THE IMPACT OF LANDSLIDES AND EROSION IN THE CORANGAMITE REGION, VICTORIA, AUSTRALIA

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Abstract: The Corangamite region in southwest Victoria, Australia is subject to a variety of geohazards, among which landslides and erosion have the most significant impact. Over the past fifty years, landslides have resulted in loss of life and many millions of dollars damage to municipal infrastructure and development. Soil erosion by water and wind has also impacted on the region's waterways and environment, threatening a diverse range of assets from urban water quality to Ramsar-listed wetlands. More assets are placed at risk each year, as the increasing regional population results in an acceleration of anthropogenic modifications to landscapes.

A comprehensive GIS database was initiated by assembling all publicly available previous databases and reports documenting landslides and erosion in the 1,340 km^2 region. New data were added by mapping occurrences which were visible on high-resolution ortho-corrected aerial photographs. The field-checking of the occurrences was assisted by the participation of the local community, municipal officers and catchment management coordinators.

At present 2163 landslides and 2380 erosion sites have been identified, mapped and referenced in the database. It is believed that thousands more instances exist, but these cannot be identified at the aerial photo scale, or are obscured by dense vegetation. A spatial analysis has been undertaken to identify landscape parameters which correlate with the occurrences. Historical aerial photography was used in selected locations to identify the rates of erosion and landslide events.

The inventory has been used to estimate the economic, social and environmental costs of landslides and soil erosion within the region, using documented instances of damage and the costs of remediation. Combined with the value of the assets and elements at risk, the potential likelihood of occurrence and associated consequences, these estimates are used to develop a strategy for the investment of public funds in remediation.

Résumé: La région de Corangamite, au sud-ouest du Victoria en Australie, est soumise à divers risques naturels, parmi lesquels les glissements de terrain et l'érosion présentent l'impact le plus important. Au cours des cinquante dernières années, les glissements de terrain ont coûté des vies et des millions de dollars en dommages à l'infrastructure et au développement des municipalités. L'érosion du sol, causée par l'eau et le vent, a eu également des conséquences sur les voies navigables et l'environnement de la région, en menaçant divers actifs naturels tels que la qualité de l'eau en milieu urbain ou les marécages répertoriés à la Convention de Ramsar. Un nombre croissant d'actifs est menacé chaque année par l'augmentation de la population régionale, qui entraîne une accélération des modifications anthropiques des écopaysages.

Une base de données SIG exhaustive a été mise en place, regroupant toutes les bases et rapports publics disponibles qui traitaient des glissements de terrain et de l'érosion sur les 1 340 km² de la région. De nouvelles données ont été ajoutées en cartographiant les évènements visibles sur des photos aériennes à haute résolution orthocorrigées. Le contrôle sur le terrain des évènements a bénéficié de la participation de la communauté locale, des agents municipaux et des coordinateurs de la gestion des captages.

2 163 glissements de terrain et 2 380 sites d'érosion ont été identifiés, cartographiés et référencés à ce jour dans la base de données. Des milliers d'autres évènements se sont probablement produits qui ne peuvent être identifiées sur les photos aériennes, ou sont masqués par une végétation dense. Une analyse spatiale a été effectuée afin d'identifier les paramètres écopaysagers qui correspondent à ces évènements. Un historique par photos aériennes successives de lieux sélectionnés a été utilisé pour identifier les taux d'érosion et les glissements de terrain survenus.

L'inventaire a été utilisé dans le but d'évaluer les coûts économiques, sociaux et écologiques des glissements de terrain et de l'érosion du sol dans la région, en utilisant des cas connus de dommages avec les coûts de restauration afférents. Associées à la valeur des actifs et éléments à risque, à la probabilité de futurs évènements et de leurs conséquences, ces évaluations sont utilisées afin de mettre en place une stratégie d'investissement de fonds publics pour la restauration.

Keywords: landslides, erosion, soil erosion, geological hazards, regional planning.

INTRODUCTION

The Corangamite region covers approximately 1.3 million hectares of south-west Victoria, Australia. The regional population is close to 400,000 and is growing at 5.2% per year, with manufacturing, tourism, agriculture and forestry as major industries. The population increase is unevenly spread, with the population becoming more urbanised in the two major provincial cities - Geelong and Ballarat, and expanding rapidly into the peri-urban fringe within 40 km from the major centres, and along the coast (CCMA 2003). Nine local government municipalities lie within the region. Major environmental attractions are several wetlands of international significance listed under the Ramsar Convention and international migratory bird treaties. Although landslides and erosion are natural processes in the evolution of the Corangamite landscapes, their rate of occurrence has increased significantly following widespread land-use change associated with European settlement over the past 200 years (Dahlhaus & MacEwan 1997; Dahlhaus & Miner 2002).

The Corangamite Catchment Management Authority (CMA) has responsibility for soil erosion under the *Catchment and Land Protection Act*, 1997, although the Victorian Department of Primary Industries (DPI) is the main adviser on erosion management issues. In 2003 the CMA developed a Regional Catchment Strategy (RCS) that identified the growing urban migration, intensification of agriculture, increasing tourism and stronger environmental ethic as the major forces affecting the management of the region's natural resources (CCMA 2003). The RCS recognised soil deterioration and natural disasters as threats to the region's assets, specifically the water quality of rivers, streams and wetlands, the viability of infrastructure, and productivity of agricultural land. As a result, the CMA is currently developing the Corangamite Soil Health Strategy (SHS) as a framework for the management of a number of soil issues, including landslides and erosion. The SHS is focused on asset protection, and the investment in erosion and landslide management is based on an analysis of the benefits and costs as measured in economic, social and environmental terms. This paper discusses the methods used to estimate the impacts of soil erosion and landslides for the SHS.

REGIONAL PHYSIOGRAPHY

The Corangamite region is characterised by three major geomorphic divisions (Joyce *et al.* 2004), *viz:* the Victorian Western Uplands, the Victorian Southern Uplands and the Victorian Western Plains (Figure 1).

Victorian Western Uplands

Dissected uplands form the northern highlands of the region, which are characterised by a variety of interwoven landforms preserved by substantial uplift during the Palaeogene and late Neogene. Undulating hills and broad valleys characterise the landscapes formed on Palaeozoic folded sedimentary rocks and granite plutons. Remnants of an early Cainozoic palaeoplain occur as caps of Palaeogene gravels sporadically distributed at various elevations. A remnant of the sands deposited during the Pliocene marine regression fringes the southern Palaeozoic rocks as a dissected tableland. During the Plio-Pleistocene, volcanic eruptions filled the broad valleys to form elongate basalt plains and a variety of other volcanic landforms. The prominent volcanic cones of Mount Buninyong (745 m), Mount Warrenheip (741 m) and Tipperary Hill (743 m) are now the highest elevations in the Corangamite region.

The climate is temperate with winter and spring dominant rainfall which varies from 500 mm to 1080 mm per annum. The major land-uses are agriculture, predominately grazing and animal production (64%), with some cropping (3%). Other significant land-uses are forestry (15%), public land and water reserves (8%), peri-urban residential dwellings and hobby-farms (5%), and urban settlement (2%).

Three river systems drain the dissected uplands of the Corangamite region – the Moorabool River (east), Leigh River (central) and Woady Yaloak River (west). The waters in the Moorabool River are utilised for urban supply to the cities of Ballarat and Geelong, as well as a number of smaller towns. Both the Moorabool and Leigh Rivers join the Barwon River system to the south, whereas the Woady Yaloak River feeds Lake Corangamite, a saline wetland of international importance and Victoria's largest permanent inland lake. Within this geomorphic province, increasing salinity, nutrients and turbidity are the dominant threats to the health of the waterways and waterbodies of the region.

Victorian Southern Uplands

The southern portion of the Corangamite region is dominated by the Victorian Southern Uplands, which form the deeply dissected Otway Ranges, moderately dissected Barrabool Hills and low hills of the Bellarine Peninsula. All three landscapes have been formed by the uplift of structurally controlled blocks of lithic sedimentary rocks of the Lower Cretaceous age (i.e. the Otway Group rocks). The Barrabool Hills and Bellarine Peninsula are smaller fault-bounded uplift blocks at lower elevations than the Otway Ranges, and are generally more planar and less deeply dissected. The Otway Ranges are a significant landform which receive the highest average annual rainfall for the Corangamite region (1900mm) whereas the Bellarine Peninsula has a much lower annual average rainfall (600mm).

The land-uses are reasonably evenly divided between forestry (37%), grazing and animal production (36%), and public land and water reserves (23%), which include large national parks. The urban and peri-urban areas (2%) are concentrated along the south west coast and around the City of Geelong. In recent years landslides have become an increasing threat to urban and rural infrastructure within the south west coastal communities. The headwaters of the major river in the Corangamite region - the Barwon River – drain the northern slopes of the Otway Ranges. The Barwon River is an important urban water supply for the City of Geelong.

Victorian Western Plains

The central Corangamite region lies within the Victorian Western Plains, the largest of the three geomorphic units, which comprise undulating plains formed on both volcanic and sedimentary rocks. Volcanic plains make up the majority of the geomorphic unit, apart from the south western portion, where dissected sand plains of Pliocene age overly marls of Miocene age. The volcanic plains comprise Pliocene and Pleistocene age basalt, with stony rises and scoria cones as more recent features. Exposures of the underlying Pliocene age sands occur in places not covered by the volcanic eruptions or where the landscapes have since been dissected.

The south western landscapes receive a higher average annual rainfall (900mm to 1000mm) then the majority of the plains (500mm to 700mm). Grazing and animal production is the dominant land-use (75%) with dairying dominant in the south west. Cropping (11%) is rapidly increasing across the volcanic plains, where the fertile soils annual rainfall make it one of Australia's most productive landscapes. Public land and reserves (8%), and urban and peri-urban development (3%) make up the remaining land-uses. Lakes and wetlands are the most important assets of the Western Plains, with the largest being Lake Corangamite. Many of these Ramsar-listed wetlands are threatened by changing salinity, nutrients and turbidity.

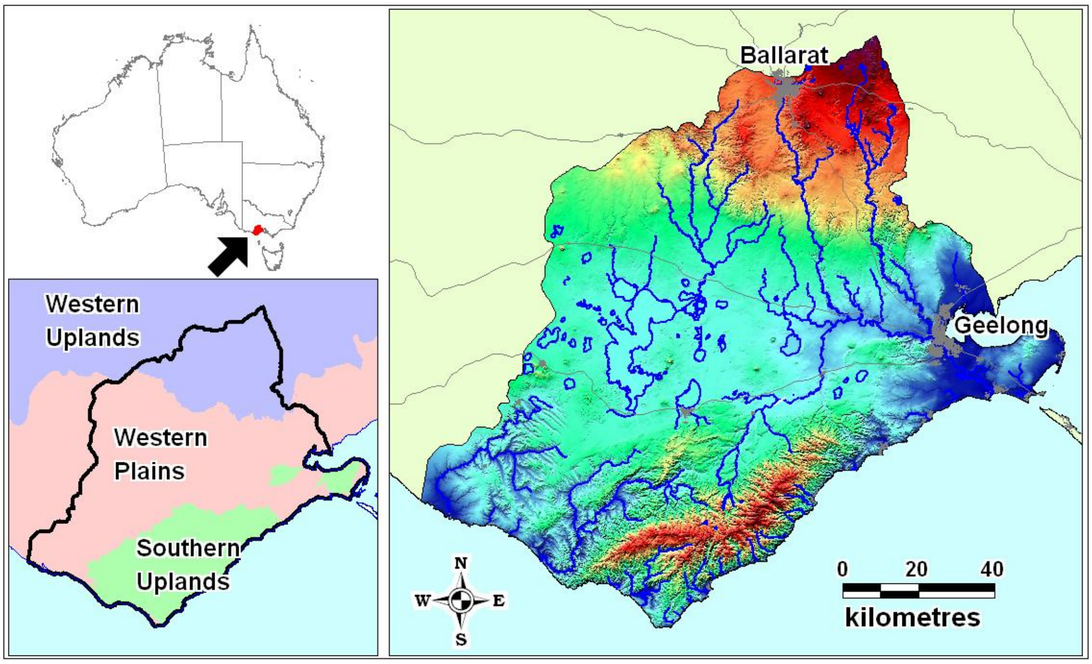

Figure 1. Location and physiography of the Corangamite region.

EROSION AND LANDSLIDE INVENTORY

The initial step in developing the SHS required the mapping of incidences of erosion and landslides so that their spatial distribution and impact on regional assets could be quantified. The resulting spatial database was assembled in six months, and contains records of incidences of landslides and the main forms of erosion by water. In the inventory, five types of features were identified and recorded, *viz:* sheet and rill erosion, gully and tunnel erosion, stream bank erosion, landslides, and other forms of land degradation.

Although widespread, sheet erosion is not as visually obvious as other forms of erosion since it develops where relatively smooth landscapes encourage overland flow. The most noticeable sheet erosion occurs on slopes where intensive horticulture or cropping is the predominant land-use, especially in sandier soils. Where the slopes are sufficient and the soil properties allow, sheet erosion has developed into rills. Rills form when water moving across the landscapes separates into individual turbulent flows which produce small meandering channels less than 300 mm deep (Charman & Murphy 2000). Ultimately the rills deepen and coalesce to form gullies, which channel the flow and increase its erosive power. The inventory did not attempt to discriminate between sheet erosion caused by water and that caused by wind. Wind erosion is generally highest across the Western Plains, which is associated with fallow areas in cropping country where deflation of the soil can winnow out organic matter and fine particles along with their nutrient and water-holding value.

Tunnel erosion is particularly prevalent in the weathered Otway Group rocks of the Southern Uplands and the soils formed on the Palaeozoic rocks of the Western Uplands. The susceptibility to tunnel erosion is related to the properties of the soil and weathered rock, the steeper slopes and the high rainfall. Tunnels commence when runoff flows through a crack, root hole or animal burrow into the B-horizon of the soil. In most soils the B-horizon has a low permeability, resulting in the water moving across the top of the B-horizon as throughflow. Where the B-horizon soils are prone to slaking and/or dispersion fine particles are carried in suspension, resulting in piping, tunnelling and seepage erosion (Young & Young 2001). Ultimately, the tunnels collapse to form gully channels. In the Corangamite region, tunnels have undermined residential buildings and roads, and caused injury to animals and operators of farm machinery.

Gullies are the most visually obvious representation of erosion in the landscape and have been the most common target for rehabilitation in the past. Spectacular examples of gully erosion are found in the Corangamite region, mostly in the Western Uplands (Figure 2). Gullies erode headward as the concentrated flow of water scours both the channel walls and bed. Eroded sediment is often deposited locally at the mouth of the gully as an alluvial fan. The deepening channel and retreating walls may intercept other subsurface tunnels and/or the groundwater table, creating additional erosion by sloughing saturated soil into the channel. Gully erosion is the ultimate result of both tunnel erosion and rill erosion. In many areas gully erosion is a legacy of past land-use, particularly gold mining along waterways. Considerable efforts have been made over the past 60 years to rehabilitate many of these areas, although the technical knowledge may have been lacking at times.

Landslides were mapped as all forms of mass movement from debris creep to rock falls. The landscapes of the Corangamite region are among the most landslide-prone in Australia, with the vast majority of landslides mapped in the Southern Uplands and the dissected south west of the Western Plains. Landslides vary in area from a few square metres to over 120 hectares and in volume from a few cubic metres to over ten million cubic metres. They are triggered by prolonged and/or intense rainfall, man-made changes to the landscape and rare earthquake events (Dahlhaus & Miner 2002). Even though some landslides are relatively small, the costs can be significant. As an example the landslide shown in Figure 2 threatens a major water supply pipeline, resulting in remedial works costing approximately $200,000.

Figure 2. Landslide and gully erosion examples from the Corangamite region.

Database construction

The initial database was constructed from the amalgamation of three existing data sets, *viz*: an informal database of landslides in south west Victoria (McVeigh 2001; Dahlhaus & Miner 2002), a 1993 map of erosion in the Woady Yaloak River catchment (Nicholson 1993), and features mapped in the municipality of the City of Greater Geelong (GHD 2004). The spatial database construction was undertaken using MapInfo, a Geographic Information System (GIS) of the MapInfo Corporation, New York.

The vast majority of features were then added to the database by mapping them onto ortho-rectified aerial photographs which were acquired for each municipality. The aerial photomosaics varied from approximately one metre resolution (i.e. pixel size) acquired in 2002 to 0.35 metre resolution acquired in 2004. The resolution of the images determined the scale at which features could be identified and captured into the database. Erosion that was not obscured by vegetation was relatively easy to identify (Figure 3), as were recent landslides. However, in the absence of stereo photogrammetery, erosion and landslides in vegetated areas were difficult to identify, particularly where the features had occurred some time ago. This problem was overcome to some degree by overlaying the contours, drainage and other landscape features in the GIS. Where possible features were entered as polygon objects, however line objects were used for stream erosion and point objects were used for small scale and uncertain features.

Field checking of the features was carried out through the physical inspection of landslide and erosion features where they were readily accessible. Features identified on the aerial photomosaics were located using a GIS application (MapX Mobile, MapInfo Corporation, 2005) on a pocket PC and a Global Positioning System (GPS). Where features were visible but inaccessible, a laser range finder was used to determine the distance from the point of observation to the feature. Features were photographed using a digital camera (4.0 megapixels resolution) and field observations were recorded in a spreadsheet on the pocket PC using text recognition software. The record of the feature in the GIS was then updated with the data collected in the field by matching the unique identifier for each record.

Regional communities were also enlisted to assist in the mapping of erosion and landslide features through 130 local Landcare groups, which have approximately 3000 members. Soil extension officers from the DPI facilitated workshops in which the Landcare group members mapped erosion and landslide features onto hardcopy plots of the photomosaic at 1:20,000 scale for their local area. This exercise provided a great deal of valuable information regarding the size and condition of the features, which was then manually captured on the spatial database.

Trend analysis

An attempt to estimate the rate of erosion was undertaken in selected areas of the region using historic aerial photographs. The results were very variable, with some areas experiencing up to 300% increase in the area affected by gully erosion over the past 30 years, while others remained relatively unchanged. However, in most areas the paucity of data made quantitative analysis unreliable, resulting in qualitative assessments for most areas. In particular, the landscapes of the Western Uplands show a significant increase in erosion sites over the past 30 years.

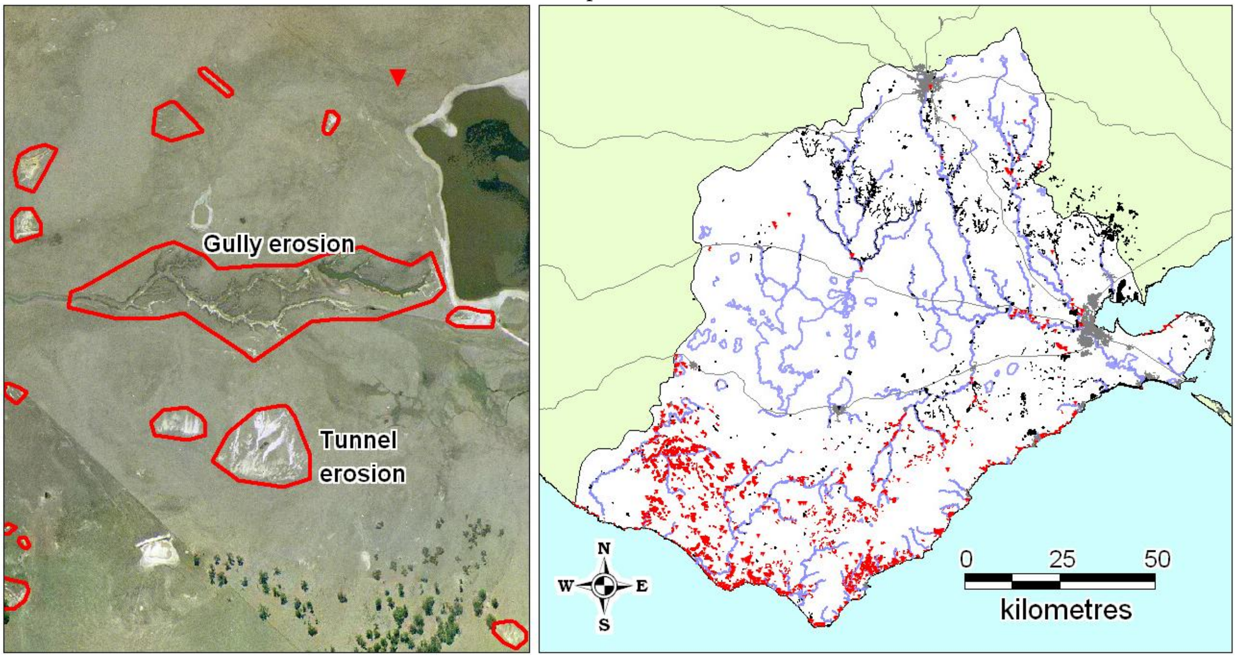

Figure 3. Mapped features in the Corangamite erosion and landslide database.

SPATIAL ANALYSIS

A total of 4925 landslide and erosion records have been captured in the database, with 3168 identified from aerial photomosaics, of which 173 were field checked. A further 151 were added from the information supplied by the Landcare group members. Each of the records was tagged with a confidence value (either certain or uncertain) since not all of the features were able to be verified (Table 1).

Table 1. Summary of records

Feature Type	Records	Records marked as certain	Total area / length
Sheet and rill erosion	1357	1027 (76%)	1810 ha
Gully and tunnel erosion	812	730 (90%)	1305 ha
Stream bank erosion	320	273 (85%)	324 km
Mass wasting (landslides)	2286	1948 (85%)	9520 ha
Other soil degradation	668	442 (66%)	N/a

The use of GIS allowed for spatial correlations to be tested against a variety of physiographic, climatic and land-use parameters. These included slope angle and slope aspect, soil-landform units and geological units. Unsurprisingly, the strongest spatial correlations of features were with geomorphology (Table 2) and rainfall (Table 3).

Table 2. Correlation with geomorphology

Geomorphic unit	Component	Number of features			
		Gully and tunnel	Sheet and rill	Landslides	Stream bank erosion
Western Uplands	Dissected landscapes on Palaeozoic rocks	480	321	4	132
	Dissected landscapes on Cainozoic rocks	218	154	10	59
Southern Uplands	Deeply dissected landscapes	3	65	963	2
	Moderately dissected landscapes	12	35	130	9
	Low hills and plateaux	46	81	377	12
Western Plains	Volcanic plains	38	188	45	63
	Sedimentary plains	74	180	761	54
	Granitic hill inliers	17	39	1	12

Table 3. Correlation of features with average annual rainfall.

Feature type	Number of features in rainfall range		
	470 – 700 mm	700 – 1000 mm	1000 – 1900 mm
Sheet and rill erosion	667	48	7
Gully and tunnel erosion	782	77	83
Stream bank erosion	239	21	1
Mass wasting (landslides)	87	854	942
Other soil degradation	254	100	58

The most useful benefit of the spatial database was the ability to determine the proximity of the erosion and landslide features to regional assets. The number and size (area) of features within nominal buffer distances to important regional assets (priority waterways, priority wetlands, sealed and unsealed roads, railways, significant ecological vegetation classes and bioregions) was determined (Table 4).

Table 4. Proximity of erosion and landslide features to major regional assets.

Proximity to asset	Gully and tunnel erosion	Sheet and rill erosion	Mass wasting (landslides)	Stream bank erosion
Within 50m of priority waterway	102 records 462 hectares	167 records 404 hectares	200 records 1623 hectares	85 records 180 km
Within 100m of priority waterway	145 records 504 hectares	204 records 444 hectares	261 records 1978 hectares	93 records 193 km
Within 50m of priority wetland	14 records 63 hectares	17 records 77 hectares	18 records 182 hectares	13 records 2.3 km
Within 100m of priority wetland	18 records 66 hectares	24 records 89 hectares	30 records 220 hectares	15 records 34 km
Within 50m of sealed road	49 records 129 hectares	61 records 177 hectares	187 records 1274 hectares	50 records 120 km
Within 100m of sealed road	64 records 156 hectares	86 records 216 hectares	276 records 1724 hectares	62 records 137 km

In summary, the spatial analysis determined that:

- Soil erosion and landslides represent a significant threat to catchment assets such as waterways, wetlands and transport infrastructure.
- Landslides dominate the southern regions of the Corangamite region, whereas sheet, rill and gully erosion are most prevalent in the three northern catchments, *viz:* the Woady Yaloak, Leigh and Moorabool rivers.
- 7.7% of all waterways within the Woady Yaloak River catchment are affected by stream bank erosion.
- 68% of mapped gully and tunnel erosion and 48% of sheet and rill erosion features occur in two broad geological units, *viz:* the sedimentary rocks of Ordovician age, and the sedimentary rocks of Pliocene age.
- 73% of landslides occur in two broad geological units, *viz:* the lithic sedimentary rocks of Cretaceous age and the marls of Neogene age.

ESTIMATING THE IMPACT

The impact of the erosion and landslides on regional assets was assessed for the development of the SHS so that the priority areas for investment in mitigation measures could be determined.

Erosion

The spatial analysis showed that sheet, rill, tunnel, gully and stream bank erosion was a significant threat to the water quality of urban water supplies and wetlands of environmental significance. In particular, erosion in the Moorabool River catchment supplies sediments and salts which threatens the quality of 30% of the urban water supply for the City of Geelong. In the Woady Yaloak River catchment, erosion is the source of sediments, salts and nutrients which are ultimately washed into Lake Corangamite, and are a potential threat to the ecological value of the lake. In addition, erosion threatens roads and other infrastructure assets, including utility conduits (water, energy and communication).

Recent examples from the Corangamite region indicate that the costs of treatment for sheet and rill erosion sites on agricultural land ranges from $500 to $5000. A small site (one hectare) may only require pasture whereas a large site (two hectares) would require the construction of diversion banks, fencing and the establishment of pasture. The on-site benefit is generally reclaiming agricultural production on erosion sites; and preventing the loss of productive land through further erosion of these sites. Treating gully erosion is significantly more expensive. A small gully, with an average length of 200 metres and a width of one metre, requires fencing and revegetation estimated at $3,000. A large gully, 750 metres in length and 10 metres wide, would require the construction of headwork structures and silt traps to minimise downstream impacts, and earthworks, fencing and revegetation. The total cost is estimated at $40,000. The on-site benefits from treating gully erosion sites on agricultural land include the sustainability of agricultural production, improved farm access and a reduction in pest plant and animals.

In relation to the impact of erosion on infrastructure, there are two recent examples in the Corangamite region that provide an indication of costs. Heavy rains in February 2005, caused erosion which resulted in a build up of sediment and debris at a bridge on the Bacchus Marsh - Geelong Road (Figure 4), with a relatively low cost for remediation ($3,000). The same event also caused a collapse of a main road (Jetty Road), with an immediate cost of $5,000 for the cleanup operation and an expected cost of around $200,000 to remediate the road.

Figure 4. Sediment impact on bridge and road infrastructure

Erosion management

Since the formation of the Soil Conservation Board (later the Soil Conservation Authority – SCA) in 1940, management of soil erosion has been the focus of State government agencies. Land rehabilitation and management techniques have been developed from extensive field experience and trials, are well documented in State agency publications (e.g. Carder & Spencer 1970; Garvin *et al.* 1979). Up until the 1980s, there was a strong community awareness that soil erosion impacted on the productivity of agricultural land and the health of waterways. With the abolition of the SCA in the mid 1980s the awareness of the impacts of soil erosion has declined.

The initial analysis of costs and benefits for the Corangamite SHS indicates that the private on-site benefits of addressing the erosion are very low relative to the on-site cost required. This highlights the need for significant public investment to supplement the on-site cost, especially where the public benefits are relatively high (by improving water quality, for example). The analysis suggests that providing soil extension officers to educate and advise landholders has greater potential net benefits in preventing new sheet and gully erosion sites being formed in the first place. Therefore the SHS will address this situation by providing both extension activities and economic incentives to landholders so that they gain advice and assistance for the remediation of erosion in priority areas.

Under the SHS it is also planned to utilise the municipal statutory planning schemes as a tool for erosion management, specifically through the implementation of an Erosion Management Overlay (EMO) for each municipality (Miner & Dahlhaus 2005). The overlay will require that developers take reasonable action to assess the risks of erosion impacting on the proposed development and the surrounding environment. It is expected that the implementation of the EMOs will mitigate the on-site impacts, thereby reducing the liability for the municipality, and reduce the off-site impacts, thereby sustaining the integrity of regional assets.

Landslides

The erosion and landslide inventory confirmed the Corangamite region as one of the most landslide-prone areas in Australia. As rainfall is the dominant trigger, the past record can be a guide to future landslide events. For most of the landslide-prone southern landscapes, rainfall well above average (i.e. above the average deviation from the mean) has been recorded in 24 years of the 110 year record. Significant episodes of landslide events have occurred during these wet years, causing asset damage. Major damage (hundreds of metres of road destroyed, one or two buildings destroyed) has occurred during the four wettest years in the hundred year record.

Some estimates of likelihood have been made in previous studies. Based on the study by Buenen (1995), the area of land affected by landslides in the south western portion of the Western Plains and Southern Uplands has been increasing at approximately 6% per year since clearing in the 1960s (Dahlhaus & MacEwan 1997). The loss of two lives due to a rockfall from the basalt cliffs at the Lal Lal Reserve, near Ballarat, initiated some research into the likelihood of such rockfalls. The research concluded that approximately 0.04 m^3/yr of rock falls from the cliff, mostly in episodes every 5 to 7½ years (Dahlhaus & Miner 2000). Ongoing research at The Bluff, Barwon Heads, concludes that potentially damaging rockfalls from the coastal cliff occur about once every two years (Muller 2003).

The impact of these landslide has been poorly documented, even though there have been significant economic, environmental and social costs in the recent past. A list of known events has been assembled for the SHS and although very few are documented, the cost amounts to many millions of dollars (Table 5). The landslide event with the greatest impact is the Lake Elizabeth landslide of 1952, which completely blocked the East Branch of the Barwon River for 14 months (Currey 1952), followed by a collapse of the landslide dam which resulted in widespread flooding and economic losses (Dahlhaus & Miner 2002). Although the total cost of that event has not been documented, it is estimated to be greater than \$100 million in today's value. In the past five years the repair of infrastructure and remediation of assets has amounted to more than \$2.5 million.

In the landslide-prone landscapes of the Corangamite region the assets most at risk are (in order): infrastructure (roads, pipelines, buildings, cables, reservoirs); agricultural (dairy pasture, farm dams, farm infrastructure, horticultural land, grazing land); environmental (environmental stream flows, lakes and wetlands, native forests, coastal cliffs, public access to tourist sites, coastal cliffs and river gorges); water quality (turbidity, sediment load); and cultural and heritage: public access (particularly coastal), historic buildings.

Table 5. Selected examples of landslides in the Corangamite region and their impact.

Date	Event / location	Description	Impact
1891	Clarke's Landslide, Eastern View	One of the first recorded landsides in region. Approximately 11 ha of coastal slopes were affected. Houses have been built on the landslide in later years, with some ongoing movement.	Houses have been built on the landslide in later years, with some sustaining ongoing damage.
Circa. 1935	The Dungeon, Aire River	Large landslide on the banks of the Aire River following timber harvesting.	Significant environmental damage and loss of timber resource.
1952	Wild Dog Road, Busty Road, near Apollo Bay	Landslide following heavy rains severs road access to Wild Dog Valley.	~ 400 m of road destroyed, creek blocked for months. Significant environmental damage.
1952	Otway Shire	Several roads destroyed by landslides following heavy rains.	Repairs to roads estimated cost £33,000
1952	Great Ocean Road, Wongarra	Landslide caused by heavy and prolonged rainfall destroys dairy and covers Great Ocean Road with landslide and building debris.	Loss of dairy and farm buildings, extensive damage to main road.
1952 - 1953	Lake Elizabeth landslide	48 ha landslide completely blocks Barwon River East Branch for 14 months. Followed by landslide dam failure causing extensive flooding (Dahlhaus & Miner 2002). .	Extensive and lasting damage to the environment, agricultural lands and rural infrastructure. Relief funds provided.
Circa. 1964	Wye River landslide	Landslide in Morley Avenue, Wye River following heavy and prolonged rains.	Damage to housing, property, roads and infrastructure.
1970	Windy Point, near Lorne	Rock slide closes Great Ocean Road for 6 months (just south of Lorne). Cable anchoring installed for stabilisation (Williams & Muir 1972).	Significant investigation, design and installation cost for cable anchors. Economic and social impact with closure of the main tourist road.
1974	Melba Parade, Anglesea	Coastal landslide severs road access at Point Roadknight.	Major damage to road requiring rerouting.
1976	Lorne landslide	Landslide in township of Lorne following heavy rains.	House destroyed, ~ 400m of road blocked by landslide.
1979	Big Slide, Wild Dog Valley, Apollo Bay	Large-scale failure of road embankment and valley slopes following heavy and prolonged rain.	House surrounded by landslide debris one metre depth. Road closed for week. Potential for injury and loss of life.
Circa. 1986	Sunnyside Road landslide	Landslide caused by impeded road drainage severs road access.	~ 30m road destroyed. Road closed for several weeks.
1990	Rockfall, Lal Lal Falls Reserve, near Ballarat	Rockfall during abseiling exercise by school students on physical exercise excursion (Dahlhaus & Miner 2000)	2 persons killed, others injured, large scale rescue, Coroner's Inquest, access to Lal Lal Creek Reserve closed
Circa. 2000	Bouwman's slide, Princetown.	Episodic reactivation of low-angle landslide. Stabilisation works (drainage) had been completed 15 years earlier.	House, dairy and farm sheds destroyed and removed. Loss of farm income. Road stabilisation works.
2001	Torquay coast	Coastal cliff collapse traps person and initiates large scale rescue mission.	Potential for loss of life, extensive rescue costs.
2001 – present	Moorabool River landslide	Relatively small-scale landslide following heavy rain, threatens to sever main water supply pipeline (Figure 2).	Water main endangered, investigation and remedial works ~ $200,000
2001 – present	Landslide, The Dell, Clifton Springs	Reactivation of landslide complex following heavy rain. Access to beach closed, buildings and recreational complex threatened.	Site closed, infrastructure damaged, investigation and works to date ~ $500,000
2002	Ocean Grove	Main sewer protected from potential damage due to landslide.	Investigations and engineering works ~$150,000
2005	Turton's Track	30 landslides following heavy rain damages ~10km of a popular tourist road.	Extensive road repairs ~$900,000
2005	Great Ocean Road	Multiple slides and closure of iconic tourist road after heavy rains	Extensive road repairs ~$250,000

Landslide management

The awareness of landslides in Australia has been of growing since the number of fatalities has risen dramatically in the past 15 years. Increasing development of landslide prone areas combined with increasing litigation in society has provided the impetus for a review of risk management practice by local government and professional societies. While many local authorities around Australia have long recognised the potential impact from landslides and slope instability on infrastructure, events such as the 1997 Thredbo landslide (18 lives lost) and the 1996 Gracetown cliff collapse (9 lives lost) have led to the implementation of various local risk management schemes. In March 2000, the Australian Geomechanics Society (AGS) published landslide risk management guidelines, based on the Australian Risk Management Standard, in an attempt to establish a uniform national approach (AGS, 2000). Current improvement of these guidelines is continuing with support from the National Disaster Mitigation Program (Leventhal, 2005).

The Corangamite SHS recognises that most appropriate landslide risk management option for the region is to implement a uniform process for landslide risk assessment, applicable to all assets within the catchment, even though the legal jurisdiction of the asset protection may not lie with the Corangamite CMA. The intention is to co-invest with the municipalities and other asset managers in implementing statutory regulations based on the AGS guidelines with the specific aim of protecting the viability of community and environmental assets.

CONCLUSIONS

The erosion and landslide database assembled for the Corangamite SHS has provided an objective basis for identifying the assets at risk and priority areas for management. Despite records of events and instances being relatively scarce, an estimation of the impact of the erosion and landslides has been documented. The inventory demonstrates the need for erosion and landslide management to sustain the viability of both private and public assets. Erosion has a greater impact on water quality and environmental value and remediation requires both extension activities and economic incentives to landholders. Landslides have greater impact on infrastructure and require a uniform approach to risk management by asset managers. The municipal statutory planning schemes are an effective tool for both erosion and landslide management and the protection of catchment assets.

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