocity of the bedload particles (m s$^{-1}$), and $\sum Q_x^{1.4}$ represents mean annual sum of daily flows raised to a power of 1.4 (Ml$^{1.4} \ y^{-1}$). This represents the disproportionate increase in sediment transport capacity with increasing discharge. The value of $\omega$ was determined for particles with a mean diameter of 2 mm, being the average size observed for sediment slug deposits (Rutherfur 1996).

**Suspended sediment load budgets**

The suspended sediment loads of Australian rivers, and rivers in general, are supply limited (Olive and Walker, 1982; Williams, 1989). That is, rivers have a very high capacity to transport suspended sediment and sediment yields are limited by the amount of sediment delivered to the streams, not discharge of the river itself. Consequently, if sediment delivery increases, sediment yields increase proportionally. Deposition on floodplains is still a significant process, however, and previous work has shown that only a small proportion of supplied sediment leaves a river network (Wasson, 1994).

Suspended sediment is supplied to a river link from four sources: river bank erosion, gully erosion, hillslope erosion and tributary suspended sediment yield (Figure 4). Prediction of surface wash and rill erosion was described above but only a small proportion of sediment moving on hillslopes is delivered to streams. The difference occurs for two reasons. First the RUSLE is calibrated against hillslope plots
considerably smaller than the scale of hillslopes. Much of the sediment recorded in the trough of the plots may only travel a short distance (less than the plot length and much less than the hillslope length) so that plot results cannot be easily scaled up to hillslope predictions. Second, there are features of hillslopes, not represented by erosion plots, which may trap a large proportion of sediment. These include farm dams, contour banks, depressions, fences, and riparian zones. The most common way of representing the difference between plot and hillslope sediment yields is to apply a hillslope sediment delivery ratio (HSDR) to the RUSLE results (e.g., Williams, 1977; Van Dijk and Kwaad, 1998). This ratio represents the proportion of sediment moving on hillslopes that reaches the stream and is generally determined by comparing the results of hillslopes plots against sediment yields from tributary streams. It was found in the NLWRA that an average value of 5% was typical of hillslopes across the region covered by the Western Port Bay basin and this was applied to all stream links and watersheds in the present study.

The main location for deposition of suspended sediment is on floodplains. A relatively simple conceptualisation of floodplain deposition is to consider that the proportion of suspended sediment load that is available for deposition is equal to the fraction of total discharge that goes overbank. This assumes uniform concentration of suspended sediment with depth.

The actual deposition of material that goes overbank can be predicted as a function of the residence time of water on the floodplain. The longer that water sits on the floodplain the greater the proportion of the suspended load that is deposited. The residence time of water on floodplains increases with floodplain area and decreases with floodplain discharge. Floodplain extent for the Western Port Bay basin was derived from the NLWRA database (see Pickup and Marks, 2001).

An increase in supply of suspended sediment from upstream results in a concomitant increase in mean sediment concentration and mean annual suspended sediment yield. Thus increases to suspended sediment supply have relatively strong downstream influences on suspended sediment loads. Sediment deposition in reservoirs is included in the model as a function of the mean annual inflow into the reservoir and its total storage capacity (Heinemann, 1981).
The procedures above were applied in sequence to each river link from the top of each watershed to the Bay, adding suspended load and predicting its loss through deposition along the way. The final calculation is of mean annual suspended sediment export to the Bay.

![Conceptual diagram for the suspended sediment budget of a river link. HSDR is hillslope sediment delivery ratio.](image)

Figure 4 Conceptual diagram for the suspended sediment budget of a river link. HSDR is hillslope sediment delivery ratio.

*Contribution of suspended sediment to the Bay*

One of the strongest interests in suspended sediment transport at present is the potential for export to the Bay and its impact on seagrass communities. Because of the extensive opportunities for floodplain deposition along the way, not all suspended sediment delivered to rivers is exported to the Bay. There will be strong spatial patterns in sediment delivery to the Bay because some tributaries are confined in narrow valleys with little opportunity for deposition, while others may have extensive open floodplains. There will also be strong, but different patterns in sediment delivery to streams. Differentiation of sub-catchments that contribute strongly to coastal sediment loads is important because it allows targeted management of specific areas. This is particularly important given that rehabilitation resources are often limited and therefore efficient use of those resources is critical.

The contribution of each sub-catchment to the mean annual suspended sediment delivery to the Bay was calculated. The sub-catchments are the internal areas for each
link described in Figure 2. The calculations were made once the mean annual suspended sediment export was calculated. The method tracks back upstream calculating from where the sediment load in each link is derived. The calculation takes a probabilistic approach to sediment delivery through each river link encountered on the route from source to sea.

The catchment area for each internal 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 delivered from 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 \((YF_x)\). The rest is deposited. The ratio of \(YF_x/TIF_x\) is the proportion of suspended sediment that passes through each link. It can also be viewed as the probability of any individual grain of suspended sediment passing through the link. The suspended load delivered from each sub-catchment will pass through a number of links on route to the Bay. The amount delivered to the mouth is the product of the loading \(LF_x\) from the sub-catchment and the probability of passing through each river link on the way:

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

where \(n\) is the number of links on the route to the outlet. Dividing this by the internal catchment area expresses contribution to the Bay \((CO_x)\) as an erosion rate \((\text{t ha}^{-1}\text{y}^{-1})\). The proportion of suspended sediment passing through each river link is \(\leq 1\). A consequence of Equation 4 is that all other factors being equal, the further a sub-catchment is from the mouth, the lower the probability of sediment reaching the mouth. This behaviour is modified though by differences in source erosion rate and deposition intensity between links.

**Hydrology**

The correct representation of river hydrology is important for routing sediment through the river network. Several hydrological parameters are used in the river sediment budget methods. These need to be predicted for each river link across the
river basin. The variables used are:

- the mean annual flow \( Q_a \)

- the mean annual sum of \( Q^{1.4} \) for calculating mean annual sediment transport capacity

- the bankfull discharge \( Q_{bf} \)

- a representative flood discharge for floodplain deposition (in this case median overbank flow \( Q_{ob} \))

As no gauging station data were provided specifically for the rivers in Western Port Bay, regionalisations of these hydrological parameters calculated for use in the NLWRA were used (see Prosser, et al., 2001a and Young, et al., 2001 for further details).
Results and Discussion

Hillslope erosion

The pattern of hillslope erosion within the watersheds of the Western Port Bay basin, as predicted by the RUSLE, is illustrated in Figure 5. The values of hillslope erosion represent local movement of soil on hillslopes. It is important to realise that hillslope erosion values using this method overestimate sediment delivery to streams as much of the sediment that is moving may be deposited before reaching the stream. For instance, material eroded on a ridge slope might end up being deposited in colluvial fans on flatter valley bottoms or on river frontage areas before reaching streams. Overall only about 5% of sediment moving on hillslopes finds its way to streams. Nonetheless the data can be used in a relative sense, comparing regions of high erosion with those of lower erosion.

The pattern of hillslope erosion illustrated in Figure 5 is relatively coarse. This is mainly due to the scale of the land use map used to derive the cover-factor. Despite this, clear patterns can be seen, with the highest predicted hillslope erosion rates occurring in the south-eastern part of the catchment, in particular the Lang Lang River and Bass River watersheds. In this area there are large areas of land where the predicted hillslope erosion rate exceeds 5 t ha\(^{-1}\) y\(^{-1}\). The high rates of hillslope erosion in this area can be attributed to the steep terrain combined with the fact that much of the natural vegetation has been removed and replaced with grazing pasture.

In comparison, the predicted hillslope erosion rates outside of the Lang Lang River and Bass River watersheds are very low with much of the rest of the basin having erosion rates below 0.5 t ha\(^{-1}\) y\(^{-1}\). This is mainly due to the low relief of much of the land within the Cardinia Creek, Bunyip River and Yallock Creek watersheds. Where the terrain is steeper, there is a good cover of forest and/or remnant vegetation which limits the erosion rates. A summary of the data by watershed is presented in Table 1. On the basis of the data the catchments have been ranked according to their erosion rate values. On this basis the Bass River watershed has the highest average hillslope erosion rate (1.8 t ha\(^{-1}\) y\(^{-1}\)) and the Bunyip River has the lowest (0.1 t ha\(^{-1}\) y\(^{-1}\)).
Figure 5 Predicted hillslope erosion (using the Revised Universal Soil Loss Equation) in Western Port Bay

Table 1 Average hillslope erosion and erosion ranking for the major watersheds of the Western Port Bay basin

<table>
<thead>
<tr>
<th>Watershed</th>
<th>Area (km²)</th>
<th>Average erosion rate (t ha⁻¹ y⁻¹)</th>
<th>Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bass River</td>
<td>266</td>
<td>1.8</td>
<td>1</td>
</tr>
<tr>
<td>Bunyip River</td>
<td>890</td>
<td>0.1</td>
<td>5</td>
</tr>
<tr>
<td>Cardina Creek</td>
<td>398</td>
<td>0.2</td>
<td>4</td>
</tr>
<tr>
<td>Lang Lang River</td>
<td>423</td>
<td>1.2</td>
<td>2</td>
</tr>
<tr>
<td>Yallock Creek</td>
<td>286</td>
<td>0.3</td>
<td>3</td>
</tr>
</tbody>
</table>
**Gully erosion**

The pattern of gully density within Western Port Bay is illustrated in Figure 6. The results are based on both direct mapping and regression-tree modelling, therefore the resultant map is a composite of measured and predicted gully densities. Figure 6 shows that the highest densities occur in the eastern part of the study area, in particular in the headwaters of the Bunyip River, Lang Lang River and Yallock Creek. Indeed these watersheds contain the only significant areas of moderate and high gully density in the study area.

![Gully density map](image)

**Figure 6 Gully density map**

To facilitate its use in the sediment budgets, gully density was converted into a soil erosion rate by considering the cross-sectional area of a gully and its approximate age. One kilometre of gully produces 10,000 cubic metres (approximately 15 000 tonnes) of sediment per km² of land. If that was eroded over an average gully age of 100 years, the mean annual rate of erosion would be 1.5 tonnes/hectare/year.
It is important to note that because gullies are well connected hydrologically with river systems, the model assumes that all of the sediment that is eroded from gullies is transported into rivers.

Gully erosion within each of the watersheds is summarised in Table 2. The significance of gully erosion within the Bunyip River, Lang Lang River and Yallock Creek watersheds can clearly be seen with these three watersheds having the highest average gully erosion rates. The Lang Lang River has the highest rate of gully erosion by a factor of two and is ranked as number 1. Given that the Lang Lang River is the second largest watershed in the basin we can expect gully erosion in this basin to contribute a significant amount of sediment to the total export.

Table 2 Average gully erosion and erosion ranking for the major watersheds of the Western Port Bay basin

<table>
<thead>
<tr>
<th>Watershed</th>
<th>Area (km²)</th>
<th>Average gully density (km km²)</th>
<th>Average erosion rate (t ha⁻¹ y⁻¹)</th>
<th>Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bass River</td>
<td>266</td>
<td>0.08</td>
<td>0.1</td>
<td>4=</td>
</tr>
<tr>
<td>Bunyip River</td>
<td>890</td>
<td>0.14</td>
<td>0.2</td>
<td>3</td>
</tr>
<tr>
<td>Cardinia Creek</td>
<td>398</td>
<td>0.08</td>
<td>0.1</td>
<td>4=</td>
</tr>
<tr>
<td>Lang Lang River</td>
<td>423</td>
<td>0.41</td>
<td>0.6</td>
<td>1</td>
</tr>
<tr>
<td>Yallock Creek</td>
<td>286</td>
<td>0.18</td>
<td>0.3</td>
<td>2</td>
</tr>
</tbody>
</table>

*Riverbank erosion*

Rivers also carry sediment generated from erosion of the river banks themselves, and this needs to be considered as a part of the river sediment budget. Because of the high level of human impact in the Western Port Bay basin, the drainage network is particularly complex. Much of the lowland area, in particular Cardinia Creek, Bunyip River and Yallock Creek, has been dissected by artificial drainage channels. In addition, natural channels have been significantly modified by dredging and straightening. Given that the sediment budget we construct through the use of the SedNet model depends on a DEM-generated drainage network to route sediment through the catchment, it is somewhat problematic to model bank erosion in
artificially constructed channels. Thus, this study only considers the erosion of material from naturally occurring channels.

One of the two main factors controlling riverbank erosion in the model is the extent of riparian vegetation. Figure 7 illustrates the extent of intact riparian vegetation, on a link basis.

![Proportion of link with riparian vegetation map](image)

**Figure 7 Proportion of intact riparian vegetation map**

It can be seen that many of the rivers in Western Port Bay have poor riparian vegetation with only the headwaters of Cardinia Creek and Bunyip River having any significant riparian cover. It should be noted that because of the scale of the source data (100 metre resolution), we have not identified any narrow bands of remnant riparian vegetation that may actually exist.

River discharge is the other factor controlling bank erosion rate in the model. When combined with riparian vegetation the results predict that much of the bank erosion occurs on the main channels in the catchment with lower rates in tributary channels (Figure 8). The highest predicted bank erosion rate, of between 8 and 12 cm y$^{-1}$,
occurs along the main channel of Bunyip River. This is due to the fact that the Bunyip River has the highest discharge in the study area in association with very degraded riparian vegetation. These high rates of bank erosion predicted by our modelling are consistent with the field-based observations contained in several unpublished reports on the Bunyip and Lang Lang rivers (Brizga and Craigie, 1988 and MWC, 1998a).

![Map of Bank Erosion](image)

**Figure 8. Predicted bank erosion**

The supply of sediment from bank erosion in each watershed is summarised in Table 3. Clearly Bunyip River generates the most sediment from bank erosion both in terms of quantity and in terms of volume per unit area per year. Again this is a reflection of the higher discharge in association with the severely degraded riparian vegetation. Bank erosion rates for Lang Lang River, Bass River and Yallock Creek are similar and primarily reflect the degraded nature of the riparian vegetation.
Table 3 Average bank erosion for the major watersheds of the
Western Port Bay basin

<table>
<thead>
<tr>
<th>Watershed</th>
<th>Area (km²)</th>
<th>Average bank erosion (kt yr⁻¹)</th>
<th>Average bank erosion rate (t ha⁻¹ yr⁻¹)</th>
<th>Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bass River</td>
<td>266</td>
<td>10</td>
<td>0.38</td>
<td>3</td>
</tr>
<tr>
<td>Bunyip River</td>
<td>890</td>
<td>37</td>
<td>0.42</td>
<td>1</td>
</tr>
<tr>
<td>Cardinia Creek</td>
<td>398</td>
<td>12</td>
<td>0.30</td>
<td>5</td>
</tr>
<tr>
<td>Lang Lang River</td>
<td>423</td>
<td>16</td>
<td>0.38</td>
<td>2</td>
</tr>
<tr>
<td>Yallock Creek</td>
<td>286</td>
<td>10</td>
<td>0.35</td>
<td>4</td>
</tr>
</tbody>
</table>

Sediment sources to the stream network

Each of the sediment sources described above deliver sediment to the stream network within the Western Port Bay basin. The predicted mean annual sediment supply rates summed for each process and for all watersheds within the basin are shown in Table 4. It can clearly be seen that riverbank erosion (54%) and gully erosion (41%) dominate the sediment supply sources. This result is typical of catchments in southeastern Australia where channel erosion processes tend to dominate hillslope erosion processes (Olley et al., 1993; Wallbrink et al., 1998; Prosser et al., 2001b).

It is predicted that bank erosion is the single most significant sediment source in the catchment. This is principally a reflection of the degraded nature of the riparian vegetation in the catchment. Bank erosion, however, may be even more important than is being indicated, given that there are many artificially constructed drainage channels that have not been considered in the budget. Given the nature of flow in a complex artificial drainage network, like that of the Western Port Bay basin, it is also possible that the drains are aggrading. A detailed analysis of the flow and sediment delivery from the drains would be required to determine their significance. This is beyond the current functionality of the SedNet model and is outside the scope of this study.
Gully erosion is also a large contributor of sediment to the rivers of Western Port Bay. Of additional importance, however, is the fact that gully erosion is localised and is therefore likely to have a significant impact on those catchments where it occurs. Hillslope erosion is a relatively minor component of the budget but the fact that, it too, is localised to the south-eastern part of the basin is also of importance.

Table 4. Combined sediment budget for all rivers draining into Western Port Bay*

<table>
<thead>
<tr>
<th>Sediment budget item</th>
<th>Predicted mean annual rate (kt y⁻¹)</th>
<th>% of total</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sediment Inputs</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gully erosion</td>
<td>64</td>
<td>41</td>
</tr>
<tr>
<td>Bank erosion</td>
<td>85</td>
<td>54</td>
</tr>
<tr>
<td>Hillslope erosion</td>
<td>7</td>
<td>5</td>
</tr>
<tr>
<td><strong>Total sediment supply</strong></td>
<td><strong>156</strong></td>
<td><strong>100</strong></td>
</tr>
<tr>
<td><strong>Storage</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dam deposition</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Floodplain deposition</td>
<td>18</td>
<td>12</td>
</tr>
<tr>
<td>Channel deposition</td>
<td>40</td>
<td>26</td>
</tr>
<tr>
<td><strong>Export</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bed load export</td>
<td>30</td>
<td>19</td>
</tr>
<tr>
<td>Suspended sediment export</td>
<td>66</td>
<td>42</td>
</tr>
<tr>
<td><strong>Total storage/export</strong></td>
<td><strong>156</strong></td>
<td><strong>100</strong></td>
</tr>
</tbody>
</table>

* This combined budget includes the five main rivers as well as all other minor streams

*Sediment delivery through the river network

On-site erosion is of concern for continued productivity of the land but can only be translated to downstream impacts if the eroded sediment is transported along the river network. The modelled sediment budget for the basin predicts that over 60% of
sediment delivered to streams is exported to the Bay. The rest is stored on floodplains or on the bed of streams, with some storage in the basin also occurring in reservoirs (Table 4). This is a relatively high contribution of sediment to the environs of the Bay and reflects the dominance of riverbank erosion, particularly in the lower reaches where erosion is high and the channels do not have far to transport the sediment therefore reducing the probability of in-channel or floodplain storage.

Tables 5 and 6, respectively, summarise the predicted suspended sediment loads and bedloads for the five major watersheds within the Western Port Bay basin. The Lang Lang River and the Bunyip River are the most significant contributors of sediment into the Bay, together supplying over 70% of the total sediment load. Given that these two catchments are the largest in the basin, this is not surprising. Significantly, however, the Lang Lang River has the highest suspended sediment yield out of all the watersheds. This is due to the high rates of both hillslope and channel (both bank and gully) erosion in the watershed coupled with low storage potential. The next two highest yields of suspended sediment came from the Bass River and Bunyip River respectively. Bank erosion is of particular significance in these two watersheds and contributes greatly to suspended sediment loads.

A similar pattern is apparent for bedload export from the five major watersheds with the Bunyip and Lang Lang rivers producing the most bedload per unit area. The Bunyip and the Lang Lang rivers are the two largest watersheds in the basin and therefore have the highest flow rates. This has resulted in a greater capacity to transport coarse sediment that has been generated from the degraded river banks and from the network of gullies.
Table 5 Total suspended sediment export for the main Western Port Bay watersheds as predicted by SedNet

<table>
<thead>
<tr>
<th>Watershed</th>
<th>Area (km²)</th>
<th>Total suspended sediment export (kt y⁻¹)</th>
<th>Rank by load</th>
<th>Suspended sediment yield (t ha⁻¹ y⁻¹)</th>
<th>Rank by yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bass River</td>
<td>266</td>
<td>8</td>
<td>3</td>
<td>0.30</td>
<td>2</td>
</tr>
<tr>
<td>Bunyip River</td>
<td>890</td>
<td>22</td>
<td>1</td>
<td>0.25</td>
<td>3</td>
</tr>
<tr>
<td>Cardinia Creek</td>
<td>398</td>
<td>6</td>
<td>5</td>
<td>0.15</td>
<td>5</td>
</tr>
<tr>
<td>Lang Lang River</td>
<td>423</td>
<td>20</td>
<td>2</td>
<td>0.47</td>
<td>1</td>
</tr>
<tr>
<td>Yallock Creek</td>
<td>286</td>
<td>6</td>
<td>4</td>
<td>0.21</td>
<td>4</td>
</tr>
</tbody>
</table>

Table 6 Total bedload export for the main Western Port Bay watersheds as predicted by SedNet

<table>
<thead>
<tr>
<th>Watershed</th>
<th>Area (km²)</th>
<th>Total bedload export (kt y⁻¹)</th>
<th>Rank by load</th>
<th>Bedload yield (t ha⁻¹ y⁻¹)</th>
<th>Rank by yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bass River</td>
<td>266</td>
<td>2</td>
<td>3</td>
<td>0.08</td>
<td>3</td>
</tr>
<tr>
<td>Bunyip River</td>
<td>890</td>
<td>16</td>
<td>1</td>
<td>0.18</td>
<td>1</td>
</tr>
<tr>
<td>Cardinia Creek</td>
<td>398</td>
<td>2</td>
<td>5</td>
<td>0.05</td>
<td>5</td>
</tr>
<tr>
<td>Lang Lang River</td>
<td>423</td>
<td>6</td>
<td>2</td>
<td>0.14</td>
<td>2</td>
</tr>
<tr>
<td>Yallock Creek</td>
<td>286</td>
<td>2</td>
<td>4</td>
<td>0.07</td>
<td>4</td>
</tr>
</tbody>
</table>

Table 7 gives suspended sediment export totals for three watersheds within the Western Port basin as determined from turbidity measurements (supplied by Melbourne Water). The results are a factor of 10 lower than those derived from the SedNet model. Despite this order of magnitude difference, the pattern is similar between the two sets of data. The Bunyip River has the highest export and more
significantly Lang Lang River has a higher total export than Yallock Creek despite the
similarities in catchment area.

Table 7 Total suspended sediment export for three Western Port Bay watersheds
as calculated from turbidity measurements (1999-2001)

<table>
<thead>
<tr>
<th>Watershed</th>
<th>Area (km$^2$)</th>
<th>Total suspended sediment export (kt y$^{-1}$)</th>
<th>Rank by load</th>
<th>Suspended sediment yield (t ha$^{-1}$ y$^{-1}$)</th>
<th>Rank by yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bunyip River</td>
<td>890</td>
<td>5.1</td>
<td>1</td>
<td>0.06</td>
<td>2</td>
</tr>
<tr>
<td>Cardinia Creek</td>
<td>398</td>
<td>0.4</td>
<td>3</td>
<td>0.01</td>
<td>3</td>
</tr>
<tr>
<td>Lang Lang River</td>
<td>423</td>
<td>3.0</td>
<td>2</td>
<td>0.07</td>
<td>1</td>
</tr>
</tbody>
</table>

*Source: Melbourne Water, Catchments & Waterways

The disparity between the two sets of results can probably be attributed to three major
factors:

i) the short time scale of the turbidity data;

ii) possible overestimation of contemporary gully input by the SedNet model; and

iii) bias of turbidity measurements to times of base flow.

With respect to i), the total suspended sediment export figures derived from turbidity
data were only calculated from three years of data, in between 1999 and 2001. Despite
their good quality, three years of flow and turbidity data are probably insufficient to accurately represent the long-term processes occurring within these watersheds. This non-representativeness is likely to be further compounded by the
fact that the period between 1999 and 2001 was particularly dry and therefore river
flows are likely to have been below average. Further evidence of this is provided in
an unpublished report on the Lang Lang River (MWC, 1998b), which calculated a
mean sediment load of 10.2 kt y$^{-1}$ (using data from between 1980-1996) at the point
where the South Gippsland Highway crosses the Lang Lang River.

With regards to ii), SedNet averages gully input over a period of 100 years, therefore
the sediment that is sourced from gullies is an average over the life of a gully. However, in many cases the input of sediment from gullies came as a pulse during the
initiation phase. It is known that many of the gullies in southern Australia were initiated during European colonisation and had stabilised by the 1950s (Eyles, 1977). It is likely then that the contribution of sediment by gullies today is somewhat less than it initially was.

To further illustrate the occurrence of sediment transport *hotspots* in the Western Port Bay basin the river budget predicted mean annual suspended sediment load through the river network allowing for deposition on floodplains and in reservoirs. The resultant mean annual specific sediment load for each river link are shown in Figure 9. The predicted mean annual export to the Bay from the five main watersheds is 62 kt y\(^{-1}\). This equates to an average specific sediment yield of 0.27 t ha\(^{-1}\) y\(^{-1}\). Figure 9 clearly shows that yields from the rivers of the eastern part of the basin are significantly higher than this. Of particular note is the Lang Lang River, although the Bass River and parts of Yallock Creek also have high specific suspended sediment yields.

![Specific suspended sediment yield](image)

**Figure 9** Predicted specific suspended sediment load
**Bedload deposition**

The bedload sediment budget predicts the accumulation of sand and gravel on the beds of rivers as a result of increased rates of gully and bank erosion. We consider that where historical bed deposition is in excess of 30 cm there is likely to be some impact on bed habitats. This might be through filling pools, smothering of cobble beds with finer sediment or reduced diversity of bed forms.

Our results suggest that there is a significant number of reaches in the basin that deposit in excess of 30 cm (Figure 10). The areas of greatest deposition are in the flatter parts of the basin where sediment transport capacity decreases but where there is also a high bedload supply from gully and bank erosion processes. Unpublished reports on the Lang Lang River, Cardinia Creek and Bunyip River confirm many of the lower reaches of these rivers are subject to aggradation by silt and fine sand (Brizga and Craigie, 1988, MWC, 1998a and MWC, 1998b). The complete picture of deposition is complicated by the extensive sand dredging and mining that has been carried out in many of the rivers.
Figure 10 Predicted bedload deposition

**Contribution to suspended sediment export to the Bay**

Estuaries and coastal waters are of particular concern for suspended sediment as they are the ultimate areas of sediment deposition. This is certainly the case in Western Port Bay where there are issues of sedimentation within the Bay and the resulting loss of biodiversity due to smothering of habitat. Sediment can also be a supply of nutrient and change the food web structure. Resuspension of sediment by waves and currents increases the turbidity of water and decreases light penetration, which can inhibit growth of organisms.

The sediment budget predicts that about 80% of suspended sediment and about 40% of bedload delivered to the river networks in any year are exported from the mouths of the major watersheds. The high suspended sediment contribution is due to limited opportunity for storage on floodplains or in reservoirs.
Given that over 60% of sediment delivered to streams within the Western Port Bay basin is exported to the coast and that channel erosion is the predominant sediment source, it can be concluded that increased erosion upstream in a sub-catchment results in a significant increase in export to the Bay. In other words, the rivers of Western Port Bay illustrate a high degree of connectivity between upstream erosion and sediment contribution to the coast.

To further examine sediment export to the Bay we have taken the results of our link by link sediment budget and worked back up the river network to trace where the suspended sediment comes from. Each river link carries sediment contributed from its internal sub-catchment and from tributaries to the link. Each river link also deposits a proportion of the mean annual load that it carries. We have worked back up each tributary to find the contribution from each internal sub-catchment to export from the Western Port Bay basin. The result is expressed as a mean annual sediment contribution in t ha\(^{-1}\) y\(^{-1}\) from each sub-catchment that reaches the Bay.

Sub-catchments that make a substantial contribution to the export at the coast are those with high erosion and limited floodplain extent between the source and sea. Sub-catchments close to the Bay are more likely to contribute to the export because of limited possibilities for that sediment to be deposited along the way. Inland sub-catchments will contribute significant amounts of sediment to the coast if the erosion rate is high and the river delivers sediment efficiently.
Overall, however, a high proportion of sediment contributed to the Bay comes from watershed areas adjacent to the main river channels. This is particularly the case in the Bunyip River where bank erosion rates are high. The contribution of these areas to the coast is typically $>1 \text{ t ha}^{-1} \text{ y}^{-1}$ (Figure 11). There are a few areas that contribute greater than $2 \text{ t ha}^{-1} \text{ y}^{-1}$. The Lang Lang River also shows a similar pattern of high sediment contribution from the main river channel.

If the goal is to reduce sediment loads to the coast then remedial works can be focussed on particular sediment sources and the land uses and erosion processes found there. Obviously targeting the areas with a disproportionately high level of contribution should be a priority, such as those adjacent to the main channels of the Bunyip and Lang Lang rivers. Targeting these areas will have the greatest effect on reducing sediment export to the coast. However, erosion is not limited to these watersheds, therefore without more widespread rehabilitation of problem areas, it is
unlikely that major reductions in suspended sediment loads to the coast will be achieved.

**Conclusions**

This report presents the results of river sediment budgets calculated for the five main watersheds in the Western Port Bay basin; Cardinia Creek, Bunyip River, Yallock Creek, Lang Lang River and the Bass River. The sediment budgets were constructed using the sediment routing model SedNet (NLWRA, 2001). From the results it is clear that channel (bank and gully) erosion are the dominant sediment generation processes in the Western Port Bay basin and because of the reasonably strong connectivity between source supply and export to the Bay, much of this is directly exported to the marine environment.

Much of the erosion that occurs in the Western Port basin is concentrated in the eastern part. While it is predicted that hillslope (sheet and rill) erosion comprises a relatively small portion of the total erosion that occurs in the basin, it does tend to be focussed in a small part in the steeper areas that have been denuded of their natural vegetative cover. The main such areas include the Bass River and the headwaters of the Lang Lang River. Gully erosion also tends to be concentrated in the eastern part of the basin with high rates apparent in localised areas of the Lang Lang River, Yallock Creek and the Bunyip River. Bank erosion is, however, more evenly spread throughout the catchment with reasonably high rates of erosion apparent in all five major watersheds. This has been attributed to the highly degraded nature of the riparian vegetation.

The Lang Lang and Bunyip rivers are the most significant contributors of sediment to Western Port Bay. The Lang Lang River is of particular concern as it has high rates of hillslope, bank and gully erosion. While the Bunyip River does not contribute as much sediment, on a per unit area basis, as the Lang Lang, it is the largest contributor of sediment to the Bay and the vast majority of this comes from bank erosion. The Bass River also contributes a relatively high volume of sediment to the Bay with sediment being sourced at moderate rates from all three erosion sources. Cardinia Creek and Yallock Creek also contribute sediment to the Bay, however, relative to the other watersheds their contribution is small.
Overall, riverbank erosion is of major concern in the watershed draining into Western Port Bay. More effective riparian zone management along the banks of the major streams will go a long way to improving water quality as a whole. While gully erosion is also of concern it is possible that a large proportion of the sediment that has been derived from gullies is already in the river network or has been transported to the Bay. However, land use practices should be adopted that reduce the potential for gully initiation in currently un-gullied areas.

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References


