Characterisation of Erosion and Nutrient Export Risk in the Lake Illawarra Catchment

Tony Andresen
University of Wollongong

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Characterisation of Erosion and Nutrient Export Risk in the Lake Illawarra Catchment

Abstract
Lake Illawarra, located on the south east coast of New South Wales, Australia, plays an important role in the lives of many people living in the region. It has economic value through the support of commercial fisheries and the tourism trade as well as providing an area that is aesthetically appealing and supports a range of recreational activities. Maintaining the ecological health of Lake Illawarra is imperative if the Lake is to continue providing these resources. The primary reason for the degradation of Lake Illawarra’s ecological health is an increase in the human population living in the catchment area, especially since early European settlement. Over the past 50 years, and continuing to the present day, extensive urban development is the greatest threat to the Lake’s ecological health. High rates of sediment and nutrient discharges have led to enhanced algal growth, higher turbidity in the water column and loss of aquatic habitat.

This project aims to develop knowledge to facilitate the management of the Lake Illawarra catchment by characterising areas with a high risk of sediment and nutrient discharge. This was done by modelling soil erosion processes within the catchment and, by also taking into account nutrient levels associated with the soils, providing an evaluation of soil erosion and nutrient export risk within the catchment. Soil erosion modelling was based on the Revised Universal Soil Loss Equation (RUSLE), and incorporated the use of a Geographical Information System (GIS). GIS has been increasingly relied upon for catchment scale modelling of soil erosion as it provides the most efficient and accurate method for the calculation of factors at the necessary scale, namely slope steepness and slope length. It also helps to provide a geographically accurate spatial representation of risk areas found during the modelling procedure.

It was found that risk areas of concern were strongly linked to factors relating to slope, which is not uncommon in soil erosion models at this scale. The Lake Illawarra catchment is characterised by the steep rise of the Illawarra Escarpment, where the coastal plain rises up to a maximum elevation of nearly 800 metres above sea level. Nutrient export risk was modelled based on the nutrients associated with mobilised soil particles, and so is strongly linked with the results found from soil erosion modelling. Extensive new developments have been approved in West Dapto and Calderwood, both of which cover areas of high erosion risk. In order for Lake Illawarra to remain as an ecologically, economically and aesthetically important resource for the people of the Illawarra region, in light of the new developments and population growth within the catchment, improvements in the application of sediment and erosion control measures and stormwater runoff management are of the utmost importance.

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Characterisation of Erosion and Nutrient Export Risk in the Lake Illawarra Catchment

By

Tony Andresen

A research report submitted in partial fulfilment of the requirements for the award of the degree of HONOURS BACHELOR OF ENVIRONMENTAL SCIENCE

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FACULTY OF SCIENCE

THE UNIVERSITY OF WOLLONGONG

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I would like to give special thanks to my two thesis supervisors John Morrison and Sarah Hamylton from the School of Earth and Environmental Sciences, University of Wollongong for all their support, guidance and encouragement throughout this study. I would also like to thank Cassy Baxter and Garry Clarke from the Lake Illawarra Authority for giving me the opportunity to undertake this study and for all their feedback and support. I would also like to acknowledge Heidi Brown from the Spatial Analysis Laboratories, University of Wollongong for assisting me in the provision of some vital spatial datasets. Finally I would like to thank my parents, Retta and John Andresen, for all their support during the study.
Abstract

Lake Illawarra, located on the south east coast of New South Wales, Australia, plays an important role in the lives of many people living in the region. It has economic value through the support of commercial fisheries and the tourism trade as well as providing an area that is aesthetically appealing and supports a range of recreational activities. Maintaining the ecological health of Lake Illawarra is imperative if the Lake is to continue providing these resources. The primary reason for the degradation of Lake Illawarra’s ecological health is an increase in the human population living in the catchment area, especially since early European settlement. Over the past 50 years, and continuing to the present day, extensive urban development is the greatest threat to the Lake’s ecological health. High rates of sediment and nutrient discharges have led to enhanced algal growth, higher turbidity in the water column and loss of aquatic habitat.

This project aims to develop knowledge to facilitate the management of the Lake Illawarra catchment by characterising areas with a high risk of sediment and nutrient discharge. This was done by modelling soil erosion processes within the catchment and, by also taking into account nutrient levels associated with the soils, providing an evaluation of soil erosion and nutrient export risk within the catchment. Soil erosion modelling was based on the Revised Universal Soil Loss Equation (RUSLE), and incorporated the use of a Geographical Information System (GIS). GIS has been increasingly relied upon for catchment scale modelling of soil erosion as it provides the most efficient and accurate method for the calculation of factors at the necessary scale, namely slope steepness and slope length. It also helps to provide a geographically accurate spatial representation of risk areas found during the modelling procedure.

It was found that risk areas of concern were strongly linked to factors relating to slope, which is not uncommon in soil erosion models at this scale. The Lake Illawarra catchment is characterised by the steep rise of the Illawarra Escarpment, where the coastal plain rises up to a maximum elevation of nearly 800 metres above sea level. Nutrient export risk was modelled based on the nutrients associated with mobilised soil particles, and so is strongly linked with the results found from soil erosion modelling. Extensive new developments have been approved in West Dapto and Calderwood, both of which cover areas of high erosion risk. In order for Lake Illawarra to remain as an ecologically, economically and aesthetically important resource for the people of the Illawarra region, in light of the new developments and population growth within the catchment, improvements in the application of sediment and erosion control measures and stormwater runoff management are of the utmost importance.
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1 Introduction

Lake Illawarra has played an important role in the lives of humans living in the Illawarra region for a very long time, well before the arrival of European settlers. It has economic value with support of commercial fisheries and tourism as well as aesthetic and recreational appeal. It also has significant ecological value in its support of a range of habitats including seagrasses, mangroves, saltmarshes and wetlands. Extensive clearing of the Lake Illawarra catchment for agricultural, urban and industrial uses has had a significant impact on the sediment and nutrient loads being discharged into the Lake (Depers et al., 1994; Pockock et al., 2003). This in turn has led to enhanced algal growth, higher turbidity in the water column and loss of deep aquatic habitat, impacting upon all of Lake Illawarra’s attractions. Continued development of the catchment area still poses a significant threat to the condition of Lake Illawarra, with the authorisation for the development of 17,010 dwellings in the West Dapto area, as well as other development sites in Calderwood (WCC, 2010; JBA, 2011). The Lake Illawarra Authority (LIA) was created in 1988 in order to address the damage that had thus far been done and continues to monitor, assess and authorise works to be performed on the Lake and its foreshores. The LIA’s concern with the impact that this new development will have on Lake Illawarra has led to the need for a better understanding of nutrient and sediment discharge potential for sites around the catchment. This study was initiated to provide that understanding.

1.1 Lake Illawarra

Lake Illawarra is a shallow coastal lagoon located approximately 80 km south of Sydney on the New South Wales coast of Australia (see Figure 1-1). Its formation can be attributed to fluctuating sea levels and the incision of streams during periods of low sea level (PWD, 1988). Approximately 18,000 years ago, sea level was 125 m below the current sea level (Sloss et al., 2005). During this time creeks such as Macquarie Rivulet and Mullet Creek, carved valleys which extended far beyond the current shoreline. The Post Glacial Marine Transgression (PMT), beginning around 8000 years ago, drowned the coastal valleys and deposited marine influenced sediments, mostly clean marine sands (Sloss et al., 2005). Around 5000 years ago, formation of the Lake’s barrier began, leading to a reduction in marine influenced sediment and an increase in the deposition of estuarine muds (Sloss et al., 2005). 3200 years ago, the Lake’s entrance had reached its present location. During this time sea levels begun to fall, reducing the accommodation space of the Lake, this in turn led to the rapid progradation of fluvial deltas (Sloss et al., 2005). The last 2500 years of
Lake Illawarra’s evolution is characterised by the infilling of the Lake and the progradation of fluvial deltas (Sloss et al., 2005). The rate of these processes has increased over past 200 years, due to anthropogenic impacts (Hopley et al., 2007); this is discussed in more detail later.

Lake Illawarra currently has a surface area of approximately 35 km$^2$, spanning the local government boundaries of Wollongong and Shellharbour City Councils. The average depth is under 2 m, with a maximum depth of 3.7 m and an area of around 35% being less than 1 m (Sherman et al., 2000).

Several freshwater creeks drain into the lake (see Figure 1-2) and there is one, narrow channel linking the lake to the ocean, which, in its natural state, intermittently closes, but was permanently opened to the ocean in 2007.

### 1.1.1 Sedimentation

Sedimentation is the infilling of a water body by sediment particles, predominantly derived from hillslope erosion within the catchment area, which is carried in streams and rainwater runoff (Sherman et al., 2000). Sedimentation within Lake Illawarra is a natural process, and has been taking place since the lake’s formation (PWD, 1988). However, rates of sedimentation have increased dramatically in the last 200 years following European settlement (Depers et al., 1994; Pockock et al., 2003; Sloss et al., 2004). The lake bed is currently comprised of three main sediment types: fluvial sands (25%), mud (55%) and marine sands (20%) (Clarke & Dooley, 2004). Fluvial sands are dominated by medium to course grained sediments, tending to be found around the mouth of freshwater streams draining into the lake from the west. The course grained sediments settle first upon entrance to the lake, creating deltas as found where Hooka Creek, Mullet Creek, Duck Creek and Macquarie Rivulet converge on the lake (Sloss et al., 2004). The sediments found in the central portion of the lake are fine grained black muds, composed of clay and silt sized particles as well as considerable organic detritus (Sherman et al., 2000). This mud has a predominantly fluvial origin and

![Figure 1-1: Location of study area in Australian context.](image)
is carried to the centre of the lake in suspension and deposited under low energy conditions (Davis, 2005). The eastern portion of the lake is significantly influenced by marine processes. Marine sediments are drawn into the lake by tidal currents, before being redistributed around the eastern shores of the lake (PWD, 1988). These marine sediments are composed of clean to slightly muddy quartzose sands originating from the barrier and flood-tidal delta on the eastern side of the lake (Sloss et al., 2004).

Sedimentation of Lake Illawarra is a natural process; however, anthropogenic impacts have significantly affected the rates at which sedimentation is currently occurring. Assuming uniform sedimentation across the lake, Depers et al. (1994), using radiocarbon dating, found sedimentation to have increased from 0.3-0.7 mm/yr prior to European settlement, up to 4.1-21 mm/yr in the last century. These increases in sedimentation are generally consistent with those found by Sloss et al., (2004), using amino acid racemisation, radiocarbon and cesium 137 dating along with analysis of remotely sensed imagery; and Pockock et al. (2003) who used historical data of bathymetric depth.

Mullet and Hooka Creek deltas are wave dominated deltas, influenced by wind generated waves and currents that rework the sediment to produce the smooth shoreline found in this region. Sedimentation at Mullet Creek delta was estimated to have increased from <1 mm/yr over the previous 2500 years up to 3.3 mm/yr over the last 200 years (Sloss et al., 2004). This has lead to a 400m extension of the fluvial delta toward Purry Burry Point between 1923 and 1988 (Pockock et al., 2003). The majority of the flow from Mullet Creek has been diverted to Hooka Creek over the past 60 years, impacting on the estimations for sedimentation rates. However, taking this into account has led to estimates for the maximum sedimentation rates at Mullet Creek to be as high as 7 mm/yr. Not surprisingly, rates of sedimentation at the Hooka Creek delta were shown to have increased due to the diverted flow from Mullet Creek, with increases in parts from 2 mm/yr up to 7.14 mm/yr over the past 70 years (Sloss et al., 2004).

The Macquarie Rivulet delta is a river dominated delta with far less influence from wind and waves. This leads to a delta that extends into the lake, significantly indenting the coastline. Sedimentation rates were estimated to have increased from 4.5 mm/yr for the period between 300 and 40 years ago up to 31 mm/yr for the last 40 years (Sloss et al., 2004). Between 1955 and 1988, the Macquarie Rivulet delta extended a further 150 m into the lake (Pockock et al., 2003). During this period, rapid increases occurred during the 1970s and 1980s due to a combination of urban and commercial expansion in the catchment (Hopley et al., 2007) and nine major flood events (Hean & Nanson, 1985). Mapping of the Macquarie Rivulet, which began in 1857, can be compared with more recent aerial photography so that a clear indication of the development of the delta can be seen, (see Figure 1-3).
Figure 1-2: Aerial view of Lake Illawarra with some important geographical locations (LIA, 2010a)
The central lagoon facies provided the best site in order to obtain uninterrupted data indicating changes in sedimentation rates over time (Sloss et al., 2004). The overall sedimentation rate in the central part of the lake is lower than when compared to the fluvial deltaic regions. This is due to the fact that only very fine particles of sediment, transported in suspension, and deposited under low energy conditions, will find their way this far into the centre of the lake. It was found that for 600 years prior to European settlement, sedimentation rates of lagoonal mud was approximately 0.35 mm/yr. The period between 160 years and 50 years ago, which corresponds with the majority of land clearing that was done for agriculture, shows an increase in sedimentation rate to 0.55 mm/yr. The past 50 years, which are characterised by increased urban and industrial development, show an increase in sedimentation rate of up to 2.6 mm/yr (Sloss et al., 2004).

**Figure 1-3: Evolution of Macquarie Rivulet delta 1857 – 1993 (Sloss et al., 2004)**

Hean and Nanson (1985) estimated that an average of approximately 100,000 m$^3$/yr of sediment was deposited from the Lake’s creeks during the 20th century, with significant increases in sediment transport in times of flood. Their long term estimate, for the last 8000 years, is between 25,000 and 50,000 m$^3$/yr. Another estimate made for total sediment load was performed by Forbes Rigby (2000), who executed a Level 1 pollutant export model, as defined by the NSW EPA (1997), on all sub-catchments for Lake Illawarra (see Table 1-1 & Table 1-2). Total sediment deposited was
found to be approximately 5368 tonnes/yr, or 4100 m$^3$/yr, assuming a sediment density of 1.3 tonnes/m$^3$ (Pockock et al., 2003). The significantly lower estimate to that made by Hean & Nanson (1985) is believed to be due to the model used by Forbes Rigby (2000), which did not take into account sediment delivery due to creek bank and bed erosion, and atmospheric deposition, but concentrated on stormwater runoff. Parameters used in Level 1 modelling include land use, annual rainfall, catchment runoff characteristics and average pollutant concentrations. Nevertheless, data obtained from Forbes Rigby (2000) gives a good indication of the contributions made by the different sub-catchments. Mullet Creek and Macquarie Rivulet, the largest of the sub-catchments, contributed the most overall sediment, whereas sediment per unit area is highest in Lake Illawarra North and Lake Illawarra South sub-catchments, due to their higher proportion of urban land use.

<table>
<thead>
<tr>
<th>Sub-Catchment</th>
<th>Average Year</th>
<th>Wet Year</th>
<th>Dry Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - Lake Illawarra North</td>
<td>900,930</td>
<td>1,293,194</td>
<td>471,280</td>
</tr>
<tr>
<td>2 - Mullet Creek</td>
<td>1,305,235</td>
<td>1,827,777</td>
<td>691,864</td>
</tr>
<tr>
<td>3 - Duck Creek</td>
<td>1,020,390</td>
<td>1,431,511</td>
<td>540,166</td>
</tr>
<tr>
<td>4 - Macquarie Rivulet</td>
<td>1,229,708</td>
<td>1,764,676</td>
<td>642,680</td>
</tr>
<tr>
<td>5 - Lake Illawarra South</td>
<td>912,643</td>
<td>1,307,159</td>
<td>476,268</td>
</tr>
<tr>
<td>Totals (tonnes/yr)</td>
<td>5,368</td>
<td>7,624</td>
<td>2,822</td>
</tr>
</tbody>
</table>

Table 1-1: Annual sediment loads by catchment (kg/yr) (Pockock et al., 2003)

<table>
<thead>
<tr>
<th>Land Use</th>
<th>Average Year</th>
<th>Wet Year</th>
<th>Dry Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urban</td>
<td>3,516,665</td>
<td>5,000,394</td>
<td>1,847,096</td>
</tr>
<tr>
<td>Industrial</td>
<td>766,583</td>
<td>1,082,536</td>
<td>404,244</td>
</tr>
<tr>
<td>Rural</td>
<td>465,842</td>
<td>662,119</td>
<td>244,827</td>
</tr>
<tr>
<td>Open Space</td>
<td>78,014</td>
<td>110,716</td>
<td>41,041</td>
</tr>
<tr>
<td>Forest</td>
<td>108,134</td>
<td>153,668</td>
<td>56,832</td>
</tr>
<tr>
<td>Main Roads</td>
<td>374,019</td>
<td>530,952</td>
<td>196,691</td>
</tr>
<tr>
<td>Railway</td>
<td>59,654</td>
<td>83,930</td>
<td>31,524</td>
</tr>
<tr>
<td>Totals (tonnes/yr)</td>
<td>5,368</td>
<td>7,624</td>
<td>2,822</td>
</tr>
</tbody>
</table>

Table 1-2: Annual sediment loads by land use (kg/yr) (Pockock et al., 2003)

Increased sedimentation has a range of deleterious effects on the ecological health of Lake Illawarra and also impacts on the aesthetic quality and recreational uses for the lake. A high rate of sedimentation leads to the smothering of seagrasses, loss of aquatic habitat, high turbidity in the water column, high pollutant and nutrient loads entering the Lake and a broadening of mud flats around the foreshore of the Lake (Pockock et al., 2003; Sloss et al., 2004; Haines & McAlister, 2006).
1.1.2 **Nutrient Budget**

An understanding of the nutrient budget is important as it tells us how nutrients enter a system, how are they transformed within the system and how they are eventually lost from the system (Sherman et al., 2000). Sediment and nutrient loads are strongly linked, with much of the nutrients delivered to Lake Illawarra being bound to sediment particles (Sherman et al., 2000). Since European settlement, nutrient enrichment of the Lake’s sediment has increased to the point where it is now the most significant process affecting nutrient concentrations (LIA, 1995; Qu, 2004). Nutrients bound to sediment will only become available for algal growth following transformation by bacteria, under appropriate conditions such as very low dissolved oxygen concentrations (Sherman et al., 2000). Similarly, organic phosphorus and nitrogen associated with plant and animal matter must also be broken down before becoming available (Sherman et al., 2000). Nutrient inputs are generally derived from five main sources: catchment and stormwater runoff, sewage overflows, groundwater infiltration, atmospheric deposition and sediment remobilisation. Streams that flow into Lake Illawarra which may deliver nutrient loads include Macquarie Rivulet and Mullet Creek, which account for 80% of catchment inflow, Oakey Creek, Horsley Creek, Albion Creek, Duck Creek, Brooks Creek, Hooka Creek, Budjong Creek, Minnegang Creek and Wegit Creek; there are also 55 stormwater drains. Nutrient outputs include tidal exchange with the ocean, algae harvesting and denitrification (Sherman et al., 2000; Qu, 2004; Rutten, 2007; LIA, 2010b). Nutrients can also be lost due to burial in the sediment, but over time, these can be returned to the system (Sherman et al., 2000).

High levels of phosphorus in Lake Illawarra make it a nitrogen limited system (Qu, 2004). This means that an increase in nitrogen levels has the potential to cause problems, leading to the development of large algal blooms and possibly eutrophication (Qu, 2004; Haines & McAllister, 2006; Rutten, 2007). This is thought to be due to the weathering of basaltic rocks found in the catchment, which form phosphorus rich sediments that are subsequently delivered to the Lake through fluvial processes (LIA, 2010b).

Once nutrients enter the Lake, they are converted into a range of different forms by seagrasses, algae and phytoplankton and will eventually be lost from the system, this is known as nutrient cycling (Sherman et al., 2000) (see Figure 1-4). Seagrasses acquire nutrients from the sediment, whereas algae and phytoplankton consume nutrients that have been dissolved in the water column (Rutten, 2007). Once organic matter has been broken down into simple inorganic molecules such as ammonia (NH$_3$), bacteria can then oxidise the ammonia to produce nitrate (NO$_3^-$) and nitrite (NO$_2^-$), by processes known as nitrification (Qu, 2004). Denitrification is the process of denitrifying bacteria reducing nitrate and nitrite into gaseous forms of nitrogen such as N$_2$. This
gaseous form of nitrogen is then lost to the atmosphere. Denitrification is an important process in the control of nutrient levels in Lake Illawarra and is sensitive to the total organic load received (Sherman et al., 2000; Qu, 2004; Rutten, 2007). With an increase in organic matter, more oxygen is required to break it down, which in turn leads to less oxygen available for the transformation of ammonia to nitrite and nitrate. Denitrification can no longer proceed with insufficient available oxygen resulting in an accumulation of bioavailable nitrogen such as ammonia and an increase in algal growth so that eutrophication of the system accelerates (Sherman et al., 2000). The reduction of dissolved oxygen in the water column enhances the release of nutrients from the sediment and decomposing organic matter, supporting further algal growth. This lack of dissolved oxygen can lead to the death of fish and other aquatic organisms (Rutten, 2007).

![Nutrient Cycling in Lake Illawarra](image)

**Figure 1-4:** Nutrient cycling in Lake Illawarra. Both nitrogen (N) and phosphorous (P) follow the paths shown with the exception of denitrification losses to the atmosphere which only affect the nitrogen budget (Sherman et al., 2000).

The increase in algal growth not only limits the oxygen available in the water column but also increases the turbidity, reducing the depth to which light can penetrate. Seagrass requires light and nutrients to grow, and will only survive in shallower waters if turbidity is increased (Harris et al., 1996; Sherman et al., 2000). Seagrass supports a range of fish species directly, through the provision of food and habitat, and indirectly by supporting invertebrates and algal epiphytes, which are in turn consumed by fish (Rutten, 2007). Seagrass also plays an important role in improving overall water quality, by trapping sediment, reducing turbidity and absorbing the nutrients within sediment (Sherman et al., 2000; Rutten, 2007).
Large algal blooms within Lake Illawarra were first seen as a significant problem in the 1970s, usually occurring after periods of heavy rainfall in shallow areas such as Griffins Bay, Koon Bay, Koong-Burry Bay, the Windang Peninsula and around Bevans Island (Rutten, 2007). Since 1988, the Lake Illawarra Authority has been manually removing algal biomass in order to reduce nutrient loads and improve the aesthetic appeal of the Lake. In 2007 – 2008, 1736 tonnes of macroalgal material was removed from the Lake, which contained approximately 4.44 tonnes of total nitrogen and 0.30 tonnes of phosphorous (LIA, 2010b).

1.1.3 Current Condition

A condition assessment of Lake Illawarra indicates that since the permanent opening of the Lake in 2007, there has been some improvement to water quality. Salinity and pH values have stabilised and there has been an increase in seagrass coverage (LIA, 2010b). However nutrient levels are still high, and above the ANZECC guidelines (ANZECC, 2000). This is despite ongoing works by the Lake Illawarra Authority which include algal harvesting, construction of stormwater drain controls and dredging of nutrient rich bed sediments (LIA, 2010b). This enhances the need for a further understanding of sources of nutrients entering the Lake.

1.2 Lake Illawarra Catchment

The total land area that drains into a body of water is known as the catchment. The catchment area for Lake Illawarra is 235 km² and is characterised by a distinct coastal escarpment which rises steeply from the coastal plain with an average elevation of 500 m and a maximum elevation of almost 800 m. The undulating coastal plain, which incorporates a majority of the Lake Illawarra catchment, extends from Thirroul, where the escarpment intersects the coastline, it then gradually widens to a maximum width of around 15 km (see Figure 1-6). The land area within the catchment includes approximately 20% urban, 35% rural, 33% forested and 3.1% industrial (Pockock et al., 2003) (see Table 3) and has a population of around 90,000 people (Clarke & Dooley, 2004). Five major sub-catchments make up the Lake Illawarra catchment including Mullet Creek and Macquarie Rivulet, the largest of the sub-catchments which account for 80% of the Lakes inflow; Lake Illawarra North, Duck Creek and Lake Illawarra South (see Figure 1-5).
Table 1-3: Sub-catchments and land-use types (Adapted from Pockock et al., 2003)

<table>
<thead>
<tr>
<th>Sub-Catchment</th>
<th>Size (ha)</th>
<th>Urban</th>
<th>Industrial</th>
<th>Rural</th>
<th>Open Space</th>
<th>Forest</th>
<th>Road</th>
<th>Rail</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lake Illawarra North</td>
<td>1,654</td>
<td>895.9</td>
<td>45.7</td>
<td>0.0</td>
<td>381.0</td>
<td>272.1</td>
<td>59.3</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>7.3%</td>
<td>54%</td>
<td>3%</td>
<td>0%</td>
<td>23%</td>
<td>16%</td>
<td>4%</td>
<td>0%</td>
</tr>
<tr>
<td>Mullet Creek</td>
<td>7,216</td>
<td>800.6</td>
<td>348.2</td>
<td>2,617.5</td>
<td>521.5</td>
<td>2,744.7</td>
<td>68.7</td>
<td>114.8</td>
</tr>
<tr>
<td></td>
<td>32.0%</td>
<td>11%</td>
<td>5%</td>
<td>36%</td>
<td>7%</td>
<td>38%</td>
<td>1%</td>
<td>2%</td>
</tr>
<tr>
<td>Duck Creek</td>
<td>2,743</td>
<td>999.7</td>
<td>116.9</td>
<td>845.1</td>
<td>144.2</td>
<td>557.5</td>
<td>67.6</td>
<td>12.0</td>
</tr>
<tr>
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<td>Lake Illawarra South</td>
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<td>Total Size</td>
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<td>4,473.2</td>
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Figure 1-6: Digital elevation model of Lake Illawarra catchment derived from the NSW Department of Lands Digital Topographical Database (DoL, 2006).
1.2.1 **Hydrology**

The hydrological characteristics of the Lake Illawarra catchment play an important role in the transport of sediment and nutrients into the Lake. The sharp rise of the Illawarra escarpment produces a strong orographic rainfall gradient, where storms are forced by the escarpment to rise, cooling the air more rapidly and increasing the rate of precipitation. This effect has lead to the average annual rainfall to vary from 1100 mm at the coast to over 1600 mm at the crest of the escarpment (Reinfelds & Nanson, 2004). These characteristics are also responsible for the high intensity, localised rainfall events which the region has experienced. The high intensity rainfall and consequent catchment runoff, combined with the ocean level and characteristics of the lake entrance channel at the time, are responsible for determining the rate and depth of flooding for the area around the lake (L&T, 2001).

One of the largest floods on record was the West Dapto Flood of 1984. Rainfall intensity during this event reached a high of 123 mm.h\(^{-1}\) with 640 mm falling in a 9 hour period (Nanson & Hean, 1985), producing a rainfall runoff of 25.5 m\(^3\).s\(^{-1}\).km\(^{-2}\) for the 61.2 km\(^2\) Mullet Creek catchment (Reinfelds & Nanson, 2004). High intensity rainfall events that have led to flooding and damage to urban and rural areas in the Illawarra occur with relative frequency (Nanson & Hean, 1985; Reinfelds & Nanson, 2004), about once every 8 years (Reinfelds & Nanson, 2001). During such events, erosion is widespread, but particularly in areas where urban development has encroached upon water courses, limiting natural overchannel flow of floodwaters (Reinfelds & Nanson, 2001) and in steep upstream reaches, where flow is predominantly confined to channels (Nanson & Hean, 1985).

The natural progression of floodwaters in the Illawarra is for high energy channels along the escarpment to drain small catchments, before emerging onto a relatively flat, low energy coastal plain. The coastal plain contains well developed macro-channels, which confine floodwaters, and vegetation which reduces the velocity of runoff, reducing flood peak discharge (Reinfelds & Nanson, 2004). Urban development within a catchment has been shown to have detrimental effects on rainfall runoff and stream morphology in Australia (Nanson, 1980; Nanson & Young, 1981; Reinfelds & Nanson, 2004) and around the world (Gregory et al., 1992; Jeje & Ikeazota, 2002; Leopold et al., 2005; Kang, 2007; Smucygz et al., 2011). Urbanisation decreases resistance to runoff, previously provided by vegetation cover, and at the same time increases the fraction of impervious groundcover, prohibiting rainfall runoff from infiltrating into the soil, where it would normally find its way gradually to the stream channels. Instead, all runoff is rapidly redirected straight into adjacent streams, increasing both the size and number of flood flows, leading to higher rates of erosion within the channel and channel enlargement (Nanson, 1980; Nanson & Young, 1981; Reinfelds & Nanson, 2004).
1.2.2 **Environmental Modelling**

A model is a simplification of real world processes, presented in a way that can be easily understood. They are developed in order to express our understanding of processes so that accurate predictions can be made and to allow for confident decision making (Brimicombe, 2003). Modelling of an environmental process will often require a large amount of spatial data as input and produce predictions which can be displayed as maps (Stocks & Wise, 2000). Geographic Information Systems (GIS) are adept at the capture, storage, retrieval, analysis and display of spatial data, and so have been increasingly used for environmental modelling (Skidmore, 2002). This study aims to characterise areas with a high potential for sediment and nutrient discharge within the Lake Illawarra catchment. Prediction of soil loss was initially developed to aid in the management of agricultural crop land (Wischmeier & Smith, 1978), which will be further discussed in Chapter 3. At this scale, there is relatively little spatial variability in the input data required. Soil loss models have since been expanded and modified in order to model much larger areas, for example entire catchments, requiring large amounts of spatially distributed data, such as land use and slope variability (Letcher et al., 1999). It is not surprising then, that GIS, with effective management tools for large spatially referenced datasets, have come to play an important role in soil loss prediction. Modelling of nutrient exports, developed primarily for water management on a catchment scale, requires a similar range of spatially distributed input data and is equally suited to GIS.

Modelling in order to predict erosion and nutrient behaviour on a catchment scale has been widespread in Australia (Rosewell, 1993; Zhang et al., 1996; Letcher et al., 1999; Boggs et al., 2001; Simms, 2007; Brodie & Rosewell, 2008) and worldwide (DeRoo, 1996; Morgan et al., 1998; van der Knijff et al., 2000; Merritt et al., 2003; Randle et al., 2006; Zhang et al., 2009). Despite Lake Illawarra being relatively well studied in terms of the history of sedimentation and its increase over time, and the cycles of nutrients into and out of the Lake, a catchment scale model detailing sediment output has not yet been devised. A primary factor in determining sediment outputs is current land use, which for the Lake Illawarra catchment, has changed and will most likely continue to change over time, primarily due to the replacement of rural landscapes with developed urban areas (LIA, 2010b). Diffuse sources of pollution, for example, urban areas, have been shown to be a significant contributor to water quality problems (Beck, 2005; Duh et al., 2008). Understanding the impacts of land use change within a catchment is an important aspect for effective management and the development of pollution control strategies.

In 2004, as part of the Comprehensive Coastal Assessment, the NSW Department of Planning developed a catchment model known as the Long-Term Hydrologic Impact Assessment model (L-THIA) (Baginska et al., 2004). This model aims to simulate nutrient emissions based on the
factors of land use, rainfall, an estimate of soil permeability, catchment runoff and event mean nutrient concentrations. The L-THIA is able to give a good indication of potential nutrient availability for an area and has been applied to the Illawarra region. The main limitations for this model are that it does not take into account suspended solids nor the possible nutrient load associated with sediment that may become available after it has drained into the lake.

More recently has been the introduction of the Coastal Eutrophication Risk Assessment Tool (CERAT), developed in 2009 by the NSW Department of Environment, Climate Change and Water (DECCW, 2009a). CERAT uses similar methodology to that of the L-THIA, while taking into account sediment delivery based on land uses and the processes within a lake or estuary, thereby making a prediction for eutrophication risk (DE&H, 2011). The tool aims to be simple in order to allow use and interpretation by non-technical users. The results found by the L-THIA and CERAT, when applied to the Lake Illawarra catchment, will be discussed further in Chapter 5, as a comparison with the results found in this study will be made.

1.3 Aims of Study

The aims of this study are to develop models that characterise areas with a high potential for mobilisation of sediment and nutrients in the Lake Illawarra catchment. An erosion risk map was developed based on the Universal Soil Loss Equation (USLE) using existing, spatially referenced datasets on a GIS platform. This was then combined with nutrient availability data for the soil types found in the catchment to provide a risk assessment of nutrients associated with sediment delivery into Lake Illawarra. This was done in order to develop knowledge to facilitate the management of Lake Illawarra and its foreshore’s in light of new urban development proposals within the catchment.

1.4 Outline of Thesis

Background information on the history of Lake Illawarra and the surrounding catchment, with respect to sedimentation and nutrient levels, has been provided at the beginning of this introduction, along with the current condition of the Lake. Ahead in this thesis is a review of the factors affecting soil erosion and soil erosion modelling techniques, previously implemented in Australia and worldwide. This is required in order to place this study in context with the broader literature base. The methods used throughout the study are outlined and then the results are discussed. The discussion includes an analysis of soil erosion factors and an overview of the soil erosion risk map generated. The validity of this model is discussed in terms of the results found from
a sensitivity analysis and from comparison to other similar modelling techniques. The nutrient export risk output is also discussed with reference to other studies which consider nutrient emissions within a catchment. The increased risk of soil erosion due to further development is also discussed along with an assessment of current sediment control practices employed during construction activities. Finally, the implications of the study findings, limitations of the model used, conclusions and recommendations are presented.
2 **Soil Erosion**

An understanding of sediment and nutrient loads entering a water body requires an understanding of soil erosion processes occurring in the catchment area. This chapter will outline the important aspects of soil erosion processes and the major contributing factors which may affect them.

2.1 **Erosion Processes**

Soil erosion occurs when the forces of water, wind and other factors act upon a surface. These forces can dislodge and transport soil particles, with the effect of wearing down the land. Soil particles within a flow of water are referred to as sediment. When sediment is deposited, this process is known as sedimentation. Within a catchment, sedimentation occurs sporadically and is not a uniform process (Rosewell et al., 1991) with high rates of sedimentation triggered by intense rainfall events (Young & Young, 2001). Soil erosion and sedimentation are natural processes, but, human interference often causes an acceleration of soil erosion due to changes in land use and vegetation cover (Young & Young, 2001). Other factors which may affect soil erosion apart from land use and vegetation are climate, lithology and soil characteristics, topography, erosion control practices which may have been implemented and the occurrence of fire, which effectively reduces the role of vegetation cover (Prosser & Williams, 1998). Soil erosion caused by the movement of water can occur in three ways, sheet erosion, rill erosion and gully erosion, but before these processes can be enacted, soil particles must be detached from the soil mass.

2.1.1 **Soil Detachment**

As a raindrop hits the surface, it has the potential to dislodge soil particles. This effect is dependent on the characteristics of the raindrops, the soil characteristics and the reaction of the water drop as it connects with the surface. The erosive effect of the raindrop will depend on characteristics such as drop size, shape and kinetic energy. Important soil characteristics include texture, organic matter content, capacity of rainfall to dislodge soil particles, moisture content and micro-topography (Terry, 1998; van Dijk et al., 2002). This factor is known as rainfall erosivity and is the most significant cause for the detachment of soil particles (Morgan, 2005).

Apart from the detachment of soil particles, raindrops can also be responsible for their transportation. The kinetic energy of a raindrop upon contact with the surface exudes forces radiating outward in all directions. If sufficient detachment has already taken place, these forces
themselves can result in the transportation of soil particles, known as rainsplash erosion. Rainsplash erosion will occur on hillslopes and results in a net downhill movement of soil particles (Terry, 1998). As the kinetic energy of an individual raindrop is a governing factor in this process, it is important to understand the importance of rainfall intensity along with the quantity of rainfall.

After prolonged rainfall events or storms, raindrops will no longer interact directly with the soil surface, but will first come into contact with puddles or overland flow. Interestingly, rainsplash erosion will increase with depth of surface water, until a threshold is reached where the effects of rainsplash erosion will cease. This threshold is again dependent on soil and raindrop characteristics (Palmer, 1964). The turbulent flow created by raindrops on the surface water is thought to be the governing factor behind this phenomenon (Morgan, 2005).

Soil detachment will continue after the effects of the falling rain. Once rainfall intensity exceeds the infiltration rate of the soil, and if the land surface is sloping, surface overland flow occurs. The infiltration rate is the rate at which water penetrates the soil at the soil surface (Baginska et al., 2004). Overland flow, or runoff, is the major transporting process for detached soil particles. However, the shear stress, or the frictional force of runoff on the soil surface, can also detach soil particles (Rosewell et al., 1991). Basically, when the forces created by runoff exceed the forces which are keeping the particles at rest, detachment will take place. This in itself is a complex process as there is an abundance of interrelated characteristics of soil, topography and runoff which must be considered. Soil characteristics which require consideration include the density of sediment, particle size and cohesion of the soil. Generally speaking, soils comprised of small particles, less than 0.002 mm, have a high cohesive force due to the clay minerals of which they are composed; however, once detached they require little energy to transport. As particle size increases beyond 0.002 mm, more force is required to transport the particles, but particles will be less cohesive and easier to detach. Sediment size, shape and density will also influence the angle of repose when the sediment is deposited, in turn influencing the topography of the surface. Topography and slope steepness will increase the force due to gravity being applied to the particle during overland flow. Runoff characteristics which require consideration are the density of the water, the effect of raindrop impact on the runoff water, which creates additional turbulence and increases runoff density as more sediment is added. Furthermore, particles within the flow will have an abrasive effect on surface soil which will add to soil detachment (Morgan, 2005).

2.1.2 Sheet Erosion

Sheet erosion occurs where soil is removed as a relatively even layer from the surface. It can be caused by rainsplash erosion or runoff, but is most commonly the result of both processes acting
together. Runoff occurring as an even layer of laminar flow, where velocity is evenly distributed, will seldom have the velocity required to detach and transport sufficient sediment to cause sheet erosion. The added effect of raindrop impact, however, can significantly increase detachment as well as the flow’s ability to transport sediment (Kinnell, 2005). Clear channels incised into the land surface are known as rills. Sheet erosion will generally occur on inter-rill areas and areas where soil has little protection from ground cover such as vegetation. Runoff will rarely occur as laminar flow, as the natural variation of the terrain inevitably leads to turbulence, with varying velocities and depths (Rosewell et al., 1991). Variations in flow velocity and flow depths will lead to areas of more intense erosion. Sheet erosion is not the removal of a uniform layer of soil, as slight variations will exist, but these variations are not as distinct as those seen in rill and gully erosion, which will be discussed in the following sections.

2.1.3 Rill Erosion

Rill erosion will occur after prolonged and usually concentrated flows, and is defined by the incision of numerous small channels with depths less than 300 mm (Young & Young, 2001) (see Figure 2-1). Concentration of flow is usually caused by microtopography, vegetation, animal tracks or on agricultural land by tillage (Bryan, 2000). Rainsplash erosion will not affect the development of rill erosion due to the depth and localised concentration of flows. However, sheet erosion occurring on interrill areas, which is affected by rainsplash erosion, will play a role in characterising rill erosion, as sediment transported by interrill erosion will eventually be carried to the rills. Consequently, the flow within rills must have sufficient force to carry sediment provided by interrill processes and to detach and transport particles from either the bed or sidewalls of the rills. The concentration of flow will not always produce rilling and will be dependent on whether sufficient flow depth is reached and characteristics of the soil. The effects of rilling will increase downslope, with further concentration of flows; similarly an increase in slope steepness will increase the amount of rill erosion (Rosewell et al., 1991). The relatively shallow incisions created means that evidence of rill erosion can be removed after prolonged rainfall events or, on agricultural land, by normal tillage. If runoff continues to concentrate and retains its erosive capacity, rills can widen or deepen and will eventually be classified as gullies.
2.1.4 Gulley Erosion

Further erosion of rills can lead to the development of gullies. Gully erosion is most commonly defined as steep sided drainage ways deeper than 300 mm that carry ephemeral runoff (McDonald et al., 1984; Rosewell et al., 1991). A gully will act as a small stream channel, where further erosion is caused by the detachment and transportation of particles from the sidewalls and bed of the gully. Undercutting can occur in gullies, causing the cave-in of larger blocks of soil, where they are then broken up and transported by the flow (Young & Young, 2001). Once gully erosion has taken place, it is significantly more difficult to regain surface stability. Gully head erosion is the lengthening of gullies due to flow over the head of a gully. Gully side erosion can be caused by runoff draining into the gully from the sides, seepage flow, flow within the gully including undercutting and rainsplash erosion (Rosewell et al., 1991). Once a gully is formed, it will drain an increasingly large area of the slope. It will intercept smaller surface drainways as well as subsurface flows moving through the soil, further increasing the flow rate and erosion within the channel (Young & Young, 2001).
2.2 Factors Effecting Soil Erosion

2.2.1 Climate

Climate is an important aspect of soil erosion and the rates at which it will occur. In relation to surface erosion, climate mainly refers to rainfall, both the erosivity of raindrops and the runoff produced by rainfall. Rainfall erosivity is the measurement of the kinetic energy of a raindrop as it impacts with the surface and can be dependent on both rainfall intensity and the amount of rain that falls (Terry, 1998; van Dijk et al., 2002; Morgan, 2005). Rainfall will cause both detachment and transportation of soil particles, depending on the role of other factors such as interception by land cover and soil characteristics such as permeability. Permeability will determine the rate at which rainfall will infiltrate the soil. Once the intensity of rainfall exceeds the infiltration rate of the soil, runoff will occur and consequently an increase in erosion (Rosewell et al., 1991; Young & Young, 2001).

The erosive effect of rain will also increase when rainfall events occur consecutively. This is due to soil disaggregation already having taken place, as well as soil saturation, which will reduce soil permeability and cohesion, increasing runoff and the overall erosive effect. If soil particles have been saturated and detached beforehand, either as a result of short intense rainfall or prolonged light rainfall, the amount of erosion occurring will usually increase significantly. However, there have been cases where secondary rainfall events have produced less soil erosion, but this is most likely due to the amount of erodible material available (Morgan, 2005). Therefore rainfall frequency, intensity, duration and the amount of rain are all key factors in soil erosion processes. Rainfall intensity, however, is considered to be the most important factor influencing erosion caused by rain (Yu, 1998; van Dijk et al., 2002). Rainfall intensity is a key aspect in understanding the amount of kinetic energy being exerted on the surface, and thus the rainfall erosivity. In Australia, rainfall intensities of less than 25 mm/hr are considered to have a low or negligible erosive effect. The erosive effect of rainfall will increase with rainfall intensity up to intensities of 75 mm/hr. Changes in the erosive effect of rainfall are minimal as rainfall intensity increases beyond 75 mm/hr. (Young & Young, 2001; White, 2006).

2.2.2 Topography

Topographical characteristics such as slope gradient, length, aspect and form, will generally define the most common types of erosion that will occur, those being sheet, rill or gully (Bryan, 1979; Bryan, 1987). Soil stability will typically decrease with increased slope gradient, where the
slope will have a significant influence on the kinetic energy available to runoff. This means that an increase in slope gradient will increase the carrying capacity of runoff, as well as its ability to detach soil particles (Bryan, 1979). Runoff will also be shallower on steeper slopes, increasing the amount of soil particle movement downslope caused by rainsplash erosion (Bryan, 2000). These relationships can be seen from the equation outlining the velocity of a falling object:

\[ v = \sqrt{2gh} \]

where \( v \) is final velocity, \( g \) is acceleration due to gravity (9.8 m.s\(^{-1}\)) and \( h \) is the height of fall. This shows that if the height from which water must flow is increased by a factor of 4, then the velocity will double, regardless of friction. The kinetic energy of water is proportional to the square of water velocity; therefore a double in water velocity will lead to kinetic energy increasing by 4. The relationship between kinetic energy and volume of particles transported is given by the formula:

\[ Q = \lambda v^6 \]

where \( Q \) is the volume of particles, \( \lambda \) is the proportion of kinetic energy due to rainfall or flowing water and \( v \) is the velocity, so that an increase of kinetic energy by a factor of 4 will lead to 64 times increase in particles being transported. Similarly, as:

\[ \text{kinetic energy} = \frac{mv^2}{2} \]

where \( m \) is the mass, a double in mass will lead to a double in kinetic energy. This large influence of kinetic energy on particle transportation shows the importance that soil detachment processes will have on the overall erosive effect (Zachar, 1982).

The length of slope will have an impact on the total amount, and therefore mass, of water and the velocity of runoff. This will in turn control the carrying capacity of runoff and the soil detachment processes of runoff acting upon the surface. However, an increase in slope length has not always been seen to increase soil erosion proportionally and in some cases there has been no increase in erosion with an increase in slope length (Zachar, 1982; Prosser & Dietrich, 1995). This is possibly due to the change in erosion processes where sheet erosion develops into rill erosion, decreasing soil loss on interrill areas where detachment due to rainsplash has occurred. However, the development of rills can also increase erosion, if rills form at high densities. The relationship between slope length and soil loss is further complicated by the fact that longer slopes will have a higher tendency for
gradient change (Morgan, 2005). Bryan (1979, 2001) has shown a relationship between slope length and erosion processes. With constant rainfall of moderate intensity, he showed that sheet erosion will occur on slopes of 10 m in length before deposition. Rill erosion did not take place until slope lengths of 46 m were obtained.

It is the combination of both slope length and gradient which will define the actual shape, or form of an area. Slope profiles may be straight, convex, concave, concavo-convex or undulating. These different forms of slope will have an effect on soil loss due to erosion and the erosion processes that may occur (Zachar, 1982). Total soil loss will increase where eroded soil is transported into streams. This is most likely on uneven topographies, comprised of shorter slopes, where the converging water on the lower parts of the slope becomes more erosive, transporting the sediment into streams, leading to a convex slope shape. When soil is deposited at the lower parts of the slope, generally on longer slopes, a concave shape will ensue, with less eroded material reaching streams (Mitas et al., 1996; Mitasova et al., 1997). On undulating terrain, the processes of erosion and deposition generally lead to a levelling affect, with little total soil loss.

2.2.3 Soil Characteristics

Soil erodibility is the resistance of soil to both detachment and transport. Factors contributing to soil erodibility are soil texture, aggregate stability, shear strength, permeability and chemical and organic matter content. Many of these factors are interrelated. Soil texture refers to the particle size of the soil, usually being categorised as sand, silt and clay content. In general, particles comprising small grain sizes such as clays, will have a high cohesiveness, meaning they will require higher energy levels to detach, but once detached are transported more readily. Large sandy grains are less cohesive, but require more energy to transport. Once clay or fine silt particles enter a flowing water body, they can be difficult to remove, and will only settle once flow velocity has been significantly reduced, making them more of a problem for water pollution (Goldman et al., 1986).

Clay and organic matter are good ‘cementing’ materials that aid in the formation of aggregates. Soils with high clay or organic matter content will form aggregates with a higher stability, being more resistant to detachment. Aggregate stability can be significantly reduced by wetting, as it softens the cements and causes some clay particles to swell. Some clay minerals will react differently to wetting, so that the type of clay mineral present will also influence aggregate stability. Soils containing kaolinite, halloysite, chlorite or fine grained micas will not expand on wetting, smectite and vermiculite will swell on wetting, producing soils of higher erodibility (Morgan, 2005).

Shear strength, or cohesiveness, is a measure of the soils frictional resistance to an applied pressure. If the forces acting upon a soil exceed the shear strength of the soil, detachment and
erosion will take place. Before detachment occurs, deformation may take place, depending on the plasticity of the soil. Shear strength is influenced by bonding agents and internal friction, which is again related to the chemical composition of the soil, therefore an increase in moisture content will again lead to a decrease in shear strength (Geeves, 1991).

The infiltration rate of a soil will be determined by the soils permeability and drainage. If a soil has high permeability, it will absorb rainfall and runoff, reducing the total runoff and subsequent erosion. Once a soil becomes saturated, however, and good drainage can no longer take place, runoff and erosion will increase (Goldman et al., 1986).

2.2.4 Vegetation and Land Use

Land use is influenced by the type of soil present as not all soils are suitable for agriculture or supporting building sites. Land use or ground cover will affect erosion rates by either protecting the soil surface or by leaving the soil surface more exposed. Native vegetation and plant cover will protect the soil from water erosion on three levels. Firstly, above the ground, rain will be intercepted by the canopy, slowing and breaking up the raindrops. This will reduce the size and velocity of the raindrops and therefore the kinetic energy. The effects of rainsplash erosion, being driven by the kinetic energy of raindrops, will subsequently be decreased. Secondly, plant cover at ground level will obstruct and slow down the velocity of runoff, effectively increasing the surface roughness. Thirdly, vegetation can improve the soil characteristics and its ability to absorb water while the root system helps to keep soil in place, improving the mechanical strength (Zachar, 1982; Goldman et al., 1986; Morgan, 2005).
3 Soil Erosion Models

This chapter provides a review of some of the more important soil erosion models which have been developed. A more comprehensive review of available soil erosion models has been provided by Letcher et al., (1999) and Merritt et al., (2003). A brief history of soil erosion modelling is provided, followed by a review of the Universal Soil Loss Equation (USLE), the Revised USLE (RUSLE) and some of their derivatives. A selection of physically-based models is then reviewed and finally the rationale behind the selection of the model used in this study is presented. The RUSLE is looked at in more detail due to its significance in the development of soil erosion modelling, its widespread use, and its close relationship with the model which has been used in this study.

3.1 History of Soil Erosion Modelling

Scientific studies into the possible factors contributing to soil erosion first began between 1877 and 1895 by the German soil scientist Martin Ewald Wollny (Pudasaini, 2010). This was followed up by work at the United States Department of Agriculture in 1907. The first model developed in order to predict erosion was in the form of a mathematical equation introduced by Zingg (1940) with the aim of evaluating the effect of length and steepness of slope. This equation was improved upon over the years until Musgrave developed an empirical equation in 1947, known as the Musgrave equation or Slope Practice equation (Hudson, 1971), which is given as:

\[ E_r = T_p \times S_t \times L_n \times A_p \times M_p \times R_f \]

where:
- \( E_r \) = Erosion
- \( T_p \) = Type of soil
- \( S_t \) = Slope
- \( L_n \) = Length
- \( A_p \) = Agronomic practice
- \( M_p \) = Mechanical protection
- \( R_f \) = Rainfall

This equation was implemented in a range of studies for almost ten years until it was replaced by the now extensively used Universal Soil Loss Equation (USLE) in the 1960s. The USLE is another
empirically-based model; such models are generally thought to be the simplest form of model, as they are primarily based on the analysis of observations (Merritt et al., 2003). Most empirically-based soil erosion models since the 1960s have been derived from, or incorporate the USLE in some way, with modifications focussing on calibrating the model to better represent local conditions. Some of these models include:

- the Revised USLE (RUSLE),
- SOILLOSS,
- OzMUSLE
- GIS-Based Rapid Assessment of Erosion Risk.

Physically-based models have since been developed, in order to help deal with the large quantities of localised, experimental data, which are required for the implementation of empirically-based models. They intend to represent critical factors controlling soil erosion, and rely on fundamental physical equations of flow and sediment generation, transport and deposition (Merritt et al., 2003). In theory, these parameters are measurable and known. In practice, however, the large number of parameters involved, and the heterogeneity of important characteristics, means that calibration against observed data is often required for these parameters (Beck et al., 1995). A common problem with physically-based models, after being calibrated for particular conditions, is model identifiability, which means that estimated input parameters will play an important role in the model output, but their accuracy cannot be determined with any degree of certainty. Some physically-based models include:

- ANSWERS
- LISEM
- WEPP

### 3.2 USLE & RUSLE

The Universal Soil Loss Equation was developed by Wischmeier & Smith (1965 & 1978). It was developed in order to guide land use and management decisions where erosion, caused by rainfall and runoff, had become a problem for agriculture. The USLE was improved upon over the years until it evolved into the Revised Universal Soil Loss Equation (RUSLE) (Wischmeier & Smith, 1978). Although the USLE and RUSLE were both developed for agricultural purposes, they have since been applied to a range of land uses including rangeland, disturbed forests, construction sites, mining sites and other land uses where soil is exposed (Renard et al., 1991; Letcher et al., 1999; Boggs et al., 2001; Erskine et al., 2002). A major factor which the RUSLE introduced to soil erosion
modelling was the difference in rainfall characteristics due to geographic location (Renard et al., 1991). The Revised Universal Soil Loss Equation takes the form:

\[ A = R \times K \times (L \times S) \times C \times P \]

where:
- \( A \) = soil loss predicted (t ha\(^{-1}\) yr\(^{-1}\))
- \( R \) = rainfall erosivity factor (MJ mm h\(^{-1}\) ha\(^{-1}\) yr\(^{-1}\))
- \( K \) = soil erodibility factor (t h MJ\(^{-1}\) mm\(^{-1}\))
- \( C \) = cover and cropping management factor
- \( L \) = length of slope factor
- \( S \) = slope gradient
- \( P \) = erosion control practice factor.

**Rainfall Erosivity (R) Factor** - is a measure of the cumulative erosive force of individual rainfall events, or the sum of the average annual EI\(_{30}\). \( E \) represents the total kinetic energy of the storm (MJ ha\(^{-1}\)) and I\(_{30}\) represents the maximum thirty minute rainfall intensity (mm yr\(^{-1}\)). In this way the R factor is able to account for the erosive force of both runoff and rainsplash. Typical values for the rainfall erosivity factor in New South Wales range from 750 to 7000 MJ mm h\(^{-1}\) ha\(^{-1}\) yr\(^{-1}\). The R factor can be calculated using the equation:

\[
R = \frac{1}{n} \sum_{i=1}^{n} \left[ \sum_{j=1}^{m} E_j (I_{30})_j \right]
\]

where:
- \( R \) = rainfall erosivity factor (MJ mm h\(^{-1}\) ha\(^{-1}\) yr\(^{-1}\))
- \( n \) = total number of years
- \( m \) = total number of rainfall storms \( i \)th year
- \( I_{30} \) = maximum 30 minute intensity (mm hr\(^{-1}\))
- \( E_j \) = total kinetic energy (MJ ha\(^{-1}\)) of \( j \)th storm of \( i \)th year (Wischmeier & Smith, 1978).

**Soil Erodibility (K) Factor** – is a measure of a particular soils susceptibility to erosion, and its effect on the runoff rate. The soil characteristics which will influence the K factor include infiltration rate, permeability and water holding capacity of a soil along with shear strength and aggregate stability,
which are related to particle size, organic matter content and mineralogy. The soil erodibility factor in the RUSLE is a value which had been calculated after a range of plot experiments, each plot was 22.1m long with a uniform slope of 9%. In New South Wales, typical K values range from 0.01 to 0.06 (Wischmeier & Smith, 1978).

Slope Length and Slope Gradient (LS) - are both important factors in determining the total amount of soil loss. In the RUSLE they are considered conjointly as a single topographic factor (LS), and this is the expected ratio of soil loss per unit area to the corresponding loss of soil found on the standardised experimental plots, with a length of 22.1 metres and a 9 percent slope (Wischmeier & Smith, 1965). This ratio for specific values of slope length and gradient can usually be found from the slope-effect chart (see Figure 3-1). When modelling an area where there may be several slope gradient and length values combined, the most erosive segment should be used because finding averages for these values can significantly underestimate soil movement. Slope length is defined as the distance from the point of origin of overland flow to either the point at which slope gradient decreases sufficiently for deposition to occur or to the point where runoff enters a well defined channel. Whichever distance is the limiting factor becomes the basis for selecting slope length (Wischmeier & Smith, 1965).

![Figure 3-1 Slope-Effect Chart for topographic factor LS (Excerpt from Wischmeier and Smith, 1965)](image)
**Cover and Cropping Management (C) Factor** – is the ratio of soil loss from land cropped under specific conditions to the corresponding loss from tilled, continuous fallow. As the USLE has been derived for agricultural application, it is a measure of a range of interrelated vegetation and land cover effects, and is largely dependent upon how much erosive rain occurs during periods when land cover provides the least protection (Pudasaini, 2010). Derivation of the C factor includes the computation of the Soil Loss Ratio (SLR):

\[
SLR = PLU \times CC \times SC \times SR \times SM
\]

where:

- **PLU** = prior land use subfactor
- **CC** = canopy cover subfactor
- **SC** = surface cover subfactor
- **SR** = surface roughness subfactor
- **SM** = soil moisture subfactor (Wischmeier & Smith, 1978).

Prior land use subfactor represents the effect of previous land use on soil consolidation. Incorporated into this is the biomass in the top 100 mm of soil which is able to resist erosion. Canopy cover is the effect of the vegetative canopy which intercepts the falling rain, reducing its erosive capacity. Surface cover characterises the small basins, exposed rocks and crop residue which may impede the rate of soil erosion. Surface roughness will reduce the velocity of flow and therefore erosion rates. Furthermore, rough surfaces will generally have a higher infiltration rate than smooth surfaces. Finally, soil moisture will also influence the infiltration rate and therefore soil loss (Pudasaini, 2010). The C factor is a combination of the weighted value of the SLR for a given period and the fraction of the rainfall erosivity factor for that period (Pudasaini, 2010). Values for the C factor can range anywhere between 0.001 for forest or dense shrub up to 1 for bare, exposed soil.

**Erosion Control Practice (P) Factor** – is again referring to practices relevant to agricultural land use. It is the ratio of soil loss with a particular control practice in place to the corresponding soil loss with cultivation up and down slopes (Wischmeier & Smith, 1965). Control practices relevant to the P factor in the RUSLE include contouring, strip cropping, terracing and subsurface drainage. These practices generally aim to reduce surface runoff velocity and subsequent soil loss. Values for the P factor range from 0 to 1.3.
Limitations – Some of the limitations of the RUSLE are that it was derived using experimental data obtained from research conducted in North America. This means that application of this model in other areas requires regional specific data. Presently, however, such data is usually readily available for many locations. As the RUSLE has been specifically designed for agricultural practices, it focuses on erosion and soil loss and does not take into account sediment deposition. Furthermore, the RUSLE does not account for spatial and temporal variability and as such will not normally provide an average annual output for an entire hillslope (Pudasaini, 2010).

3.3 SOILOSS

Description - SOILOSS is a model derived from RUSLE which has been adapted to suit conditions for New South Wales, Australia. Input parameters remain the same, with modifications made to rainfall erosivity, land cover and soil erodibility in order to suit Australian conditions (Rosewell, 1993). These modifications were based on data collected using USLE standard plots, with soil erosion estimates reflecting Australian conditions (Edwards, 1987).

Advantages - The major advantage of SOILOSS over the RUSLE is its adaptation to Australian conditions (Letcher et al., 1999).

Disadvantages – As with the RUSLE, SOILOSS will only provide a spatially and temporally averaged estimate of soil removal, with no consideration for sediment deposition (Letcher et al., 1999).

3.4 GIS Based Rapid Assessment of Erosion Risk

Description – This model primarily aims to provide a relative erosion risk output map. It is applicable to the catchment scale and uses a modified version of the RUSLE. Modifications made generally involve the normalisation of factors to values between 0 and 1, in order to reflect net differences within the catchment and as such will not provide absolute quantitative values for soil loss or deposition that are comparable to other sites. Rather, an internally comparable map of relative risk is produced. Rainfall erosivity was exempt as it is assumed that this will be constant across a single catchment area (Boggs et al., 2001). Remaining inputs therefore include:

- Soil erodibility factor
- Slope angle factor
- Slope length factor
- Cover management factor.
Being GIS-based, outputs are provided in map format. During this study it was also found that an increase in resolution of the elevation data did not greatly enhance the erosion assessment. It was found, however, that a reduction in data resolution did lead to the erosion assessment to be increasingly effected by area (Boggs et al., 2001).

**Advantages** – The main advantage for the rapid assessment method is that it provides a quick representation of relative erosion risk within a catchment, relying on data that is readily available for most catchments. Data availability, particularly within Australia, is a considerable constraint for the applicability of many soil erosion models (Boggs et al., 2001). Being GIS based, it can provide a good, readily interpretable, spatial representation in the form of a map, and can provide powerful tools for evaluating changes within the catchment (Boggs et al., 2001).

**Disadvantages** – The rapid assessment method will not provide quantitative values for soil erosion or deposition. There is no consideration for temporal variations within the catchment. Therefore, the information provided in the output of the rapid assessment is significantly lacking when compared to most other soil erosion models.

### 3.5 OzMUSLE

**Description** – OzMUSLE is an adaptation of the USLE developed by Simms (2007). There have been a range of adaptations made to the USLE including modifications to suit the region of southeastern Australia, the ability to account for temporal variation and to allow the model to be incorporated into a GIS platform. This model requires the same inputs as for the USLE; however, in order to make it event-based and thus represent temporal variation, significant changes to the input data are necessary. The inputs required include:

- Event-based erodibility
- Event-based land cover
- Slope and angle and slope length factors
- Event-based rainfall runoff erosivity factor.

Outputs provided represent the spatial distribution of soil loss and sediment yield for a particular event. This model is also designed to work at the catchment scale, as opposed to the USLE, which is better suited for small scale, homogenous plots.

**Advantages** – The GIS nature of the model allows for good spatial representation of soil erosion and deposition. An event based model is also an advantage for estimating soil erosion, as a significant amount of erosion occurs during high intensity events (Yu & Rosewell, 1996).
Disadvantages – Soil mobilisation was found to be quite different to that of the measured rates in one of the catchments used in the initial study. This model was also found to be unsuitable for the estimation of single outcomes of sediment yield. With further refinements, this model could be advantageous, particularly in southeastern Australia. However, a relatively large amount of data and calculations are required in order to convert available data into the event-based format necessary for application with OzMUSLE.

3.6 ANSWERS

Description – The Areal Non-point Source Watershed Environment Response Simulation (ANSWERS) is a physically-based erosion model which uses a cellular approach. This involves dividing the landscape into cells, where each cell is then modelled and summed in order to give an output for the entire catchment (Beasley et al., 1980). The five main categories of inputs, within which lie numerous other parameters, include:

- Soil characteristics
- Land uses
- Elevation based slope and aspect
- Channel descriptions
- Storm event details.

ANSWERS delivers outputs describing runoff and erosion, although does have the capacity to be extended to include nutrients (Merritt et al., 2003).

Advantages – Outputs are both temporally and spatially distributed. The effects of rainfall intensity and spatial variation in soil infiltration capacity, surface conditions and topography are clearly explained by ANSWERS (Letcher et al., 1999)

Disadvantages – There is a requirement for large amounts of spatial and temporal input data. Where there is a lack of data, parameters will need to be calibrated, raising problems with model identifiability. There is the possibility that some model outputs may be insensitive to changes in the spatial distribution of input variables, although this may be dependent upon certain catchment characteristics or validity of input data used (Letcher et al., 1999).

3.7 LISEM

Description – The Limburg Soil Erosion Model (LISEM) is a physically-based model developed by the Department of Physical Geography at Utrecht University and the Soil Physics Division at the Winard
Staring Centre in Waneningen, the Netherlands (DeRoo, 1996). It aims to describe the processes involved in overland flow, channel flow, rainfall, interception, surface storage in micro-depressions and infiltration. LISEM is an event based model which utilises a Geographic Information System (GIS). Approximately 25 GIS layers are required as inputs including:

- Catchment morphology
- Leaf area index
- Soil roughness
- Fraction of soil with crop cover
- Rainfall data.

LISEM can provide spatially detailed map outputs describing soil erosion and deposition as well as overland flow for a given time period. The model will also give total runoff, sediment, infiltration and storage depression as well as having the capacity to produce hydrographs and sediment graphs for a rainfall event simulation (DeRoo, 1996).

**Advantages** – LISEM can provide a range of detailed outputs, with both spatial and temporal distributions, all incorporated within the GIS platform (Letcher et al., 1999).

**Disadvantages** – Large amounts of data, in GIS format, are required in order to effectively execute this model. The accuracy of this model will be dependent upon the resolution of the data acquired. As with most other physically-based models, apart from data availability, another difficulty may include model identifiability (Merritt et al., 2003).

### 3.8 WEPP

**Description** - The Watershed Erosion Prediction Project (WEPP) is a physically-based model developed in the USA in an initiative between the Agricultural Research Service, the Soil Conservation Service, the Forest Service in the Department of Agriculture and the Bureau of Land Management in the US Department of the Interior (Laflen et al., 1991). The model aims to assess the mechanisms which are critical to erosion caused by water, including any anthropogenic impacts.

Some of the factors required for the WEPP model include:

- Characteristics of the vegetation, both above and below the soil surface.
- Hydraulic processes, including surface runoff volumes, hydraulic roughness and typical runoff duration and peak rates.
- Temporal variations in soil properties, taking into account the effects of management practices, weathering, consolidation and rainfall on soil.
- Surface variables, including roughness, density, saturated hydraulic conductivity and erodibility factors of the rill and interill.

The WEPP can provide estimates for the spatial and temporal distributions of soil loss, sediment yield, sediment size characteristics, runoff volumes and the soil water balance (Merritt et al., 2003).

**Advantages** – The WEPP model is available for the hillslope scale and for entire catchments. It gives an accurate output in terms of both spatial and temporal distributions of soil detachment and deposition (Letcher et al., 1999). The various processes and mechanisms which effect erosion, including the complex interactions between factors and the variability due to temporal changes, are effectively described (Zhang et al., 1996).

**Disadvantages** – Computational requirements are high, with a large number of inputs necessary. In order to accrue these inputs, an in depth knowledge of a number of factors is required. Many catchments, particularly within Australia, do not have the available data required to perform the WEPP model. Where data is available, the model parameters will still need to be calibrated. The WEPP model is limited to sheet and rill erosion, and erosion occurring in channels where detachment is due to hydraulic shear (Letcher et al., 1999). Although the WEPP model can be applied to the catchment scale, the method used of summing up individual hillslopes, could lead to problems associated with cumulative error when applied to large catchments exceeding 600 ha (Merritt et al., 2003; Pudasaini, 2010).

### 3.9 Model Selection Rationale

The evolution of soil erosion modelling has tended towards an increase in complexity and as such, an increase in the amount of data inputs required. When modelling soil erosion at the catchment scale, particularly in Australia, the data required is often unavailable, due to the limited amount of research that has been done in this field. Where data is available, it often requires calibration in order to make it compatible with the model being used. On top of this, an increase in the amount of input information further increases the likelihood of error associated with the model. The spatial uncertainty of many input parameters is known to be high and the inclusion of temporal data can further increase the possibility of error (Quinton, 2004).

The actual effect of increasing the number of input parameters on the output derived is shown by a study performed by Quinton (2004). This was done through the use of the revised Morgan-Morgan-Finney model, which is similar to the WEPP model discussed earlier. This study involved comparing outputs of the model, which was run up to 5 times with a different number of input parameters used each time, to actual observations. The results (see Figure 3-2) indicate that
there is no significant difference between the outputs when many of the parameters are excluded. When slope angle is increased, the shape of the output distribution curve is the same, although shifted upwards. It should be noted that this experiment was applied to only one, small scale, experimental plot with cultivated crops for cover. Therefore, it is not necessarily indicative of model performance on the catchment scale or for the wide variations in vegetation cover possible. It does, nevertheless, signify the validity of less complex models, particularly when addressing relative soil erosion risk.

![Figure 3-2: Cumulative distribution of total soil loss.](image)

Time constraints, data availability and the apparent validity of simpler erosion models, lead to the decision to use the GIS Based Rapid Assessment of Erosion Risk (Boggs et al., 2001) for the Lake Illawarra Catchment. Data requirements, including a soil map, vegetation cover, and topography are all available in GIS format, without the need for excessive data calibration to achieve compatibility with the model. It was also the only model found which aims to give an indication of relative soil erosion risk, rather than quantitative outputs for soil loss.
4 Methods

Data quality plays an important role in defining the legitimacy of any model output. Before running a model, all data must undergo quality checks to ensure its compatibility with other model inputs and to assess the overall accuracy and validity of the data. This chapter outlines the methods used to assess data quality and the methods used during the modelling process itself. Modelling involved the development of factors contributing to soil erosion in a format usable on a GIS platform, the combining of these factors to produce a model output and finally a sensitivity analysis to assess the robustness of the model output.

4.1 Data Quality and Availability

The datasets available that allowed for the production of soil erosion factors to be used on a GIS platform are shown in Table 4-1. The data quality was checked in terms of resolution, accuracy, completeness and logical consistency. Logical consistency is an assessment of the spatial relationships between objects in a dataset (ANZLIC, 2011). Tests for logical consistency are generally in the form of the following questions:

- Are all points labelled?
- Do lines intersect at nodes?
- Do lines cross unintentionally?
- Do all lines exist?
- Are lines duplicated?
- Do lines undershoot or overshoot?
- Are all lines labelled?
- Do all polygon boundaries close?
- Are all polygons labelled?
- Do any polygons have duplicate labels?
- Are all points, lines and polygons topologically related?

The NSW Department of Lands Digital Topographical Database (DoL, 2006) provided topographical data in the form of a contour map and some spot heights, as well as updated information on urban land use. The DTDB map is presented at a scale of 1:25000 with a horizontal accuracy of 100 m and a vertical accuracy of 5 m (DoL, 2006). The DTDB shows complete data for the Illawarra region as of 2006 and is logically consistent, as all points are labelled, all lines intersect at nodes and all polygon boundaries close (DoL, 2006). Topographical data was then interpolated using
the “Topo to Raster” tool in ArcGIS. This method of interpolation is based on a program developed by Hutchinson (1989), and generates a digital elevation model (DEM) in raster format that is hydrologically correct with a connected drainage structure (see Figure 1-6). Other data utilised in the interpolation process, originating from the DTDB, included streams and sinks (known topographic depressions in the landscape). The DEM generated had a spatial resolution of 100 m, the best that could be achieved given that the horizontal accuracy of the input data was 100 m. The most common method for evaluating the DEM output generated is to create contours from the new surface and compare them to the original contour data (ESRI, 2010). The contours created for the evaluation had an interval of 5 m, rather 10 m in order to better examine the differences occurring. The difference between the contour datasets was generally within 100 m. The accuracy and spatial resolution of the DEM is not ideal. Topography is averaged out over the 100 m cells, leading to a smoothing of the landscape and an underestimation of topographical change. A higher resolution would better represent topographic changes, particularly when assessing smaller areas within the catchment, for example proposed development areas. It was this DEM that was then used to produce slope gradient and slope length factors, discussed in sections 4.2.2 and 4.2.3 respectively.

Soil Landscapes of the Wollongong-Port Hacking 1:100000 Sheet (Hazelton, 1990) and the Soil Landscapes of the Kiama 1:100000 Sheet (Hazelton, 1992) provide polygon data outlining soil landscapes possessing different soil characteristics. The maps are presented at a scale of 1:100000 with a horizontal accuracy of 100 m (DECCW, 2010b; DECCW, 2010a). The maps display complete data for the Illawarra region, in the form of polygons, with the only polygons not displayed are those with an area less than 40 hectares or those less than 300 m wide. All polygons are logically consistent with closed boundaries (DECCW, 2010b; DECCW, 2010a).

Land cover data was provided from three different sources, the Eastern Bushland Database (DECCW, 1998), Native Vegetation of the Illawarra Escarpment and Coastal Plain (NPWS, 2002) and the urban areas from the DTDB (DoL, 2006). The Eastern Bushland Database provides polygons outlining vegetation communities at a scale 1:100000 with a horizontal accuracy of 200 m. All polygons are labelled with boundaries closed and the data is logically consistent (DECCW, 1998). Inadequate accompanying literature describing the different vegetation communities led to the use of the Native Vegetation of the Illawarra Escarpment and Coastal Plain (NPWS, 2002). This dataset covers around 80% of the study area, missing the south and the southeast of the catchment, but provides accompanying literature with detailed descriptions of the vegetation in the area. There is sufficient overlap between the two data sets, so that a good comparison can be made. This map provides polygons outlining vegetation communities at a scale of 1:25000 with a horizontal accuracy of 10 m. All polygons are closed, nodes are formed at the intersection of lines and there is only one
label per polygon, ensuring logical consistency of the data (NPWS, 2002). Finally, polygons outlining a more detailed and recent representation of urban areas were added from the DTDB (DoL, 2006). The combination of these three data layers produced good coverage of land cover factors in the Illawarra region.

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Accuracy</th>
<th>Format</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil Landscapes of the Wollongong-Port Hacking 1:100000 Sheet (Hazelton, 1990) and Soil Landscapes of the Kiama 1:100000 Sheet (Hazelton, 1992).</td>
<td>Horizontal 25 m</td>
<td>Vector</td>
<td>These two maps provide polygon features outlining areas with different soil and landscape properties.</td>
</tr>
<tr>
<td>NSW Department of Lands - Digital Topographical (DoL, 2006).</td>
<td>Horizontal 100 m</td>
<td>Vector</td>
<td>Topographic data with 10 m contours represented as a line feature class and some spot heights. Topographic data was interpolated to create a digital elevation model (see below). Also provides polygon data outlining urban areas.</td>
</tr>
<tr>
<td>NSW Department of Environment, Climate Change and Water - Eastern Bushland Database (DECCW, 1998).</td>
<td>Horizontal 200 m</td>
<td>Vector</td>
<td>This map provides polygon features outlining different vegetation communities as well as non forested and urban areas found along the east coast of NSW.</td>
</tr>
<tr>
<td>NSW National Parks and Wildlife Service – Native Vegetation of the Illawarra Escarpment and Coastal Plain (NPWS, 2002).</td>
<td>Horizontal 10 m</td>
<td>Vector</td>
<td>This map provides polygon features outlining detailed classifications for native vegetation in the Illawarra region. This map did not cover the entire catchment for Lake Illawarra and so was used in conjunction with the Eastern Bushland Database (DECCW, 1998).</td>
</tr>
<tr>
<td>Digital Elevation Model</td>
<td>Horizontal 100 m</td>
<td>Raster</td>
<td>A digital elevation model (DEM) was created by interpolating contour, spot height, stream and sink data from the DTDB (DoL, 2006).</td>
</tr>
</tbody>
</table>

Table 4-1: Datasets used for the production of soil erosion factors
4.2 Rapid Based Assessment

The method used for the assessment of soil erosion risk in the Lake Illawarra Catchment, was an amended version of the GIS based rapid assessment of erosion risk that was first outlined by Boggs et al. (2001). This method follows on from the traditional erosion assessment methods of the USLE and RUSLE, previously discussed, which have since been used extensively around the world (Edwards, 1987; Renard et al., 1991; Moore & Wilson, 1992; Rosewell, 1993; Letcher et al., 1999; Ismail & Ravichandran, 2008). The rapid assessment method allows for a relatively quick evaluation of erosion risk within a catchment, rather than attempt to calculate gross soil loss or movement. This is done through the comparison of characteristics within a particular catchment, and allows for the removal of characteristics which will be constant across a particular area, for example, rainfall erosivity (Boggs et al., 2001). Comparing characteristics within a catchment also allows for the use of readily available datasets, with minimal alterations, which are normally required in order to calibrate a model for any particular region.Datasets used for the rapid assessment of soil erosion risk (A) in the Lake Illawarra Catchment include soil erodibility factor (K), slope steepness factor (S), slope length factor (L) and cover and management factor (C). The formula used takes the form:

\[ A = K \times S \times L \times C \]

4.2.1 Soil Erodibility Factor (K)

Data relating to soil characteristics were readily available for the Lake Illawarra Catchment and was found in the Soil Landscapes of the Wollongong – Port Hacking 1:100000 Sheet, and the Soil Landscapes of the Kiama 1:100000 Sheet (Hazelton, 1990; Hazelton, 1992). The accompanying map sheets were digitised for use in ArcGIS. Within the study area, twenty five soil landscapes were identified, each labelled according to the area within which they are predominantly found. Data available for each soil landscape included dominant soil materials, pH, fertility and erodibility, the most important being soil erodibility for an erosion risk assessment. Fertility ratings can be utilised in order to complete an estimation on possible nutrient exports (see 4.4 Nutrient Export Risk). The erodibility factor supplied in this literature was derived from a series of laboratory tests including particle size analysis and carbon test data, as well as field assessment of soil structure and permeability (Hazelton, 1990; Hazelton, 1992).

The soil landscape maps used contain the twenty five dominant soil landscapes and within each of these soil landscapes, there can be up to five subcategories defining different characteristics.
relating to that landscape. As the soil landscape map sheet does not differentiate between these subcategories, characteristics of the dominant surface soil type within a landscape were used. The dominant soil type was determined using cross sectional data of the soil landscape as well as data obtained from the soil landscape descriptions provided. There were eleven classifications in all for the soil erodibility factor, ranging from very low to very high (Hazelton, 1990; Hazelton, 1992) (see Table 4-2). These classifications were then ranked from 0 to 1, for example very low erodibility is equal to 0.11, low is equal to 0.22 and so on, with very high erodibility equal to 1.

<table>
<thead>
<tr>
<th>Soil Landscape</th>
<th>Erodibility</th>
<th>Fertility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Albion Park (ap)</td>
<td>High</td>
<td>Moderate - High</td>
</tr>
<tr>
<td>Barren Grounds (ba)</td>
<td>Low</td>
<td>Very Low</td>
</tr>
<tr>
<td>Berkeley (bk)</td>
<td>Low</td>
<td>Moderate - High</td>
</tr>
<tr>
<td>Bombo (bo)</td>
<td>High</td>
<td>Low - Moderate</td>
</tr>
<tr>
<td>Bundeena (bu)</td>
<td>Moderate</td>
<td>Very Low</td>
</tr>
<tr>
<td>Cambewarra (ca)</td>
<td>Moderate</td>
<td>Moderate</td>
</tr>
<tr>
<td>Fairy Meadow (fa)</td>
<td>Low</td>
<td>Low - Moderate</td>
</tr>
<tr>
<td>Faulconbridge (fb)</td>
<td>Very Low - Low</td>
<td>Low</td>
</tr>
<tr>
<td>Fountaintale (fo)</td>
<td>High</td>
<td>Moderate - High</td>
</tr>
<tr>
<td>Gwynneville (gw)</td>
<td>Moderate</td>
<td>Moderate</td>
</tr>
<tr>
<td>Hawkesbury (ha)</td>
<td>Low</td>
<td>Very Low</td>
</tr>
<tr>
<td>Illawarra Escarpment (ie)</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Killalea (ki)</td>
<td>Very Low</td>
<td>Moderate - High</td>
</tr>
<tr>
<td>Kurnell (kn)</td>
<td>Very Low</td>
<td>Very Low - Low</td>
</tr>
<tr>
<td>Lucas Heights (lh)</td>
<td>Moderate - High</td>
<td>Low</td>
</tr>
<tr>
<td>Mangrove Creek (mc)</td>
<td>Very Low</td>
<td>Very Low</td>
</tr>
<tr>
<td>Maddens Plains (md)</td>
<td>Low</td>
<td>Very Low</td>
</tr>
<tr>
<td>Robertson (ro)</td>
<td>Low</td>
<td>Moderate to High</td>
</tr>
<tr>
<td>Shellharbour (sh)</td>
<td>Very High</td>
<td>Moderate</td>
</tr>
<tr>
<td>Seven Mile (sm)</td>
<td>Very Low</td>
<td>Low</td>
</tr>
<tr>
<td>Warragamba (wb)</td>
<td>Low - Moderate</td>
<td>Low - Moderate</td>
</tr>
<tr>
<td>Wollongong (wg)</td>
<td>Very Low</td>
<td>Low</td>
</tr>
<tr>
<td>Wildes Meadow (wm)</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Wattamolla Road (wt)</td>
<td>Moderate</td>
<td>Moderate - High</td>
</tr>
<tr>
<td>Disturbed Landscapes (xx)</td>
<td>High</td>
<td></td>
</tr>
</tbody>
</table>

Table 4-2: Soil Erodibility and Fertility ratings for the soil landscapes present in the Lake Illawarra Catchment (adapted from Hazelton (1990) & Hazelton (1992))
4.2.2 **Slope Angle Factor (S)**

The slope angle factor was calculated from a digital elevation model (DEM) of the Lake Illawarra Catchment. Of note is the steep escarpment to the west of Lake Illawarra that rises to a maximum height of almost 800 metres above sea level. The DEM was constructed from contour data acquired from the NSW Department of Lands Topographic Data Model (DoL, 2006). By calculating the rate of change in elevation from the DEM, the slope angle factor can be derived. This can be expressed in degrees, with a maximum of 90, or as percent rise, where no slope would be equal to 0%, a 45 degree slope would be expressed as 100% and as the slope angle increases to become more vertical, the percent rise will continue to increase, tending toward infinity. As the DEM has a resolution of 100 m, it is important to remember that any calculation in slope will also have a resolution of 100 m. The implications of this are that the slope will be averaged out over this area, and will not give an entirely true representation of undulating terrain or slope variability within a 100 m area.

4.2.3 **Slope Length Factor (L)**

Slope length can also be calculated from a DEM using the accumulated flow function. Firstly, flow direction is required, which gives a numeric representation of the aspect of the slope, then the accumulated flow function can be applied in order to obtain the slope length factor. Areas with an accumulated flow value of zero are local topographic highs, whereas areas with high accumulated flow values are areas of concentrated flow, and are most likely stream channels. This assessment of erosion risk, attempts to capture the effect of surface runoff. In order to achieve this, areas under the influence of fluvial processes should be discarded. Therefore, cells which had an accumulated flow value of greater than 100, were deemed to be operating under fluvial processes and were exempted from the final analysis (Boggs et al., 2001). The remaining values for slope length were normalised between 0 and 1, so as to be compatible with K, S and C factors. As the slope length factor was derived from the DEM, it too will have a spatial resolution of 100 m.

4.2.4 **Cover Management/Land Use Factor (C)**

The cover management factor accounts for the protection provided by vegetation or any other erosion control measures which may be in place. Three datasets were used during the formulation of the cover management factor, the Eastern Bushland Database (DECCW, 1998), Native Vegetation of the Illawarra Escarpment and Coastal Plain (NPWS, 2002) and the urban areas from the DTDB (DoL, 2006). Both the Eastern Bushland Database (DECCW, 1998) and the Native
Vegetation of the Illawarra Escarpment and Coastal Plain (NPWS, 2002) datasets were created by the NSW National Parks and Wildlife Service using predominantly remote sensing techniques in conjunction with some field sampling.

The values obtained for the C factor, which were based on vegetation descriptions, are somewhat arbitrary, and are the authors own interpretation of the data available. For this reason, a description for each vegetation class has been provided, focusing on the key features which determined the final values for the C factor. This involved the vegetation communities being ranked, due to density of the canopy covers, including the overstorey, sub canopy or shrubs and the groundlayers, as well as the amount of disturbance affecting a particular category. This method is deemed acceptable, as the rapid assessment of erosion risk relies on a comparison of factors within a given catchment, so that further, more detailed, information on the cover management factor is not required.

4.2.4.1 Moist Forest System

Moist forest systems are often found adjoining rainforests in fertile to moderately fertile soils (Gellie, 2005). Common tree species include *Ceratopetalum apetalum*, *Acmena smithii* and *Doryphora sassafrass*, which can provide up to 75% canopy cover. The understorey generally consists of shrubs including *Eupomatia laurina*, *Pittosporum undulatum* and *Trochocarpa laurina*. The groundlayer is usually dominated by ferns such as *Microsorum spp.* and *Arthropetris tenella*. Ground cover and shrub species are relatively sparse, each creating canopy cover of no more than 25% (NPWS, 2002). Moist forest systems within the catchment have low disturbance levels. A C factor value of 0.01 was applied, this is the same as values given to similar forest types by Roose (1977), forest or dense shrub, and Blanco and Lal (2008), forest with greater than 90% cover.

4.2.4.2 Rainforest System

The rainforest system represents vegetation with a dense overstorey canopy with heights of up to 30m, with a relatively sparse coverage in the understorey. These systems are usually found in deep gullies or other sheltered areas. The upper canopy provides 75% coverage consisting of species such as *Ceratopetalum apetalum*, *Acmena smithii* and *Doryphora sassafras*. Subcanopy trees and shrubs have a canopy cover of 25% consisting of the species *Tasmannia insipid*, *Pittosporum undulatum* and *Cyathea Australia* with the groundcover species *Blechum cartilagineum*, *Arthropteris tenella* and *Asplenium flabellifolium* also providing canopy cover of 25% (NPWS, 2002). This vegetation classification contains areas suffering from light to moderate disturbance levels, however ample canopy cover is provided and being located in sheltered areas. It was given a relatively low C factor.
value of 0.001. This is again the same as values given to similar forest types by Roose (1977), forest or dense shrub, and Blanco et al. (2008), forest with greater than 90% cover.

4.2.4.3 Plateau Complex

Plateau complex represents vegetation growing on plateau regions along the Illawarra Escarpment, with soils derived from the underlying sandstone bedrock (Gellie, 2005). Overstorey species include *Eucalyptus sclerophylla*, *Corymbia gummifera* and *Eucalyptus sieberi*, which provide in excess of 15% canopy cover. The understorey is generally more dense providing canopy cover of up to 35%, and consists of shrubs such as *Banksia spinulosa*, *Hakea dactyloides* and *Leptospermum trinervium* along with smaller ground cover species including *Entolasia stricta*, *Lomandra obliqua* and *Cyathochaeta* with canopy cover of 20% (NPWS, 2002). This vegetation category is relatively sparse, but disturbance levels are quite low. A C factor value of 0.16 was applied, this compares with Young (1991), woodland with appreciable undergrowth and 20 to 40% ground cover.

4.2.4.4 Dry Forest System

Dry forest systems are generally found in areas with shallow soils of low fertility and water holding capacity. There is a combination of tree species including *Syncarpia glomulifera*, *Corymbia gummifera*, *Eucalyptus agglomerata* and *Eucalyptus sieberi*; a sparse cover of shrubs including *Acacia obtusifolia*, *Oxylobium ilicifolium*, *Leucopogon lanceolatus* and a ground layer consisting of *Platysace lanceolata*, *Entolasia stricta*, *Joycea pallida* and *Dianella caerulea* (Gellie, 2005). Although this vegetation contains canopy cover from trees and shrubs as well as providing groundcover, it is relatively sparse with each layer providing coverage of no more 30% (NPWS, 2002). Most of this vegetation class within the catchment is disturbed forest. A C factor value of 0.16 was applied, this again falls into the class, woodland with appreciable undergrowth and 20 to 40% groundcover (Young, 1991).

4.2.4.5 Woodland System

The Woodland system represents an open vegetation community predominantly located in areas of shallow sandy soils with low fertility. The main feature of this system is the sparse canopy cover of 15% for the overstorey, 35% for the shrub layer and 20% for groundcover. Common species may include trees such as *Eucalyptus sclerophylla*, *Eucalyptus racemosa* and *Eucalyptus haemastoma*, shrubs consisting of *Banksia spinulosa*, *Leptospermum trinervium* and *Platysace linearifolia*, and groundcovers *Entolasia stricta*, *Lomandra obliqua* and *Cyathochaeta diandra* (Gellie, 2005).
Vegetation communities within this classification usually suffer from light to moderate disturbance. A C factor value of 0.16 was also applied due to the ground cover percentage (Young, 1991).

### 4.2.4.6 Coastal Complex

The coastal complex vegetation class represents a range of vegetation growing on the fore, mid and hind-dunes. Species may vary with distance from the coast due exposure to salt laden winds and soil improvements (Gellie, 2005). Where small trees and tall shrubs (5 – 7 m tall) such as *Banksia integrifolia* and *Leptospermum laevigatum* are present, a mean canopy cover of 60% can be provided. Shrubs (1 – 2 m tall) including *Acacia longifolia*, *Correa alba* and *Monotoca scoparia* can provide up to 30% canopy cover and ground covers *Lomandra longifolia*, *Carpobrotus glaucescens*, *Pelargonium australe* and *Commelina cyanea* can provide up to 80% canopy cover (NPWS, 2002). Significant sections of this vegetation class are moderately or highly disturbed. Again, due to the ground cover percentage, a C factor value of 0.16 was applied (Yang et al., 2007).

### 4.2.4.7 Non Forest Systems

Non forest systems generally represent areas cleared for agricultural uses. The predominant agricultural land use for the Lake Illawarra catchment is the grazing of livestock. Such areas tend to be more susceptible to erosion risk due to the lack of protection otherwise provided by well established vegetation. This classification has been given the highest C factor value of 0.3, based on Young (1991), pastureland and Lee & Lee (2006) for agriculture.

### 4.2.4.8 Urban System

The urban system represents all built up areas, including urban and sub-urban areas, commercial and industrial. Due to the impervious nature of these landscapes, post development erosion risk is generally low. The C factor applied was 0.3, based on Lee & Lee (2006).

Following the estimation of the C factors, land cover types were then ranked from 1 (least protective against erosion) to 5 (most protective against erosion), to produce a cover index (CI). The value used in the rapid erosion assessment was calculated from the inverse of the CI (Boggs et al., 2001). This provides a relative estimation of gross differences in land cover in the Lake Illawarra catchment. Following further analysis of the cover index, four broad land cover classes were identified. These were classified as undisturbed forest, disturbed forest, grazing land and urban areas. The values attributed to the land cover classes are summarised in Table 4-3.
### Vegetation Class  Estimated C Factor  Cover Index  Broad Land Cover Class
<table>
<thead>
<tr>
<th>Vegetation Class</th>
<th>Estimated C Factor</th>
<th>Cover Index</th>
<th>Broad Land Cover Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moist Forest System</td>
<td>0.001</td>
<td>5</td>
<td>Undisturbed Forest</td>
</tr>
<tr>
<td>Rainforest System</td>
<td>0.001</td>
<td>5</td>
<td>Undisturbed Forest</td>
</tr>
<tr>
<td>Plateau Complex</td>
<td>0.16</td>
<td>3</td>
<td>Disturbed Forest</td>
</tr>
<tr>
<td>Dry Forest System</td>
<td>0.16</td>
<td>3</td>
<td>Disturbed Forest</td>
</tr>
<tr>
<td>Woodland System</td>
<td>0.16</td>
<td>3</td>
<td>Disturbed Forest</td>
</tr>
<tr>
<td>Coastal Complex</td>
<td>0.16</td>
<td>3</td>
<td>Disturbed Forest</td>
</tr>
<tr>
<td>Non Forest Systems</td>
<td>0.3</td>
<td>1</td>
<td>Grazing</td>
</tr>
<tr>
<td>Urban</td>
<td>0.002</td>
<td>4</td>
<td>Urban</td>
</tr>
</tbody>
</table>

Table 4-3: This table summarises the values applied to the land cover classes

### 4.3 Sensitivity Analysis

A sensitivity analysis aims to assess how the variability, or uncertainty, of input factors will impact upon the output of the model (Quinton, 2004). A sensitivity analysis was conducted on the erosion risk model in order to assess the influence of the land cover factor and the slope length factor. The derivation of the land cover factor is both subjective and the most prone to change and the output produced initially appeared to have been heavily influenced by the slope length factor. This lead to the sensitivity analysis being focussed on the variability of these two factors and the consequent effect incurred on the model output.

Land cover input factors were altered by assigning new values to the cover index. After the cover index was adjusted, it was inverted using the raster calculator, to produce the land cover factor. The model was then rerun in order to assess the outputs generated. An assessment was made on the effects of:

- Decreasing the cover provided by undisturbed forest to that equivalent to disturbed forest,
- Decreasing disturbed forest to that equivalent to grazing lands and
- Increasing the cover provided by disturbed forest to that of undisturbed forest.

The slope length factor was adjusted by varying the entire slope length dataset using raster calculator. Adjustments were in the order of increasing and decreasing the normalised values by 20% and 50%. Lastly, the slope length factor was exempted from the analysis.
4.4 **Nutrient Export Risk**

The fertility of the different soil landscapes found in the Lake Illawarra catchment were utilised in order to find the nutrient export risk associated with soil mobilisation. These were acquired from the Soil Landscapes of the Wollongong – Port Hacking 1:100000 Sheet, and the Soil Landscapes of the Kiama 1:100000 Sheet (Hazelton, 1990; Hazelton, 1992) and are a combination of soil characteristics including organic matter, Bray phosphate, P sorption, cation exchange capacity, acidity and alkalinity and provide a good estimation for overall nutrient availability within a particular soil type. Fertility ratings for each soil landscape found in the Lake Illawarra catchment can be seen in Table 4-2. These ratings were then normalised from 0 to 1 to allow compatibility with the erosion risk assessment. The erosion risk output was multiplied by the normalised fertility ratings to generate an output presenting the potential risk of nutrient exports associated with soil erosion.
5 Results and Discussion

This chapter will present and discuss the results obtained during the soil erosion risk assessment and the associated nutrient risk assessment. This includes an outline of the important aspects of the soil erosion factors used and an analysis of the erosion risk output produced. The sensitivity analysis conducted on the soil erosion risk map and a brief comparison with other similar soil erosion risk models are both discussed in order to determine the validity of the model used. The nutrient export risk output is also discussed along with two other nutrient export models developed by the NSW Department of Planning (Baginska et al., 2004) and the NSW Department of Environment, Climate Change and Water (DECCW, 2009a) that have been used on the Lake Illawarra catchment. An overview of current erosion and sediment control measures, used during construction, which aim to mitigate the risk of sediment and nutrient exports, is provided. Finally, the proposed major housing development areas of West Dapto and Calderwood will be discussed in light of their relationship with risk areas found during the current study.

5.1 Soil Erosion Risk Map

5.1.1 Soil Erosion Factors

The normalised values for the factors contributing to soil erosion used during the analysis can be seen in Figure 5-1. The soil erodibility (K) factor relates to the characteristics of the soil landscapes found in an area, adapted from the Soil Landscapes of the Kiama 1:100,000 sheet and the Soil Landscapes of the Wollongong-Port Hacking 1:100,000 Sheet (Hazelton, 1990; Hazelton, 1992). Slope percent shows the average slope gradient, derived from the NSW Department of Lands Digital Topographical Database (DoL, 2006). A 45 degree gradient will have a percent slope of 100%, as the gradient approaches 90 degrees, the percent slope will tend towards infinity. The slope percent is highly dependent upon the resolution of the digital elevation model (DEM) used. The DEM used for the generation of the slope percent was derived from 10 m contours, with 100 m horizontal accuracy, found on the DTDB. Therefore, the DEM has a resolution of 100 m and slope percent is the averaged slope over a 100 m area. DEMs with a higher resolution will produce a higher slope percent and DEMs with a lower resolution will average out the slope over a larger area, producing lower slope percentages (Boggs et al., 2001). Slope length shows the areas where the continuity of a slope will influence the rainfall runoff and erosion processes. Land cover shows the extent of human impact on the land, outlining areas of urban and agricultural uses, as well as forested areas, both
disturbed and undisturbed. The topography layer underlying each factor helps to distinguish the relationships between different factors and the landscape.

The soil erodibility factor is relatively low along the high points of the escarpment, despite the steep slopes generally ranging from 20% to nearly 70%. This is due to the erosion resistant Hawkesbury Sandstone and Illawarra Escarpment soil landscapes. The geology of these areas is that of course grained quartz sandstone, usually detached due to the prior erosion of the underlying facies, undercutting the sandstone and detaching “blocks” of sandstone. These detached blocks of sandstone along with other detritus and soil materials form talus deposits (Hazelton, 1990). Talus deposits situated on the steep slopes of the escarpment can be a significant mass movement hazard; however, the erodibility of the soil on its own is relatively low. A similar soil erodibility factor is also shared with the Fairy Meadow soil landscape, which covers much of the low lying areas of the catchment. This is again quartz sand, but derived from a fluvial origin. Fluvial derived silts and clays are also common in this landscape (Hazelton, 1990).

With the exception of the Fairy Meadow soil landscape, as the elevation drops, moving east from the escarpment toward the centre of the catchment, erodibility increases as soil becomes derived from less resistant underlying geology. Below the Illawarra Escarpment and Hawkesbury Sandstone landscapes, still in steep terrain with percent slope generally greater than 30%, lies the Cambewarra soil landscape, which is predominantly derived from felsic latite (Hazelton, 1992). As the landscape flattens into undulating and rolling hills with a slope steepness range of 5% to 15%, the Wattamolla Road soil landscape, which shares a similar erodibility factor with that of the Cambewarra landscape, emerges. The Wattamolla Road soil landscape is also derived from volcanic materials, namely Budgong Sandstone, a volcanic lithic sandstone, but also contains areas of latite derived materials (Hazelton, 1992). At lower elevations but with a similar slope steepness range of 5-15%, is the Albion Park soil landscape. This landscape is predominantly derived from the Berry Formation of fine sandstone, mudstone and siltstone, with localised outcrops of Budgong Sandstone (Hazelton, 1992). The Shellharbour soil landscape has the highest soil erodibility and is located on low lying rolling hills with slope gradient less than 20%. It is derived from the red-brown and grey volcanic lithic sandstone, Budgong Sandstone (Hazelton, 1992).

Land cover factor shows the intensity of human land use on the low lying, flatter areas of the catchment, including both urban and agricultural uses. As the escarpment rises and the slope increases, grazing and urban areas give way to disturbed forest before denser, undisturbed forest. This trend allows vegetation to help protect soils located on the steep slopes of the escarpment. Among the four broad categories found in the Lake Illawarra catchment, grazing land has the lowest erosive protection. Although urbanisation has been shown to have an indirect impact upon
Figure 5-1: Normalised values for soil erodibility, slope length and land cover and percent slope for Lake Illawarra Catchment. (Predominant soil landscapes present for each soil erodibility (K factor) value signified by sm = Seven Mile, fb = Faulconbridge, ie = Illawarra Escarpment, ha = Hawkesbury, fa = Fairy Meadow, wb = Warragamba, ca = Cambewarra, wt = Wattamolla Road, lh = Lucas Heights, ap = Albion Park and sh = Shellharbour)
sedimentation within catchments (Nanson, 1980; Nanson & Young, 1981; Reinfelds & Nanson, 2001; Reinfelds & Nanson, 2004; Sloss et al., 2004; Brodie & Rosewell, 2008), in terms of soil erosion processes, urban land cover provides relatively good protection (Olson, 1981; Lee & Lee, 2006). Protection provided by disturbed forests, and non-disturbed forests, will generally depend upon the percentage of canopy and ground cover provided, which was discussed in Chapter 4.

Steep slopes are generally found at higher elevations around the escarpment, due to the undercutting of erosive resistant sandstone that caps the escarpment. Lower elevation generally leads to a more undulating landscape with gentler slopes. Some isolated areas with steeper slopes and longer slope lengths occur, most notably at the hill in the Lakesland district, near the shore of Lake Illawarra (see Figure 5-8 for localities). Slope length shows the continuity of the slopes, while disregarding areas where this accumulation has given rise to permanent creeks. Erosion of stream channels has been shown as a potential source for sedimentation of Lake Illawarra, particularly during high intensity rainfall events (Nanson, 1980; Nanson & Young, 1981; Reinfelds & Nanson, 2004). However, the model used here outlines risk areas associated with hillslope erosion, either by sheet erosion or rill and gully incision, which is why stream channels are disregarded in the analysis.

5.1.2 Soil Erosion Risk Map Overview

The erosion risk map produced from the erosion factors shows the relative erosion risk within the Lake Illawarra catchment (see Figure 5-2). The strong influence of slope percent is evident around the escarpment, with linear occurrences of very high erosion risk coinciding with areas of high slope length. These very high risk areas outline a significant skew in the data, where a small number of high values led to some difficulties in utilising a simple classification method. As the majority of data values lay between 0 and 0.01, these values were categorised as low, moderate or high. Low risk areas, although containing only values from 0 to 0.001 outline a large zone where slope steepness is insufficient to cause major erosion risk. Values from 0.001 to 0.01 were equally divided into categories for moderate and high erosion risk. Moderate risk areas either contain steep slopes, generally greater than 20%, or areas with a combination of high soil erodibility and low protection from land cover, namely grazing areas. High risk areas are a combination of slope steepness exceeding around 30%, high soil erodibility and grazing or disturbed forest land cover. Very high risk areas generally coincide with areas of high values for slope length, with the exception of the Lakesland district where it is a combination of high soil erodibility and grazing land cover but only moderate slope steepness and low slope length factors.
Figure 5-2: Soil Erosion Risk Map produced from soil erosion factors of soil erodibility (K), slope percent (S), slope length (L) and land cover (C).
The north of the escarpment shows a significant reduction in erosion risk, due to a lower soil erodibility factor for the soils in this region and more expansive natural vegetation cover, aiding in erosion protection. Toward the south, although slope remains relatively constant along the escarpment and decreases eastward, there is a considerable increase in erosion risk. This is due to areas of undulating terrain being used for grazing in conjunction with a change of soil type to the Cambewarra and Wattamolla Road soil landscapes, which possess higher soil erodibility. Also notable, are high erosion risk areas around the Lakesland district and to the south of the catchment, where the Shellharbour soil landscape, containing the highest soil erodibility, is most prevalent.

5.1.3 Sensitivity Analysis

The evaluation of values used for the land cover factor was somewhat subjective, being the authors own interpretation of the data available. Both data sets used in this evaluation, the DECCW’s Eastern Bushlands Database (DECCW, 1998) and the NSW National Parks and Wildlife Service’s Native Vegetation of the Illawarra Escarpment and Coastal Plain (NPWS, 2002), both relied on the interpretation of remotely sensed data, with some limited ground truthing, and as such will contain some margin of error in themselves. Land cover is also a factor subject to change, on the undulating floodplains of the catchment change is generally an increase of urban landscapes replacing rural areas. Closer to the escarpment in steeper forested areas, increases in population can also have impacts upon the forest systems leading to higher levels of disturbance.

A sensitivity analysis was conducted on the erosion risk model in order to assess the influence of the various factors used, in particular the land cover (C) factor. Undisturbed and disturbed forest land cover is most likely to have variability in interpretation and is located in steeply sloped areas providing important erosion protection. Figure 5-3 shows three outputs from the sensitivity analysis along with the final erosion risk map for comparison. It shows that decreasing the protection provided by undisturbed forest systems to a value equivalent to disturbed forest shows some isolated increases to erosion risk. Decreasing values of disturbed forest shows a greater distribution of very high risk on sloped areas, although these sloped areas are unlikely to be suitable for other land uses such as grazing or urbanisation. Increasing the protection provided by disturbed forest shows a reduction in high and very high risk zones, particularly to the south of the catchment where disturbed forest is most prominent. In all cases, however, the magnitudes of output values for erosion risk remain the same.
Figure 5-3: Outputs for sensitivity analysis. Here the effect on risk distribution of undisturbed and disturbed forest systems can be compared.
Further assessment was conducted in order to gain an insight as to the effect of the slope length factor on the erosion risk output. The dramatic impact on slope length can be seen from the strong relationship between very high risk areas in the erosion model and the high values for slope length. Adjustments to the slope length factor resulted in high magnitude shifts of erosion risk values; however, the general spatial distribution of erosion risk remained constant. The changes in magnitude and similar relative values for erosion risk indicate that each soil erosion factor input is playing an important role in the output achieved. The results obtained from the sensitivity analysis signify sufficient robustness in the model with which an outline for relative erosion risk can be obtained within the Lake Illawarra catchment. Various methods for slope length calculation, using a GIS platform, are currently available (Mendicino, 1999; Boggs et al., 2001). In order to gain a better understanding of the influence of slope length on soil erosion risk within Lake Illawarra catchment, and the diverse range of methods used to calculate slope length, experimentation using different slope length calculations is recommended for future research.

5.1.4 Comparison with other Soil Erosion Risk Assessments

Typically, erosion risk is assessed with the aim of quantifying the total loss of soil in weight per unit area per year. However, this requires reliable and complete data, which can be difficult to obtain, particularly at the catchment scale. Relative erosion risk assessments found in the broader literature, generally give no indication as to the numerical values obtained, relying on the display of the categorised values from low to high, or very low to very high. As no erosion risk assessment has previously been carried out on the Lake Illawarra catchment, there is a difficulty in comparing this model with those published in the wider literature in order to further assess the validity of the model. The spatial distribution (or patterns found in erosion risk) is the only real method available for comparison. Boggs et al. (2001) found that the accumulated flow method for the determination of the slope length factor gave the most realistic account of erosion risk distribution, and also contained linear high erosion risk areas. As the numerical values of erosion risk were not eluded to, the extent of influence of slope length and the range in magnitude for each class are not available for comparison with the current model. Studies on soil erosion risk assessment from around the world show that areas with high values for slope percent and slope length generally exhibit these two factors playing a significant role in determining erosion risk distribution. Smaller scaled models, or topographically flat areas being modelled show the land cover or C factor having a more significant effect on erosion risk distribution (Bartsch et al., 2002; Lu et al., 2004; Panagopoulos & Antunes, 2008; Yue-Qing et al., 2008; Yuksel et al., 2008; Zhang et al., 2009).
5.2 Nutrient Export Risk Map

5.2.1 Fertility Ratings

Fertility ratings associated with the soil types found within the Lake Illawarra catchment, were combined with the soil erosion risk in order to find the risk of nutrient exports. Fertility ratings were taken from Soil Landscapes of the Kiama 1:100,000 sheet and the Soil Landscapes of the Wollongong-Port Hacking 1:100,000 Sheet (Hazelton, 1990; Hazelton, 1992), and represent a combination of soil characteristics including organic matter, Bray (extractable) phosphate, P sorption, cation exchange capacity, acidity and alkalinity. As can be seen from Figure 5-4, high fertility ratings are associated with Albion Park, Robertson, Shellharbour and Wattamolla Road soil landscapes, which are soils predominantly derived from underlying geology of a volcanic origin. The high rating for the Illawarra Escarpment soil landscape is surprising, due to the sandy and rocky nature of the soil. This can be attributed to the high percentage value for cation exchange capacity, which is a measure of the soils ability to hold positively charged ions, and is an indicator as to the potential for the soil to hold nutrients (Hazelton, 1992).

Figure 5-4: Normalised values for fertility ratings found in Lake Illawarra catchment. (*Predominant soil landscapes present for each fertility rating signified by ap = Albion Park, ro = Robertson, sh = Shellharbour, wt = Wattamolla Road, ca = Cambewarra, ie = Illawarra Escarpment, fa = Fairy Meadow, sm = Seven Mile, wb = Warragamba, ha = Hawkesbury, lh = Lucas Heights and fb = Faulconbridge)
5.2.2 Nutrient Export Risk Map Overview

The nutrient export risk map produced shows, not surprisingly, strong similarities to the soil erosion risk map (see Figure 5-5). It is an indication of both the risk of sediment movement and the nutrients associated with that sediment, which may drain into watercourses before discharging into Lake Illawarra. This is a useful indicator as sediment derived from hillslope erosion has been shown to be a major contributor to nutrient levels (Sherman et al., 2000). For example, in the USA it was shown that up to 80% of nutrients found in streams can be attributed to eroded sediment (Fennessey & Jarrett, 1994). The nutrient export risk map generated in this study does not, however, take into account the possible nutrient discharges related to current land management practices such as fertilisation of agricultural landscapes or increases in nutrient releases from urban areas. Due to the similar trend in values to that of the Soil Erosion Risk Map, a similar method for classification and display was used, with low nutrient export risk showing high correlation with flatter areas and moderate risk being associated with undulating terrain. However, there is an increase in high and very high nutrient export risk in areas of high fertility, in particular with those of the Shellharbour and Albion Park soil landscapes. This gives a rudimentary indication of nutrient loads that can be expected from suspended solids discharged into Lake Illawarra. These loads will be a particular problem during construction of new developments, where soil is exposed and more vulnerable to mobilisation. High rainfall events can lead to particularly high discharges of nutrients and sediment if effective sediment control practices are not in place or properly maintained.

5.2.3 Nutrient Exports in the Lake Illawarra Catchment

Modelling of nutrient exports generally focuses predominantly on land use and the event mean nutrient concentrations (Baginska et al., 2004; Drewry et al., 2009; Dela-Cruz, 2010). This requires the collection of runoff data, including both flow magnitude and nutrient concentrations, during rainfall events. Two models have been applied to the Lake Illawarra catchment which aim to outline nutrient exports, the Long-Term Hydrologic Impact Assessment model (L-THIA) developed as part of the Comprehensive Coastal Assessment for NSW, by the NSW Department of Planning (Baginska et al., 2004) and the Coastal Eutrophication Risk Assessment Tool (CERAT) developed by the NSW Department of Environment, Climate Change and Water (DECCW, 2009a).

The L-THIA also incorporated soil permeability, rainfall and runoff, giving potential total nitrogen and total phosphorus exports in kilograms per hectare per year over long term rainfall conditions (see Figure 5-6). The CERAT applies a coefficient to each land use type found in a catchment or sub-catchment area, and multiplies the coefficient by the area of that land use type.
found, while allowing for variability in runoff due to land use, soil types, climate and terrain. The CERAT is designed to provide management authorities with a method of predicting the ecological impacts of land use change on coastal estuaries and lakes. It achieves this by allowing for modification of input parameters, in particular land use type and area for each sub-catchment. Furthermore, the CERAT, being a eutrophication risk assessment, takes into account processes such as the natural nutrient cycle of the lake and flushing from tidal interaction (Dela-Cruz, 2010). Figure 5-7 shows one possible output from CERAT, the total suspended solids in kilograms per year.

As these models focus on land use, rather than nutrients associated with soil, they are not directly comparable with the Nutrient Export Risk Map produced in this study. High nutrient exports found by the two models strongly relate to the land use (C) factor used during this study, in particular, the land used for agriculture or grazing. This is due to agricultural activities being found to be the greatest source of anthropogenic nutrients (Baginska et al., 2004). The high nutrient export areas found by the L-THIA and CERAT are represented by low risk areas in the Nutrient Export Risk because they are predominantly located in areas of shallow slope, where rapid runoff and soil movement will be minimal. The Nutrient Export Risk developed gives an indication of naturally derived nutrient exports, which still play a major role in the nutrient cycle of Lake Illawarra and can still be increased by human activities, particularly those which expose soils, allowing for pronounced soil mobilisation.
Figure 5-5: Nutrient Export Risk Map for Lake Illawarra catchment produced from fertility ratings of soil landscapes and the Erosion Risk Map for Lake Illawarra catchment.
Figure 5-6: Potential exports for total nitrogen and total phosphorous in the Illawarra over long term rainfall conditions (Baginska et al., 2004).

Figure 5-7: Total suspended solid exports in kilograms per year for the Lake Illawarra catchment, an output from CERAT (Coastal Eutrophication Risk Assessment Tool) (DECCW, 2009b).
5.3 **Implications for Catchment Management**

The recent approval of extensive development sites in the Lake Illawarra catchment pose a major threat to the ecological health of Lake Illawarra. *Figure 5-8* shows the extent of these new development sites, covering a significant proportion of previously undeveloped land, in relation to the relative soil erosion risk within the catchment. Both development sites cover areas of high erosion risk, with the West Dapto development also containing areas of very high risk where approval has been granted on long, steep slopes near the escarpment. The findings in this study can aid in catchment management by outlining areas of soil erosion and nutrient export risk. Special consideration should be made where development proposals fall within high and very high risk zones.

The post development effects of urbanisation on Lake Illawarra are also of significant importance. Models such as the CERAT (DECCW, 2009b) and the L-THIA (Baginska et al., 2004) indicate the increase in nutrient exports that is caused by urbanisation. The CERAT was used on the Lake Illawarra catchment in order to obtain an estimate on total suspended solid exports caused by the West Dapto and Calderwood development sites. The CERAT is designed for such assessments and allows for the alteration of land use within each sub-catchment. The percentage of urban area covering the sub-catchments affected by the developments was increased, this lead to an escalation of total suspended solid exports from 3903 tonnes per year up to 4157 tonnes per year.

These developments pose a considerable problem for the Lake Illawarra Authority, whose primary role is to restore and maintain the ecological environment of the lake and its foreshores. This is to ensure that the Lake can continue to play its important role in the community, as a place that supports recreation and tourism and provides an aesthetically pleasing environment. The ability for the Lake Illawarra Authority to achieve this end is jeopardised by the continued approval of urban development within the Lake Illawarra catchment. As the catchment covers two local government jurisdictions, the Wollongong City Council and the Shellharbour City Council, it is important that both these two councils work in conjunction with the Lake Illawarra Authority when considering proposed developments for approval.
Figure 5-8: Soil Erosion Risk Map with outline of major housing developments in West Dapto and Calderwood.
5.3.1 Soil Erosion and Sediment Control Practices

Erosion occurring during the clearing and construction of development sites has been recognised as a threat to water quality (Moore, 2004). Construction sites without proper erosion and sediment control measures in place have been shown to increase surface erosion by up to a magnitude of 200, where previous land use was for grazing, or up to a magnitude of 2000 where previous land cover was undisturbed forest (Moore, 2004). This is due to the clearing of vegetation, dislodgement of compressed soils and the exposure of topsoil and subsoil (USEPA, 1976). Figure 5-11 shows the possible increase to soil erosion risk in the development sites of West Dapto and Calderwood if proper sediment control practices are not enforced. This output was produced by reducing the protection provided by the land cover factor to that equivalent to bare soil, which is a widespread occurrence during construction. This output shows the considerable role of land cover on the protection against soil erosion. Increases in high and very high risk zones are extensive throughout both development sites, particularly in sloped areas. Soil erosion and sediment control practices are required for any construction site in the Lake Illawarra catchment area and information on control measures to be used are provided in the Development Control Plan (DCP). Information required by the DCP includes contours of the land, waterways and drains, measures to be used to prevent erosion, location of sediment fences and traps, location of wash out areas, location of stockpile areas, location of vegetation buffer zones and location of site access points. Typical erosion control measures used on construction sites in the Illawarra region involve the diversion of runoff through the provision of temporary drains, channels or diversion structures or reducing the flow velocity and therefore erosive energy of flow through lining of stormwater drains and channels, increasing the resistance to flow (DCP, 2009). Sediment control generally involves the construction of sediment fences, made of
self supporting geo-textile fabric, which should be run parallel to the contours of the land. Additionally, sediment fences need to be placed in a 150 mm trench to prevent sediment discharges beneath the fences (see Figure 5-9). In front of any stormwater drain inlets found in the vicinity of the construction site, mesh and gravel inlet filter sediment traps need to be placed to prevent coarse sediment entering the stormwater drain (see Figure 5-10). Erosion and sediment control measures are required to be inspected daily during construction, weekly when no work is occurring or immediately after a rainfall event (DCP, 2009).

Despite these requirements, inspection of construction sites in the Lake Illawarra catchment show erosion and sediment control measures in poor condition. Although initially put in place, poor maintenance and neglect along with incorrect installation leads to the control measures having a negligible effect on sediment control. Figure 5-12 is an example of a poorly placed and degraded mesh and gravel inlet filter sediment trap. It is placed uphill of the construction site and a trail of sediment can clearly be seen where runoff has carried it downhill. A stormwater inlet drain (see Figure 5-13) is located just out of shot to the right Figure 5-12(b), with no further sediment control measures in place. There is also evidence of sediment fences being neglected and poorly maintained during clearing of land and construction (see Figure 5-14). Although there may be a need to move fences to allow access to certain parts of the site during construction, failure to replace them diminishes their effect in sediment control. In light of the extensive increase to soil erosion risk, found due to the clearing of land during construction, and due to the approval of large development areas in West Dapto and Calderwood, it is imperative that effective erosion and sediment control measures are implemented in order to protect Lake Illawarra from further degradation.
Figure 5-11: This Erosion Risk Map for Lake Illawarra catchment shows the possible increase to relative erosion risk with poor sediment control practices during construction in the West Dapto and Calderwood development sites. This was produced by reducing the protection normally provided by land cover.
Figure 5-12: (a) A mesh and gravel inlet filter sediment trap at a construction within Lake Illawarra catchment. This has been incorrectly placed uphill of the construction site and is severely degraded. The stormwater drain inlet is located just out of shot to the right of figure 5-12 (b). The effect of sediment being transported from the construction site is clearly visible.

Figure 5-13: Stormwater drain inlet near sediment trap pictured above. Note the sediment at the inlet carried from the construction site with rainfall runoff and no further sediment control measures.

Figure 5-14: A sediment fence in the Wollongong area which has been moved, most probably for accessibility reasons, but has not been replaced effectively and is no longer providing protection from sediment runoff.
5.4 **Limitations and Further Research**

The primary limitation for this study is the 100 m resolution of the DEM used in the generation of the slope angle and slope length factors. A finer resolution DEM would make the model much more responsive to variability in these factors. This is because the topographical changes occurring will not be averaged out, which leads to a smoothing effect, over the 100 m area. When assessing the catchment in its entirety, this smoothing effect does not have a major impact on relative erosion risk. However, when looking at smaller scale areas, such as proposed development sites, the smoothing effect can dramatically underestimate slope angle and therefore underestimate erosion risk. There are now a variety of ways with which to calculate slope length (Hickey et al., 1994). This study looked at only one method, the accumulated flow function in ArcGIS. Considering the major impact of slope length on the assessment of erosion risk, investigation into other slope length calculations, and the resulting effect on the erosion risk assessment, is a worthy area for further research.

This model is principally concerned with soil erosion and the nutrients associated with eroded soil. A limitation of the nutrient export risk assessment is that nutrients produced by land use are not taken into account. This is an important aspect when considering total nutrient inputs into Lake Illawarra as the increase of urban land use has been shown to have a considerable effect on nutrient exports within a catchment (Baginska et al., 2004; DECCW, 2009b). Another consideration for sediment and nutrient input, not covered by the assessment used in this study, are the effects of increased urbanisation on erosion within stream channels. Urbanisation causes an increase in runoff volumes and velocity due to the increase of impervious area within the catchment. Consequently, stream channel widening can occur along with an increase in sediment and nutrient inputs into Lake Illawarra (Reinfelds & Nanson, 2004).
6 Conclusions

Sedimentation of Lake Illawarra, although a natural and ongoing process, has greatly increased over the past 200 years due to the expansion of human land use in the catchment area (Depers et al., 1994; Pockock et al., 2003; Sloss et al., 2004; Hopley et al., 2007). Sedimentation within catchments is generally sourced from hillslope erosion, either by sheet erosion or by rill and gully incision (Sherman et al., 2000). For Lake Illawarra, clearing of land is the main contributor to this phenomenon, either for logging and agricultural use or the more recent increase in urbanisation and industrialisation. Increased sediment discharge has detrimental effects on the ecological health, economic viability and the aesthetic appeal of the Lake (Pockock et al., 2003; Sloss et al., 2004; Haines & McAlister, 2006). This study has characterised areas within the Lake Illawarra catchment which have a high potential for soil erosion and nutrient export risk. This study has also found that construction sites without proper erosion and sediment control measures in place can drastically increase the soil erosion risk. These findings are supported by studies in the USA where it has been shown that soil erosion rates on construction sites can increase by up to a magnitude of 200, where previous land use was for grazing, or up to a magnitude of 2000, where previous land cover was undisturbed forest (Moore, 2004). This is due to the clearing of vegetation, dislodgement of compressed soils and the exposure of topsoil and subsoil (USEPA, 1976).

Precise levels of nutrient input due to sediment discharge is hard to detect, as nutrients released by sediment are rapidly utilised by plants, and the algal biomass can expand to absorb all available nutrients (Sherman et al., 2000). However, increased sediment discharge due to anthropogenic impacts have shown a clear increase in the nutrient budget (Depers et al., 1994). The use of a soil erosion risk map as the basis for nutrient exports is useful due to the high levels of nutrients that have been found to be associated with sediment derived from hillslope erosion or from within streams (Fennessey & Jarrett, 1994; Sherman et al., 2000).

Estimations and modelling of nutrient exports in catchments is generally focussed on land use practices, with reference to soil characteristics usually limited to permeability, in order to estimate runoff (Baginska et al., 2004; Dela-Cruz, 2010). The model developed in this study helps to predict areas with a high level risk of sediment discharge, taking into account hillslope erosion processes. Overlaying the soil erosion risk map with nutrient levels associated with the soil produces an output that characterises risk areas for nutrient discharge that accounts for sediment mobilisation rather than runoff from land use practices. The findings of this study can facilitate in catchment management by outlining areas of major concern, so that attention can be focussed on the areas with higher risk levels of soil erosion, or associated sediment discharge.
7 Recommendations

Further research areas and adjustments are available that will improve the modelling process used in this study. A digital elevation model with higher resolution could potentially provide a more detailed and accurate map output, particularly when considering smaller areas within the broader catchment area, for example, proposed development sites. There is a variety of different methods available for calculation of the slope length factor (Hickey et al., 1994). In some cases, these methods require specialist programs or extensions to programs, which were unavailable during this study, but could potentially improve the results achieved. With improvements to some of the factors used in soil erosion prediction, and the incorporation of some new factors, an estimate for actual soil erosion loads is a possible area for future research. Alterations to the slope steepness factor will be required, as the RUSLE can only account for a steepness of up to 22%. There are formulae available which account for this, for example Liu et al. (1994) and Nearing (1997). A more accurate representation of the land use factor will be required, including a direct assessment of canopy and ground coverage and improved knowledge of past land uses. Finally, the incorporation of the rainfall erosivity factor will allow this model to be expanded to make a prediction for soil loss in kilograms per hectare per year.

The expansion of urban development in the Lake Illawarra catchment, and the effects of urban development on the erosion within stream channels (Reinfelds & Nanson, 2004), leads to discharges from streams being responsible for significant volumes of sediment being deposited into the lake (Sherman et al., 2000). It is important that this factor is not overlooked in the planning and management of developments in the catchment. Developments should be required to incorporate Water Sensitive Urban Design (WSUD) in the planning, and reduce stormwater runoff from urban areas to as close to natural levels as possible. For extensive developments, or developments occurring in high or very high erosion risk areas as identified in this study, the installation of local stormwater management measures such as swales, bioretention systems and constructed wetlands, should come first in order to minimise sediment runoff during construction. It is also imperative that current erosion and sediment control measures implemented are correctly installed and maintained. Erosion and sediment control measures used during the construction phase, although a requirement in the Council’s Development Control Plan, need to be inspected regularly to ensure they are properly maintained. Education of those involved in the development as to the implications of erosion and sedimentation in Lake Illawarra may provide an incentive for proper management of control measures.
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