ABSTRACT

A GIS-based quantitative landslide risk assessment was carried out in the Cairns area to provide information to the Cairns City Council on landslide hazard, community vulnerability and risks for planning and emergency management purposes. Magnitude recurrence relations were tentatively established for the two main slope processes: landslides on the hill slopes and large debris flows extending out from the gully systems on to the plains. From the recurrence relations, landslide hazard \( (H) \) was estimated as the annual probability of a point being impacted by a landslide. The nature, number \( (E) \) and geographic distribution of the elements at risk were obtained by interrogating the GIS, and their vulnerabilities \( (V) \) to destruction by the two main landslide slope processes were assessed. From this information, specific risk \( (= H \times V) \) and total risk \( (= H \times V \times E) \) maps were produced.

Landslide risk may increase as development extends further into the hill slopes. Large debris flows could impact on subdivisions at the base of the slopes. Blockage by landslides of roads and railways could cause isolation of the community. Flash flooding in Freshwater Creek, or debris flows, have the potential to disrupt the Cairns water supply by blocking the intake or destroying sections of the pipeline.

1 CONTEXT OF THE RISK ASSESSMENT

The Cities Project undertakes risk assessments aimed at reducing the risks posed by a range of geohazards to Australian urban communities.

Cairns is the most northerly eastern Australian city with a resident population of about 120,000. It is the transport, logistic and administrative centre for a large hinterland and a fishing and sugar industry centre. It is also a popular tourist centre. At the time of the 1996 census, there were almost 10,000 overseas visitors. (Granger et al., 1999).

The present-day boundaries of Cairns City were established in 1995 following the amalgamation of the former local governments of Mulgrave Shire and Cairns City. The Local Counter-Disaster Committee is chaired by the Cairns City Council. Other members include officers of the State Emergency Service and of other organisations relevant to disaster management.

The area covered by this study extends from Ellis Beach in the north to Gordonvale in the south. It also includes the Yarrabah Aboriginal Community to the east of Cairns. The study area is indicated in Figure 1.

Quantitative landslide risk assessment is a relatively new approach to dealing with landslide zoning or regional stability studies. A workshop on the subject was reported in some detail (Cruden & Fell, editors, 1997). The quantitative landslide risk assessment described here was part of a multi-hazard risk assessment of the Cairns area undertaken by the AGSO (now Geoscience Australia) Cities Project. Its aim was to provide information to the Cairns City Council and the State Emergency Service on hazards, community vulnerability and risks for planning and emergency management purposes. All authors worked for AGSO at the time, either as employees or consultants. The material for this paper was entirely sourced from Michael-Leiba et al., 1999; Granger et al., 1999; Michael-Leiba et al., 2000; and Michael-Leiba et al., 2001.

2 IDENTIFICATION OF LANDSLIDE HAZARDS

The landscape around Cairns is dominated by a series of escarpments that are developing by scarp retreat. Weathering, erosion and removal of debris cause scarp retreat from the slope by two main processes (Michael-Leiba et al., 1999):

- ‘on steeper bedrock slopes, and bedrock slopes masked with a relatively thin mantle of broken rock and finer material, weathering and erosion leads to landslides (rock falls, rock slides, debris slides and small debris flows confined to the slope). By this process rock and soil moves down slope under the influence of tropical rainstorms and gravity and
Figure 1: Locality map
• during the more extreme rainfall events, the combined effect of multiple landslides in the upper parts of gully catchments and the remobilisation of accumulated debris in the major gully systems periodically results in large debris flows. These can extend on to the depositional plains at the base of the bedrock slopes.

While most of Cairns is built on the coastal plain, as the community expands development is encroaching on to the prominent escarpments and hill slopes of weathered Silurian and Devonian meta-sediments and Permian and Permo-Triassic granite and a number of colluvial fans and deposits near the foot of the escarpments.

Cairns has a wet tropical climate, with distinct wet and dry seasons and the heaviest rain in the summer months. Rainfall intensities of a sufficient magnitude to trigger landslides have a mean recurrence interval of considerably less than one year and landslides are not rare events.

One definite and two probable large debris flow events are known to have occurred in the Cairns region since European settlement.

On 12 January 1951, a deluge of about 700 mm of rain in just under five hours triggered debris flows that affected 10 km of the Captain Cook Highway behind Ellis Beach. Huge quantities of debris were swept from the mountainside onto the road and over the precipice into the sea. Boulders up to three metres long were hurled into the Pacific “like marbles”. Large slabs of bitumen were tilted up from the road and landslide debris was piled up as high as three metres. All culverts and inverts in this area were either damaged considerably or washed away entirely. The highway was not expected to carry normal traffic for at least two weeks (Cairns Post, 15 January 1951).

The probable debris flow events happened in 1878 and 1911 on the eastern side of Trinity Inlet. Deposits from numerous debris flows have been identified in this area. On 8 March 1878, a “flood” followed by a severe cyclone triggered many landslides across the Inlet. They could be heard distinctly in Cairns (Jones, 1976). On 1 April 1911, a big landslide occurred in the Nisbet Range, also across the Inlet from Cairns. The scar could be seen in photos for several years afterwards (A. Broughton, Cairns Historical Society, personal communication, 1997). This landslide brought away trees, rocks and everything else from a considerable distance up the mountain side (Cairns Post, 3 April 1911).

Landslides on hill slopes periodically block roads, particularly Lake Morris Road and Kuranda Range Road, and the Cairns-Kuranda railway has an even more spectacular history of dislocation by landslides. Instances of landsliding have been recorded in the established suburbs, either on cuts behind houses or road cuts or fills. Two houses have been destroyed and several building blocks written off as a result.

3 ANALYSIS OF RISKS

3.1 LANDSLIDE HAZARD ASSESSMENT

3.1.1 Magnitude Recurrence Relations

The landslide magnitude was taken to be the logarithm of the landslide volume in cubic metres per 10 km of escarpment. The use of process rate models to assess the likelihood of the hazard eventuating is reviewed in Baynes and Lee (1998) where several instances of this approach are provided. Log scales are conventionally used for analysing magnitude recurrence relationships for the process rates of natural phenomena, as available data on both magnitude and recurrence interval invariably extend over several orders of magnitude. The use of a log scale for landslide magnitude is analogous to its use in stellar and also earthquake magnitudes (e.g. Richter, 1935).

Using a detailed catalogue of events based on field observations in Cairns and historical research, recurrence relations per 10 km of escarpment (Figures 2a, 2b and 3) were established for:

- the total volume of a set of landslides triggered by a rainfall event, along roads and the railway up the escarpment;
- the total volume of a set of landslides triggered by a rainfall event on fully developed slopes and
- the total volume of a number of debris flows, triggered by a single rainfall episode, which extend on to the plain.

The recurrence relations relate the logarithm of the volume of a landslide event (landslide magnitude) to the number of landslide events per year per 10 km of escarpment with volumes greater than or equal to the plotted volume. The landslide event volume would be the maximum volume of a single landslide triggered by the rainfall event. However, often a landslide event consists of a number of smaller landslides, rather than one large one. In this case, the landslide event volume is calculated by summing the volumes of the smaller landslides.
In Figures 2a and 2b, Bureau of Meteorology rainfall intensity-frequency-duration (IFD) curves were used to assess the mean recurrence intervals of the April 1911 rainfall event, and of those brought by cyclones Justin and Rona. The 24-hour rainfall figures were used for this purpose, but more work is needed to ascertain whether these are most appropriate. Landslides logged along Lake Morris Road during initial fieldwork in March 1997, prior to cyclone Justin, were assumed to have been triggered by the 1-year rainfall event.

In Figure 2a, Recurrence of landslides along roads and railways along the escarpment

In Figure 2b, Recurrence of landslides on hill slopes

In Figures 2a, 2b and 3 involves torrential rain over the entire area causing debris flows in all gullies, and that one fifth to one quarter of the hill slope area not involved with large debris flows is affected by other landslides.
3.1.2 Shadow angles

A landslide or debris flow originating in one geomorphic unit can extend and impact on the unit downslope. The extent of any impact may be conveniently defined by the shadow angle relevant to that process (Hungr, 1997; Wong et al., 1997). In this study, the shadow angle is taken to be the angle between the horizontal and a line drawn from the limit of the proximal or distal part of the debris flow to the top of the escarpment or ridge crest (Figure 4).

The proximal portion is that part of the debris flow closest to the source of the landslide. It has a lumpy or convex surface and contains large boulders up to several metres in size. The distal portion of a debris flow is more gently sloping and contains the finer grained sediments that are deposited further from the landslide source.

Based largely on field observations, shadow angles of 19° and 14° were chosen to represent the limits of the proximal and distal portions respectively of potential debris flows. Using a GIS, the extent of areas covered by these shadow angles were delineated thus defining hazard zones on the gentle slopes below the gullies. These zones represent the limit to which a debris flow might conceivably extend were it to originate high in the catchment of a particular gully system. The polygons thus defined may be thought of as being at some risk from debris flow.

3.1.3 Landslide Hazard Polygons

GIS polygons were used to delineate and characterise the areas that could be affected by landslides. Three main categories were chosen:
3.1.4 Landslide Hazard

The landslide hazard is the probability, $H$, per annum, at any one point in a polygon, of that point being impacted by a landslide. The hazard value is assumed to be the same for all points in the polygon.

For each of the three categories of landslide hazard polygon, the appropriate magnitude recurrence relation was used to estimate $H$. The method is shown in Figure 5, where it can be seen that the ratio of the total area of landslides in a rainfall event to the polygon area was used in calculating $H$ – the larger the landslide event area, the greater the value of $H$. A mean landslide thickness (1.5 m for landslides on hill slopes, 2 m for the proximal part of debris flows, and 0.6 m for the distal part of debris flows), was estimated from field observations and was used to calculate the landslide event area from its volume.

Under this simplifying assumption of a uniform thickness for all landslides of a given type, $H$ will be the same, when calculated using the method in Figure 5, irrespective of whether the landslide events that contribute to its calculation consist of a single large landslide or a number of smaller landslides with the same total volume. With $H$ defined simply as the probability of impact of a landslide at a point, the uniform thickness assumption will tend to underestimate the contribution to $H$ from a series of smaller landslides, because their real thicknesses will tend to be less than assumed, so their actual area will be greater than that calculated using the mean thickness. Similarly, the contribution to $H$ will tend to be overestimated from a large landslide because its thickness will often be greater than the mean, leading to an overestimation of area when the mean thickness is assumed. However, the damage potential of a single large landslide would usually be greater than that of a series of smaller landslides.

In Figure 5, $H$ is calculated by adding together the probability of impact, at a chosen point in the study area, of landslides in each of the volume ranges. The landslide hazard calculated by this method may be an over-estimate because the hazard calculations do not subtract the probability of a point in a polygon being hit by more than one landslide in a year.

For points on the escarpment, the hazard occurrence probability, $H$, is estimated to be 0.02% (an ARI of 6 000 years), assuming that the slope is developed. Thus, for undeveloped parts of the escarpment, this figure predicts what $H$ would be if the slope were to be developed without adequate mitigation measures being taken. $H$ would be expected to be considerably less on slopes developed with geotechnical consultation. It would also probably be less on undisturbed slopes. The hazard probability, rounded to one significant figure, in areas which may be impacted by the proximal parts of debris flows is calculated to be 0.01% (an ARI of 8 000 years), and for the distal parts of debris flows, 0.01% (an ARI of 9 000 years).

3.2 Vulnerability

The vulnerabilities ($V$) of people inside their residence, of buildings and of roads, to death or destruction by smaller landslides on hill slopes, and by large debris flows that run out on to the plain, were assessed. The vulnerability was
**Figure 5: Hazard assessment from magnitude recurrence graph**

<table>
<thead>
<tr>
<th>Volume interval</th>
<th>Number of landslide events in volume interval</th>
<th>Mid-point on graph of volume interval</th>
<th>Area of landslide = vol/thickness =v/v2/thickness, etc</th>
<th>Probability of impact at a specified point in a polygon with area $A_{\text{polygon}}$, given that a landslide happens in the polygon</th>
<th>Hazard = annual probability of impact at a specified point</th>
</tr>
</thead>
<tbody>
<tr>
<td>$v_1$ to $v_2$</td>
<td>$N_1 - N_3$</td>
<td>$v_2$</td>
<td>$A_2$</td>
<td>$P_2 = A_2 / A_{\text{polygon}}$</td>
<td>$P_2 \ (N_1 - N_3)$</td>
</tr>
<tr>
<td>$v_2$ to $v_3$</td>
<td>$N_3 - N_5$</td>
<td>$v_3$</td>
<td>$A_3$</td>
<td>$P_3 = A_3 / A_{\text{polygon}}$</td>
<td>$P_3 \ (N_3 - N_5)$</td>
</tr>
<tr>
<td>$v_3$ to $v_4$</td>
<td>$N_5 - N_7$</td>
<td>$v_4$</td>
<td>$A_4$</td>
<td>$P_4 = A_4 / A_{\text{polygon}}$</td>
<td>$P_4 \ (N_5 - N_7)$</td>
</tr>
<tr>
<td>$v_4$ to $v_5$</td>
<td>$N_7 - N_9$</td>
<td>$v_5$</td>
<td>$A_5$</td>
<td>$P_5 = A_5 / A_{\text{polygon}}$</td>
<td>$P_5 \ (N_7 - N_9)$</td>
</tr>
<tr>
<td>$v_5$ to $v_6$</td>
<td>$N_9 - N_{11}$</td>
<td>$v_6$</td>
<td>$A_6$</td>
<td>$P_6 = A_6 / A_{\text{polygon}}$</td>
<td>$P_6 \ (N_9 - N_{11})$</td>
</tr>
<tr>
<td>$v_6$ to $v_7$</td>
<td>$N_{11} - N_{13}$</td>
<td>$v_7$</td>
<td>$A_7$</td>
<td>$P_7 = A_7 / A_{\text{polygon}}$</td>
<td>$P_7 \ (N_{11} - N_{13})$</td>
</tr>
<tr>
<td>$v_7$ to $v_8$</td>
<td>$N_{13}$</td>
<td>$v_8$</td>
<td>$A_8$</td>
<td>$P_8 = A_8 / A_{\text{polygon}}$</td>
<td>$P_8 \ (N_{13})$</td>
</tr>
</tbody>
</table>

Sum of this column = $H$

$H = \text{hazard} = \text{probability per annum of impact of a landslide (volume in the range } v_1 \text{ to } v_6 \text{) at any point in the polygon}$

$= P_2(N_1 - N_3) + P_3(N_3 - N_5) + P_5(N_5 - N_7) + P_6(N_7 - N_9) + P_8(N_9 - N_{11})$

$V = \text{vulnerability} = \text{probability of an element at risk being destroyed by a landslide, if impacted}$

$E = \text{number of elements at risk in a polygon}$

Specific risk $= H \cdot V = \text{annual probability of a given element being destroyed by a landslide}$

Total risk $= H \cdot V \cdot E = \text{number of elements per annum expected to be destroyed by a landslide}$
taken to be the probability of death or destruction given that the residence or road was hit by a landslide. The value of \( V \) ranges between 0 (none destroyed) and 1 (all destroyed) with the type of landslide and element at risk, as shown in Table 1. The uncertainties in these values are not known.

For smaller landslides hitting a residence on hill slopes, it should be noted that resident people may not be home, or may be in a room not affected by the landslide that hits their house. We have taken this into account by incorporating the probability of a resident person actually being present in the part of their home that gets impacted by a landslide into the estimate of vulnerability for people living on hill slopes. This is common practice in quantitative landslide risk assessment (e.g. Fell, 1994; Wong et al, 1997; Baynes, 1995).

For people and buildings on hill slopes, the assessment was based on information in the Australian Landslide Database, and for roads on hill slopes, the vulnerability was estimated from information provided by the Cairns City Council. The calculations are given in detail below.

### 3.2.1 Vulnerability of buildings on hill slopes

In the Australian landslide database and Cairns landslide database there were 24 landslides, which impacted buildings, and which may be equivalent to the hill slope landslides in Cairns. In 11 of these, no buildings were destroyed, giving vulnerabilities of 0 in these cases. In 11 cases, all the buildings were destroyed (the number of buildings per landslide varying from one to three), so the vulnerability for these is 1.0. For the remaining two out of the 24 landslides, two out of 16 and three out of seven buildings were destroyed, giving vulnerabilities of 0.1 and 0.4 respectively. The weighted mean vulnerability of buildings for the 24 landslides is \( V_s = 0.5 \). This may be a conservative value, because there could be cases where buildings were impacted by landslides and not destroyed that have gone unreported. Assuming that only half the cases were reported in the database, then \( V_s = 0.25 \).

### 3.2.2 Vulnerability of resident people on hill slopes

In three of these 24 landslides, people were killed. At Walhalla in Victoria, both people were killed, giving a vulnerability of 1.0. At Coledale, NSW, two out of five people were killed, giving a vulnerability of 0.4. At Thredbo, NSW, 18 out of 19 people were killed, giving a vulnerability of 0.9. For the remaining 21 landslides, either no people were in the buildings, or else they were not killed, giving a vulnerability of 0. This gives a weighted mean vulnerability for the 24 landslides of \( V_p = 0.1 \). This value could be conservative because landslides which cause death are more likely to be reported than those which do not, and because fill failures were the cause of two of these landslides. Assuming that only half the cases of buildings being impacted by landslides were reported in the database, then \( V_p = 0.05 \). This figure is in good agreement with the value suggested by Wong et al, 1997, for the vulnerability of a person in a building if debris strikes the building. As it is derived from figures relating to buildings impacted by landslides in the database, it takes into account the fact that buildings may not be occupied all the time.

### 3.2.3 Vulnerability of roads on hill slopes

The data in the Australian landslide database are not detailed enough to calculate a vulnerability for roads. However, Cairns City Council informed us that Kuranda Range Road is totally blocked about once a year, but needs partly remaking no more than once in two years. This gives a vulnerability of no more than 0.5. Lake Morris Road gets totally blocked about three times a year, but needs partly remaking at most once every two years. This gives a vulnerability of at most 0.17. The mean of 0.5 and 0.17 is 0.3, so 0.3 was taken as the value of the vulnerability, \( V_r \), of roads.

### 3.2.4 Vulnerability to proximal debris flows

If the occupants of a house are in the path of a 3 m-high wall of swiftly moving water- laden debris then the chance of being killed may be as high as 90%. Similar values have been assumed in Hong Kong studies (Wong et al, 1997). Assuming that the occupants are there all the time during periods of torrential rainfall, \( V \) for resident people is about 0.9. All housing and roads would be completely destroyed in the proximal portion of a debris flow.

### 3.2.5 Vulnerability to distal debris flows

The distal portion of a debris flow is taken to be a relatively shallow swift moving debris flow or sheetwash accumulation of the order of 0.6 m thick. In the distal portion of the path of a large debris flow, which is a swift and powerful event, there might be a 1 in 20 chance of a person being killed inside a building. Assuming that the occupants are there all the time because of the torrential rain, this gives a vulnerability of 0.05. This figure is in good agreement with the value suggested by Wong et al, 1997, for the vulnerability of a person in a building if debris strikes the building. Such distal debris may cause minor scouring of roads, but will just cover them most of the time, so the vulnerability of roads has been assumed to be 0.3. The vulnerability for buildings has been taken to be 0.1.
Table 1: Vulnerability to destruction of people, buildings and roads

<table>
<thead>
<tr>
<th>Unit</th>
<th>Vulnerability of resident people</th>
<th>Vulnerability of buildings</th>
<th>Vulnerability of roads</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hill slopes</td>
<td>0.05</td>
<td>0.25</td>
<td>0.3</td>
</tr>
<tr>
<td>Units susceptible to proximal debris flow</td>
<td>0.9</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Units susceptible to distal debris flow</td>
<td>0.05</td>
<td>0.1</td>
<td>0.3</td>
</tr>
</tbody>
</table>

3.3 RISK ASSESSMENT

3.3.1 Specific Risk of Destruction

Specific annual risk of destruction is the probability per annum of a person, building or section of road at a given point in the Cairns area being destroyed by a landslide. The specific risks to individual people, buildings and roads in susceptible parts of Cairns, if the areas were to be developed, have been calculated from the equation

\[
\text{specific risk} = H \times V
\]

and mapped using the GIS.

The specific annual risk of destruction of individuals, buildings and roads, and of road blockage is shown in Table 2. The possible range in values, attributed to uncertainties in the recurrence relations, is given in brackets.

3.3.2 Total Risk of Destruction – Residential People and Buildings

Total risk is the number of elements at risk expected to be destroyed by a landslide in a given GIS polygon in a given period of time. The GIS polygons were interrogated to assess the nature and number of elements at risk (E).

Total risk per annum was calculated using the equation

\[
\text{total risk} = H \times V \times E
\]

where H is the probability of impact per annum of a landslide at any selected point in a polygon, V is vulnerability, and E is the number of houses and flats, or people living in houses and flats, in a polygon.

Maps which quantitatively depict the total risks per km² per 100 years for residential people and buildings in each GIS polygon in the currently developed parts of Cairns, were constructed from the data for each polygon.

The total risk per 100 years for a polygon was estimated by multiplying the total risk per annum for that polygon by 100. The total risk per 100 years for, say, the hill slopes was obtained by summing the total risks per 100 years for the polygons that comprise the hill slopes. Using this methodology, the greatest total risk for buildings (houses and flats) is on the hill slopes, where it is estimated that a total of 13 buildings throughout the map area could be destroyed in 100 years, if no mitigation measures had been taken. The highest total risk for people living in houses and flats is in the proximal parts of debris flows. It is estimated that a total of 16 people in the map area could die over 100 years in these areas.

Table 2: Specific annual risk

<table>
<thead>
<tr>
<th>Unit</th>
<th>Specific annual risk of death – resident people</th>
<th>Specific annual risk of building destruction</th>
<th>Specific annual risk of road destruction</th>
<th>Specific annual risk of road blockage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hill slopes</td>
<td>0.0008%</td>
<td>0.004%</td>
<td>0.005%</td>
<td>0.02%</td>
</tr>
<tr>
<td></td>
<td>1 in 100 000+</td>
<td>1 in 20 000</td>
<td>1 in 20 000</td>
<td>1 in 6 000+</td>
</tr>
<tr>
<td></td>
<td>(1 in 5 million to 1 in 40 000)</td>
<td>(1 in 1 million to 1 in 8000)</td>
<td>(1 in 1 million to 1 in 8000)</td>
<td>(1 in 300 000 to 1 in 2000)</td>
</tr>
<tr>
<td>Units susceptible to proximal debris flow</td>
<td>0.01%</td>
<td>0.01%</td>
<td>0.01%</td>
<td>0.01%</td>
</tr>
<tr>
<td></td>
<td>1 in 9 000</td>
<td>1 in 8 000</td>
<td>1 in 8 000</td>
<td>1 in 10 000+</td>
</tr>
<tr>
<td></td>
<td>(1 in 50 000 to 1 in 2000)</td>
<td>(1 in 50 000 to 1 in 1000)</td>
<td>(1 in 50 000 to 1 in 1000)</td>
<td>(1 in 60 000 to 1 in 2000)</td>
</tr>
<tr>
<td>Units susceptible to distal debris flow</td>
<td>0.0005%</td>
<td>0.001%</td>
<td>0.003%</td>
<td>0.007%</td>
</tr>
<tr>
<td></td>
<td>1 in 200 000</td>
<td>1 in 90 000</td>
<td>1 in 30 000</td>
<td>1 in 10 000+</td>
</tr>
<tr>
<td></td>
<td>(1 in 1 million to 1 in 30 000)</td>
<td>(1 in 500 000 to 1 in 20 000)</td>
<td>(1 in 200 000 to 1 in 5000)</td>
<td>(1 in 60 000 to 1 in 2000)</td>
</tr>
</tbody>
</table>
3.3.3 Total Risk – Roads on Hill Slopes

The hill slope failure rate along roads, in the first magnitude recurrence relation, is the volume of landslide debris per 10 km of road. The recurrence relation was largely derived from failure volumes logged along roads up the escarpment after rainfall events.

The calculations of the total length of road covered by debris, and the length destroyed, in a 1 in 10-year rainfall event in the Cairns local government area are shown in Table 3. The landslide volume per 10 km of road was read from the landslide recurrence graph. The landslide area was calculated assuming a mean depth of 1.5 m. The width was estimated by assuming that the landslide failure surface is square in plan. It was assumed that all the debris from the batter is dumped onto the road.

Table 3: Total risk for roads on hill slopes for the 1 in 10-year rainfall scenario.

<table>
<thead>
<tr>
<th>Landslide volume (m³/10km of road)</th>
<th>617</th>
</tr>
</thead>
<tbody>
<tr>
<td>Landslide volume (m³/10km of road)</td>
<td>411</td>
</tr>
<tr>
<td>Maximum length of road covered by debris (m/10km of road)</td>
<td>20</td>
</tr>
<tr>
<td>Maximum length of road destroyed (m/10km of road)</td>
<td>6</td>
</tr>
<tr>
<td>Maximum total length (m) of road covered by landslide debris</td>
<td>238</td>
</tr>
<tr>
<td>Maximum total length (m) of road destroyed</td>
<td>71</td>
</tr>
</tbody>
</table>

Notes: 1. Length of road affected assumed equal to width of landslide
2. width x V, where V = 0.3, vulnerability of roads

In Cairns there are 119 km of roads on the hill slopes. It was estimated that a 14 m³ landslide could block a 6 m wide road, and a 60 m³ landslide could block a 10 m wide road, so that total road blockage could occur in the 1 in 10-year rainfall event. However, the estimates of road blockage and destruction are maximum values, because the batter failures could occur as a large number of tiny landslides, instead of a few larger ones, and not block the road completely.

3.4 DISCUSSION

3.4.1 Advantages of this Risk Assessment Methodology

This approach to landslide risk assessment was adopted for the following reasons:

- It provides a rigorous, transparent, robust assessment methodology.
- It is based on an understanding of all the available observational data relating to geology and geomorphology, slope processes and the complex factors that control slope process rates.
- Because it is quantitative, it is more effectively communicated, and more effectively supports the development of management strategies to respond to, and to mitigate against the landslide risks, in proportion to the absolute level of risk.
- Because it is quantitative, it allows comparison with other risks affecting the community. For example, the risks associated with, say, flood can be compared with those associated with landslide, and limited resources allocated in proportion to the level of each risk.

3.4.2 Limitations

There are some limitations that should be recognised but could not be dealt with in this reconnaissance study. The main ones are:

- the paucity of the data from which the landslide magnitude-recurrence relations were derived. As the error bars for the data points are, in some cases, more than two orders of magnitude, errors in the risk estimates may be large;
- the regional nature of this study. Mapping was at a reconnaissance level only;
- the assumption of a uniform process rate in time;
- the assumption, for landslides on hill slopes, of a uniform process rate across, and from top to bottom of, the entire escarpment profile, irrespective of local geomorphology, rock type, soil cover, proximity to cuts or fills, or position on the escarpment. This assumption may lead to risk being grossly underestimated in some areas and grossly overestimated in others;
- the assumption of a uniform process rate in all debris flow polygons. This assumption may lead to risk being grossly underestimated in some areas and grossly overestimated in others;
• the assumption that the shadow angles are uniform for all debris flows in the area;
• the assumption that vulnerability is independent of landslide magnitude;
• the assumption that debris flow runout is not affected by the presence of large obstacles;
• the assumption that landslide intensity is uniform across a landslide;
• lack of discrimination between the effects of shorter duration, higher intensity rainfall events, of antecedent rainfall, and of longer duration, lower intensity rainfall events. The data tend to be skewed towards observations after tropical cyclones, which tend to be shorter duration, higher intensity rainfall events.

4 RISK EVALUATION

4.1 RISK EVALUATION CRITERIA
From a consideration of the de-facto record of acceptable and tolerable annual risk criteria deduced from questionnaires and land use planning documents for potential hazards such as dams, nuclear power stations, and landslides, Fell & Hartford (1997) have suggested 1 in 1 million as a possible tolerable specific annual risk level for the average of persons at risk on both new and existing engineered slopes. They suggest 1 in 10,000 and 1 in 100,000 as the tolerable specific annual risk levels for the person most at risk on existing and new engineered slopes, respectively. For landslides on natural slopes the situation is less clear, but they think that the public may tolerate risks as high as 1 in 1,000.

4.2 ACCEPTABILITY OF SPECIFIC RISK ESTIMATES
Table 2 gives estimates for the specific risk of fatality from landslides on hill slopes, and from the proximal and distal parts of debris flows. It should be emphasised that these figures were produced under the assumption of a single uniform process rate in all hill slopes polygons, and a different but uniform process rate in all polygons assessed to be susceptible to debris flow. This assumption may lead to risk being grossly underestimated in some areas and grossly overestimated in others. Because of the regional nature of this study, this has not been taken into account in Table 2.

The following discussion considers only the risk figures in Table 2, and does not take into account possible gross underestimates and overestimates of risk introduced by the uniform process rate assumptions. The specific risk for people living on the escarpment is acceptable, using Fell & Hartford’s (1997) criteria, if the slopes are developed with appropriate landslide mitigation measures, as these may reduce the risk to around 1 in 5 million. If new developments took place on the escarpment without these mitigation measures, the risk could rise to about 1 in 40,000, which may not be considered tolerable under Fell & Hartford’s (1997) criterion for newly developed slopes. It is possible that the specific annual risk of fatality assessed in this report for people living in areas susceptible to the proximal parts of large debris flows may be considered tolerable, provided that people are informed of the risk before they purchase property, and because the large debris flows in the Cairns area are a natural feature of the landscape. For the distal parts of debris flows, the risk is probably tolerable, considering the uncertainty in the estimates.

4.3 ACCEPTABILITY OF TOTAL RISK ESTIMATES
There are no commonly accepted acceptance criteria for total annual risk. However, decision makers in the community can use fatality, building and infrastructure destruction estimates to ascertain whether to spend limited community resources to mitigate landslide risk, or whether those resources would be better used on other projects.

It is estimated that a total of 23 houses and/or blocks of flats could be destroyed, and 29 of their residents killed, by landslides in the Cairns area in a 100 year period, if no mitigation measures were taken. This assumes the present distribution of buildings and people. If the population continues to grow and spread into areas vulnerable to landslide, these totals could be considerably higher.

Thirteen of these 23 buildings and eight of the estimated fatalities are on the hill slopes, and this toll could be reduced, and in many cases has been, possibly to zero, by appropriate mitigation measures with geotechnical consultation.

However, six of the 23 buildings and an estimated 16 of their residents could be destroyed over a 100 year period in areas susceptible to the proximal parts of large debris flows. A further four buildings out of the 23, and five of their residents could succumb to the distal parts of large debris flows. While risk could be mitigated by engineering works, such as levees, for the smaller of these debris flows, there is residual risk from rare, larger debris flows. This would be difficult, if not impossible, to mitigate cost-effectively.
4.4 COMMUNITY RISK

As part of risk evaluation in a regional risk assessment, one needs to consider the impact of a hazard not only on individual people and structures, but also on the resilience and viability of the community as a whole.

4.4.1 Building destruction

Most of the critical facilities, such as hospitals and emergency services, essential to community recovery after a disaster, are in the older, flatter parts of Cairns that are not susceptible to landslide.

The currently settled areas that are at greatest risk of building destruction by landslide are dormitory suburbs either on hill slopes, or near the base of the slopes in potential runout zones for large debris flows. As the population of Cairns increases, more development will take place in such areas, and the landslide risk may increase unless adequate mitigation measures are put in place at the time of development.

4.4.2 Isolation

Because the highways and railway that provide access to Cairns from the north and the Tableland pass through country with steep slopes, they may be blocked by landslides in the event of prolonged or intense precipitation. Outside the study area, the highways to the south may also be blocked by landslide. This makes the Cairns community particularly vulnerable to isolation by land.

4.4.3 Utilities

The Cairns water main crosses Freshwater Creek. Flash flooding in the creek, or debris flows, have the potential to disrupt the Cairns water supply by blocking the intake or destroying sections of the pipeline. There have been two instances this century of the Cairns water main being broken by debris flows or flash floods.

5 RISK TREATMENT

General observation and the results of the preliminary risk assessment indicate that there are landslide risks in the Cairns area. Also, flash flooding in Freshwater Creek, or debris flows, have the potential to disrupt the Cairns water supply by blocking the intake or destroying sections of the pipeline.

Risk treatment was outside the scope of this work but its findings were discussed with the Cairns City Council and the State Emergency Service while the work was in progress, and at the completion of the landslide risk assessment.

The following general recommendations were made in Michael-Leiba et al., 1999:

- The mitigation measures, which may already be in place on currently developed land, for hill slope developments could include, where appropriate, adequate drainage, retaining walls, planting of trees, and appropriate siting of buildings on properties. Geotechnical advice is recommended for detailed site specific assessments.

- Previously unrecognised risks are associated with the potential for large debris flows from the escarpment. While engineering works, such as levees, could be used to mitigate the risk from the smaller debris flows, there is a residual risk to people, buildings and roads from rare, very large debris flows.

- This preliminary assessment indicates that areas are being developed that may be in the path of future debris flows. It is recommended that advice concerning mitigation measures, and the development of such areas, be sought from geotechnical consultants with expertise in the behaviour of debris flows.

- Evacuation plans, to be used in the event of impending extreme rainfall events which may trigger large debris flows, should be drawn up for areas deemed susceptible. The plans should be supported by a public awareness and education campaign, addressing both the nature of the debris flow hazard and the evacuation plan.

- Because of the high velocity of debris flows and the potential for escape routes to be blocked by flooding during very heavy rain, it would be desirable for evacuation to take place before, or in the very early stages of the onset of an extreme rainfall event. A complicating factor is that very heavy rain is often brought by tropical cyclones, so people make also need evacuating from low-lying flood or storm surge-prone areas. Therefore, it is desirable that detailed studies of debris flow source and runout areas be undertaken to ascertain which areas of higher ground are safe for evacuees, and which are likely to be affected by debris flows under extreme rainfall conditions. Studies also need to be undertaken to determine the rainfall intensity-duration conditions that could trigger large debris flows so that a useful warning system can be established.
6 REFERENCES


