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Landslide Inventory, Susceptibility, Frequency and Hazard zoning in the Wollongong and wider Sydney Basin Area

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Keywords: Landslide, Susceptibility, Hazard, Zonation, GIS, Data Mining.

ABSTRACT

The University of Wollongong Landslide Research Team has been working on the development of GIS-based Landslide Inventory, Susceptibility and Hazard Zoning projects for over 15 years. To undertake the zoning work we use knowledge-based methods including Data Mining techniques which are facilitated within a GIS framework. This work is ongoing, and as with this paper, there are two main aims; firstly for those smaller sub-regions of Sydney where considerable data have been obtained and the landslide inventory development is comprehensive, increasingly more reliable modelling, analysis and synthesis is being done, and secondly, for the entire 31,000km² geological extent of the Sydney Basin region where the available data are relatively small scale and the process of developing the landslide inventory is in the early stages, preliminary studies which are described as 'proof of concept' have been completed and are reported herein. The most advanced sub-region is a large portion of the Illawarra Escarpment within the Wollongong Local Government Area (LGA). Another advanced sub-region is the Picton area within the Wollondilly LGA. All the while, input data is being refined and improved in particular with the advent of Airborne Laser Scan derived DEM's and the ongoing development and populating of Landslide Inventories. In tandem with refined input data, computing capabilities are also rapidly evolving and this is enabling ever growing terrain modelling capacity. With higher resolution input data for the Sydney Basin project, including a more rigorous Landslide Inventory which is already well under development, higher resolution geology information and possibly even a better or more recent DEM, the regional yet large scale GIS-based Susceptibility modelling outcomes are likely to be suitable for use at Local Government Planning levels. Furthermore, susceptibility modelling at a national scale to identify preliminary or 'first pass' binary type (i.e., in/out) areas for further assessment is also achievable in the very near future.

1 INTRODUCTION

This paper follows two previous papers by the same authors (Flentje et al, 2007a and Flentje et al, 2007b) that outline the methodology employed in Wollongong, GIS-based datasets and zoning maps that have been developed by the University of Wollongong (UoW) Landslide Research Team (LRT) for the assessment of landslide susceptibility and hazard in the Wollongong Study Area (Figure 1). A Landslide Risk Management project is currently underway in the Picton area of the Wollondilly Local Government Area (LGA) and preliminary outcomes from this work are also mentioned, briefly. Importantly, this paper also presents for the first time an overview of the now completed 'Proof of Concept' 25m² pixel resolution Susceptibility zoning for the entire 31,000km² Sydney Basin region. A brief summary of these three study areas is given in Table 1 and this immediately highlights the large size of the Sydney Basin study area as compared with the relatively smaller sizes of the Wollongong and Picton study areas (still 188 and 93 km² respectively). The Sydney Basin study is referred to as a 'Proof of Concept' at this stage. This definition arose due to the fact that initially it was difficult to find useable data sets covering the proposed study area and that furthermore it was problematic, with the available University and financial resources to find computers and GIS software that could handle spatial modelling at 25m² pixel resolution over an area of 31,000 km². Once these challenges were met, first pass data was assembled and the modelling process designed and allowed to run to completion. Through several early iterations to remove spurious data and edge mis-matches etc an output grid was developed that subjectively looked acceptable.

Table 1. GIS based numerical comparison of Study Regions discussed in this paper.

LGA/Project	Area km ²	Pixel count	Number of Inventory Landslides	Landslide Pixel (10m ²) Count	Landslide area as % of SA	Reported Landslide Inventory 'completeness' %	Postulated total Landslide % coverage of LGA
Wollongong Study part of LGA	188	1,880,000 10m ²	426	29,480	1.57	95	1.65
Picton area within Wollondilly	93	936,729 10m ²	874	138,535	14.79	100	14.79
Sydney Basin	31,000	49,597,232 25m ²	575	6,293	0.01	~ 0.7	unknown

2 RECAP OF THE WOLLONGONG PROJECT- SUSCEPTIBILITY

The main element of this methodology comprises of a comprehensive large scale GIS-based Landslide Inventory (Flentje and Chowdhury, 2005, Mazengarb et. al., 2010) with regional coverage. The landslide inventory identifies 'affected areas' and contains 3 main types of landslides; falls, flows and slides (Cruden and Varnes, 1996). The Susceptibility classification that has been developed for Wollongong thus far relates to 'slide' category landslides only. Susceptibility zones, in addition to the known landslides, have been classified as (a) high susceptibility with 8.12% of this area subject to landslides and containing 60.3% of the known landslide population, (b) moderate susceptibility with 4.12% of this area subject to landslides (contains 32.3% of known landslides), (d) low susceptibility with 0.85% of area subject to landslides (contains 3.3% of known landslides), and (e) very low susceptibility with 0.09% of the area subject to landsliding (contains 4.1% of known landslides) and yet representing 70.9% of the study area. The high susceptibility zone identifies over 2,300 hectares of land, outside of known landslides, as being highly susceptible to landsliding. Furthermore, the model also identifies over 13,000 hectares of land as having a very low susceptibility to landsliding. The percentage of the landslide inventory population in each zone compares well with AGS 2007a Table 4b, except the Very Low class. Having related these landslide percentages for each zone, it is important to note that every landslide is classified in the zoning as a landslide and does not, therefore actually comprise part of any of the susceptibility zones.

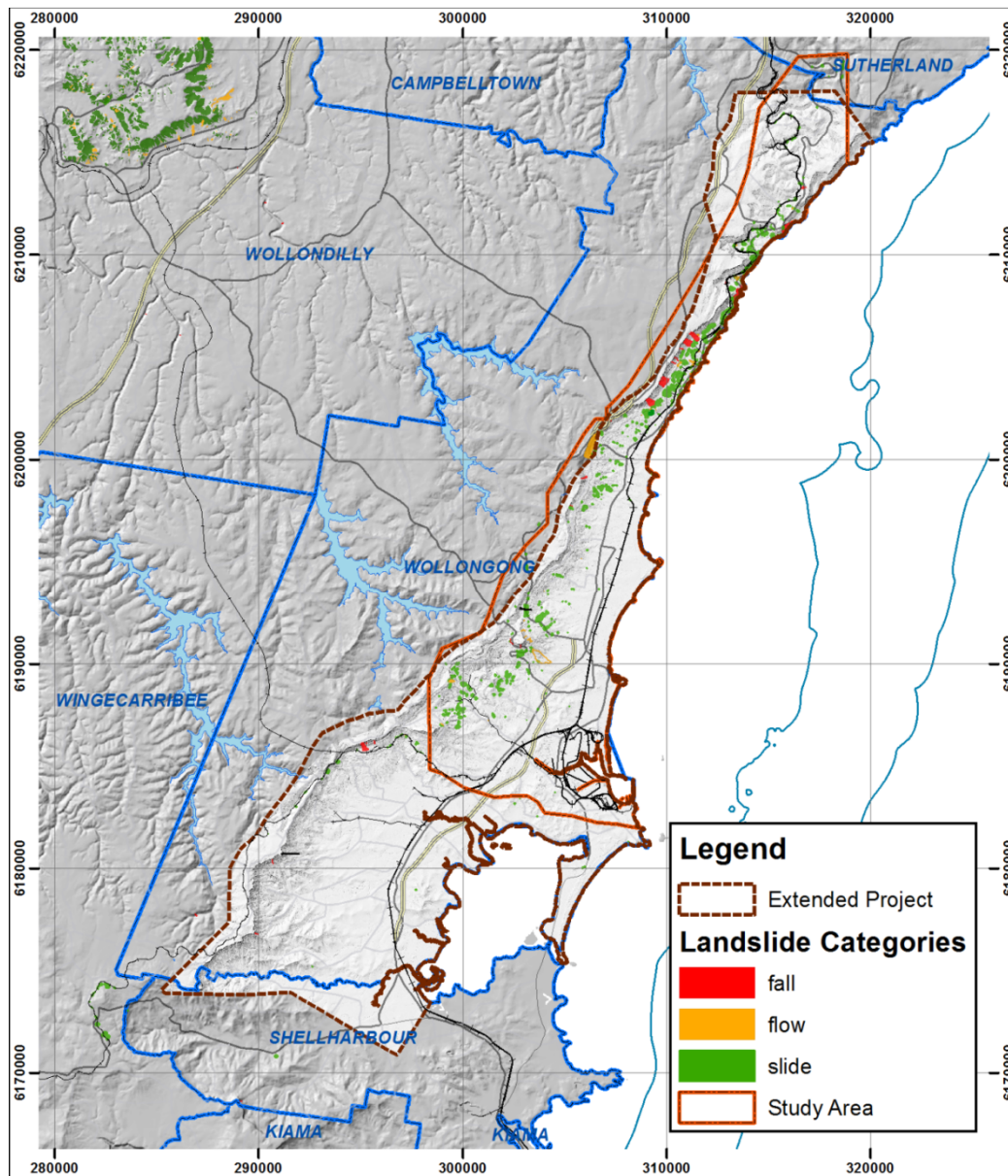


Figure 1. The Wollongong LGA and the Study Area and Extended Project Area with known landslides.

3 HAZARD ASSESSMENT - WOLLONGONG PROJECT

The 'Slide' category Susceptibility maps described in the previous papers have been enhanced with relative Susceptibility and relative Annual Likelihoods, additional detail regarding each landslide site and averages per zone such that they can be regarded as 'Slide' category Hazard maps as shown in Figure 2. The Susceptibility and Hazard zones have the same boundaries. On both the Susceptibility and Hazard maps, each landslide site is identified and labelled with its own unique Site Reference Code. On the Hazard Maps each landslide is also 'stack' labelled with its landslide volume below the SRC, the specific landslide frequency and 'profile' angle (see below) as shown in Figure 2. Landslide Frequency has been calculated from the total number of known recurrences at each landslide site. The specific landslide frequency for each landslide appears as the third label for each landslide. The average annual landslide frequency has been determined for all landslides within each Hazard Zone. The average distribution of landslide frequency between the years 1880 to 2006, and for the period 1950 to 2006 has also been determined. The later, shorter period is based on more complete data and is considered to be more reliable. Whilst discussing this method, Lee (2009) also highlights normalising data (as discussed below) and the complex nature of assessing landslide probability. The average landslide volume per zone has been determined with the GIS, based on the zone in which the central point of each landslide was located. The average landslide volume per zone is another descriptor for Hazard on this map as described in the previous papers.

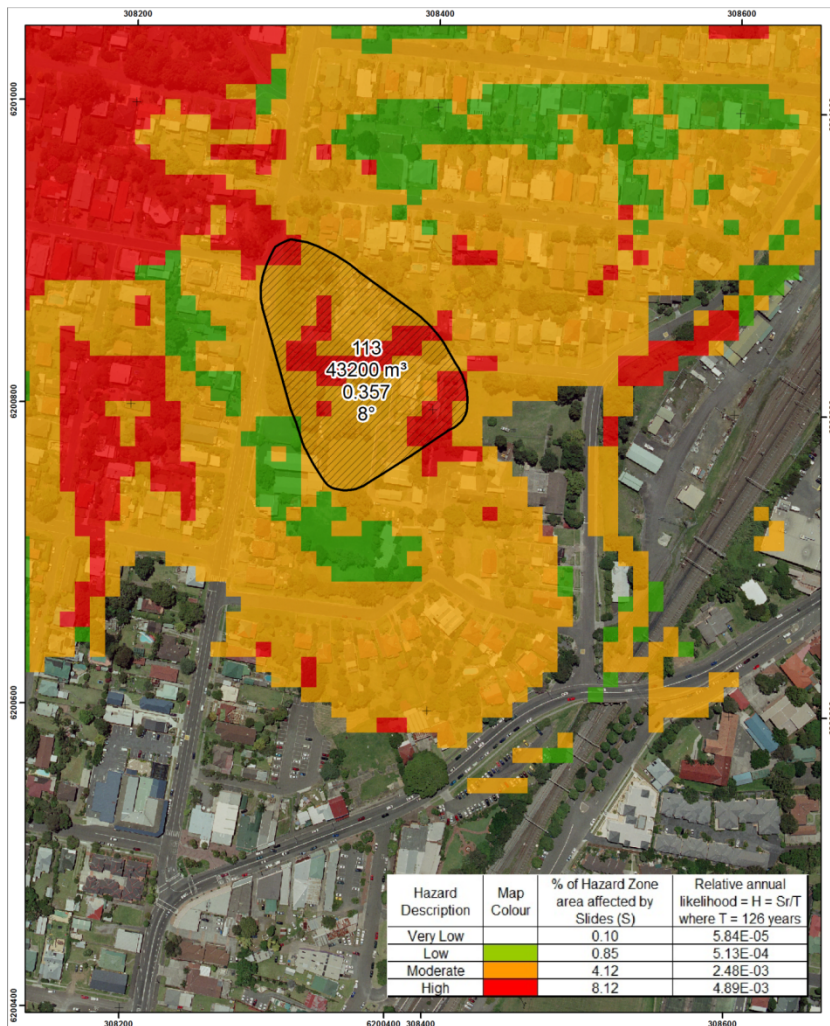


Figure 2. Wollongong City Council LGA map segment near Thirroul showing individual site labelling, 10m pixel Hazard Zoning and in the Table, the Hazard Zone annual Likelihood of landsliding (refer Table 1 and 2).

The relative annual likelihood of failure per hazard zone, estimated from the proportion of total landslides which occurred in each zone over a period of 126 years, are presented in Table 2. These values can be used, in the absence of any better information, as the Likelihood of 'slide' category landsliding within these Hazard zones. This is the main descriptor for each Hazard zone on this map. Once the identification of Susceptibility and Hazard

zones is achieved, various zone statistics and other numerical analyses can be developed. An interesting discussion on the Probability of Failure (based on the Relative Susceptibility of each zone), the Reliability Index and 'average slope' Factors of Safety derived from these zones is included in Chowdhury and Flentje, (2008 and 2011).

Table 2. Relative Annual Likelihood based on relative spatial % of each zone affected by slides.

Hazard Description	Map Colour	% of Hazard Zone area affected by Slides (S)	Zone area affected by slides (S/100)	Relative Susceptibility of each Zone = S_r where $S_r = (S/100)/\text{Sum}$	Relative annual likelihood = $H = S_r/T$ where $T = 126$ years
Very Low		0.10	0.001	7.36E-03	5.84E-05
Low		0.85	0.009	6.46E-02	5.13E-04
Moderate		4.12	0.041	3.12E-01	2.48E-03
High		8.12	0.081	6.16E-01	4.89E-03
			Sum = 0.132		

The 'profile angle' of each slide category landslide has been determined by digitising a point mid way along the rear main scarp and at the toe and querying the elevation at each of these points using a 2m DEM elevation grid. The profile angle of known landslides is considered important as it has implications for landslide mobility. It is also very useful to consider the distribution of the profile angles and this has been considered. The average 'profile angle' is 17°. The profile angle for each landslide is shown as the fourth label for each landslide (Figure 2).

4 FUTURE DEVELOPMENT OF THE WOLLONGONG PROJECT

The Wollongong work was largely completed in 2008 for the Study Area outlined with the solid boundary in Figure 1. Over the last decade, the Wollongong work has been based on a 10m DEM derived from 2m contours that were developed photogrammetrically in Oct 1976 by the NSW Central Mapping Authority. Wollongong City Council has since acquired a contemporary Airborne Laser Scan (ALS) point data set from several ALS data collection flights between 2005 and 2007. The LRT has developed a range of GIS-based DEM products from this ALS data set. The extent of this data is shown as the Extended Project area outlined with the dashed line in Figure 1. This new DEM area covers the entire escarpment area and slopes within the Wollongong Local Government Area. The LRT is now proceeding to extend the required data coverage to this wider project area, with the aim of producing Landslide Susceptibility and Hazard Zoning for the wider study area for falls, flows and slides by mid 2015. Hence, the current zoning may change and the extent will also be expanded.

5 PICTON AREA LANDSLIDE MAPPING AND SUSCEPTIBILITY MODELLING

Preliminary data from a 90 km² project area within the Wollondilly Local Government Area (partly covered in the top left corner of Figure 1) includes the development of a landslide inventory that contains to date in excess of 800 fall, slide and flow category landslides. One of the most striking features of the landscape is that slope instability affects entire hill slopes from ridge crests down to lower slopes of 11°. The inventory represents approximately 15% of the study area ground surface, whereas in the Wollongong project, the quite mature landslide inventory represents 1.5% of the ground surface. The work that is currently proceeding in this study area is most important in that this area is underlain by the Late Triassic Wianamatta Group. When considered together with the Wollongong Study area, the combined geological sequence is representative of the entire Sydney Basin geological sequence. This developing 'combined' Landslide Inventory coverage of the full geological sequence augers well for an improved Data Mining model of the entire Sydney Basin landslide susceptibility as is discussed below.

6 THE SYDNEY BASIN WIDE STUDY AREA AND DATASETS

To further investigate and validate the Data Mining methodology, it has been applied to the entire 31,000km² geological extent of the Sydney Basin region. This area is shown in Figure 3 and extends from Newcastle and Singleton in the north, west to Lithgow and south to Batemans Bay and includes, of course Sydney and Wollongong. The population of this area indicated by the 2006 Census was approximately 4.9 million people, representing approximately one quarter of the population of Australia.

The highest resolution Digital Elevation Model (DEM) coverage available to the UoW LRT in 2008 for this complete area was a 25m² pixel DEM. This DEM was generated from 10m NSW CMA contours derived

photogrammetrically during the 1970's. At 25m² pixel resolution, this involves a GIS-based raster grid of approximately 50 million pixels, notwithstanding that this is at a resolution significantly coarser than is preferable. Of course higher resolution DEMs are available for smaller areas, but the main requirement for this project, was complete coverage of the study area.

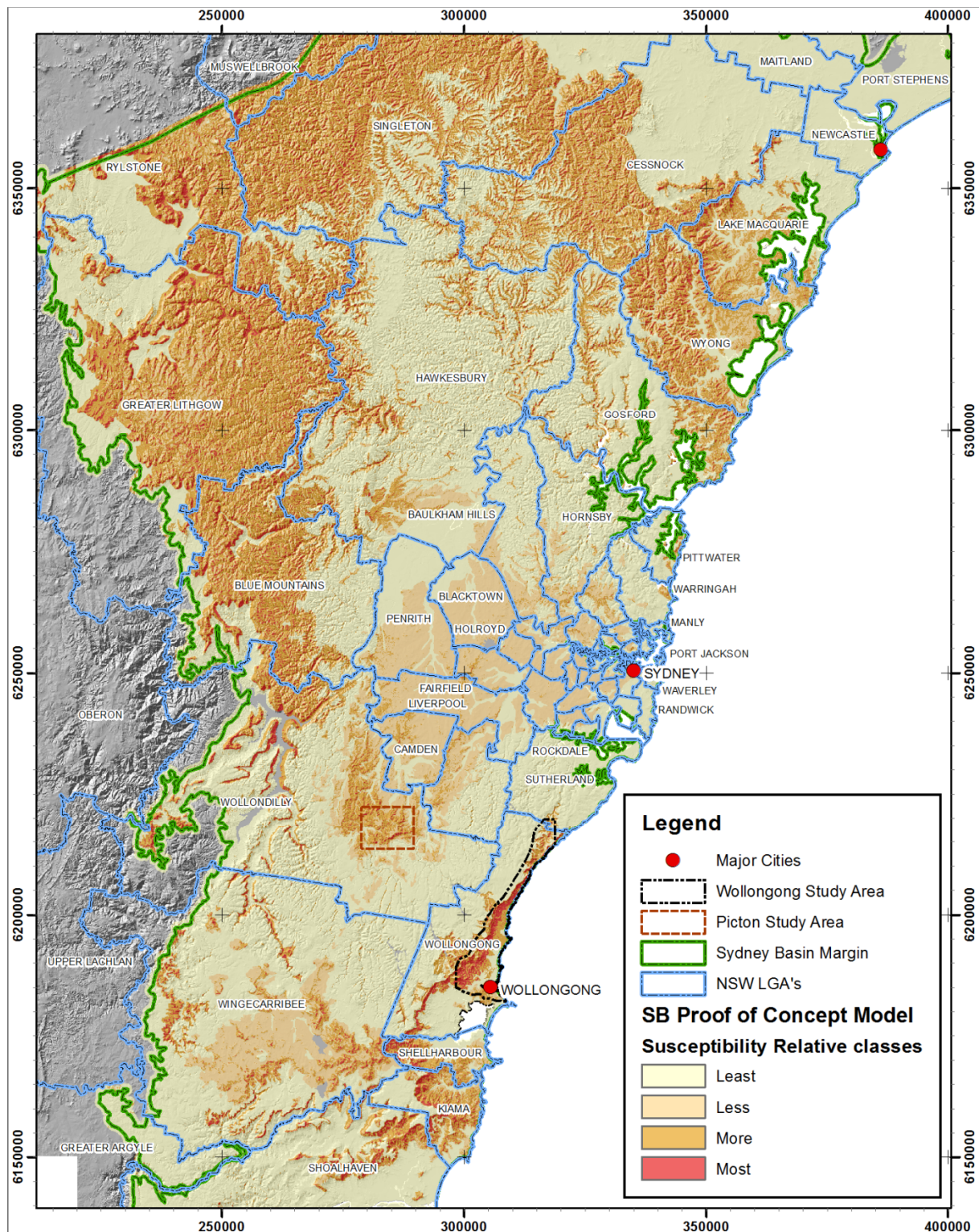


Figure 3. Proof of Concept Susceptibility Zoning for the entire Sydney Basin Region.

The same regional Landslide Inventory as used in the Wollongong Project complimented by the Geoscience Australia's (GA) National Landslide database (downloaded from the GA web portal) for additional coverage of the Sydney and Central Coast region, has been used to develop the Data Mining landslide 'training data set'. The GA

database is a point feature class whereas the UoW LRT LI is a polygon feature class. To upgrade the GA dataset, without having to undertake any field mapping, the landslide points were simply buffered with a 20m radius to create a 40m diameter circle, ensuring each landslide would represent at least one or more pixels on the 25m² pixel DEM. This combined inventory to date includes 575 'slide' and 'flow' category landslides within the geological extent of the Sydney Basin. In the preliminary model, rock falls have not been included. The 575 landslides are represented by 6293 pixels.

In addition to the base DEM and GIS-based Landslide Inventory, other GIS-based data sets have been generated by the GIS software (ESRI ArcGIS™ and IDRISI Taiga™) using the Digital Elevation Model. In total, eleven GIS-based data sets have been compiled. The data sets include:

- 25m² pixel Digital Elevation Model (DEM)
- Landslide Inventory
- NSW Department of Primary Industries 1:1,000,000 NSW statewide Geology (95 mapped geological formations contained within the Sydney Basin area)
- Slope Inclination (continuous floating point distribution)
- Slope aspect (continuous floating point distribution)
- Terrain Classification (IDRISI Taiga Toposhape integer)
- Curvature (continuous floating point distribution)
- Profile Curvature (continuous floating point distribution)
- Plan Curvature (continuous floating point distribution)
- Flow Accumulation (continuous integer)
- Wetness Index (continuous floating point distribution)

Whilst higher resolution data exists in regards geology, the prerequisite for this project was complete coverage of the study area. The only geological dataset to meet this criteria available to the UoW LRT in 2008 was the NSW Department of Primary Industries Geological Survey 1:1,000,000 NSW statewide geology. Whilst this dataset is a simplified compilation of 1:250,000 datasets, this scale (either) places serious constraints on the useability of the model output for any landslide zoning. Higher resolution geology datasets are available, with reduced coverage. One important issue with this dataset is the very poor edge matching with the 25m² DEM. To allow the model to run and not incorporate null data as a value in the output rulesets, the model area was defined as the area where both datasets exist. As a result, there are thin areas along the coastline and foreshore of Sydney Harbour, Broken Bay and the mid north coast Lakes with no zoning. Importantly, some of these areas require zoning. These are further reasons to place the label of 'Proof of Concept' on this modelling work to date.

7 PRELIMINARY SYDNEY BASIN WIDE SUSCEPTIBILITY ASSESSMENT

The Data Mining (DM) process as employed in the Wollongong Project has been described in detail in Flentje et al. (2007a) and the same process has been employed here for the Sydney Basin modeling. In summary for the Sydney Basin project this process includes; (1) the afore mentioned datasets are assembled into an ArcGIS Project, (2) create a point shapefile of the almost 50 million points based on the DEM and further reattribute this with a column of data representing every dataset listed above using an Intersect Point utility, (3) This point shapefile includes one column of data entitled landslides where all the 6293 pixels which represent the 575 landslides are designated as class 1. A similar number of randomly distributed non-landslide points (in this case 6068 points within the model area are designated as class 0 and all the remaining points are designated as class 2), (4) The point shapefile is exported as a text file for input into the C5 Data Mining software. The landslide class 0 (non landslide) and class 1 (landslide) data form the DM training data set. The confidence and other pruning parameters for this DM were systematically adjusted until an acceptable combination (or trade off) was reached between the accuracy (assessed from 10 way-cross validation) and rule set size. The training data is used to generate structured patterns (in the form of rule sets), and (5) the rule sets were used to establish the map algebra in Model Builder within ArcGIS to calculate the output susceptibility grid.

To date, this work has been completed to demonstrate the overall capability, without really having sufficiently high resolution datasets in place. Therefore, analysis of the model output to categorise and define Susceptibility Zones as per the AGS 2007a Guidelines Table 4 is not considered appropriate, yet. In place of such analysis, the Sydney Basin Susceptibility Zoning has been subjectively categorised as Most, More, Less and Least Susceptible. The model is shown in Figure 3. Despite not having an extensive inventory coverage or particularly

high resolution input data (25m² DEM and 1:250,000 scale geology datasets) quite a remarkable preliminary zoning outcome has been achieved over the study area. Having made this comment however, it is important to note that no field inspections or validation work of any type has been carried out to confirm the 25m² pixel modelling, other than the visual comparisons, one of which is shown below in Figure 4. The spatial details of the 10m² WCC LGA Susceptibility modelling have been reported above and are shown here on the right hand side of Figure 4. The 25m² pixel Sydney Basin modelling compares fairly well, albeit considerably more conservative, than the 10m² WCC LGA modelling. The relatively higher susceptibility zones (most, more and less) cover larger areas while the least susceptible zone covers a smaller area. For a simpler, broad brush style or first pass approach, this would serve to limit the areas for further investigation, whilst at least providing some direction to aid planning decisions in the interim period until higher resolution more focussed work can be carried out.

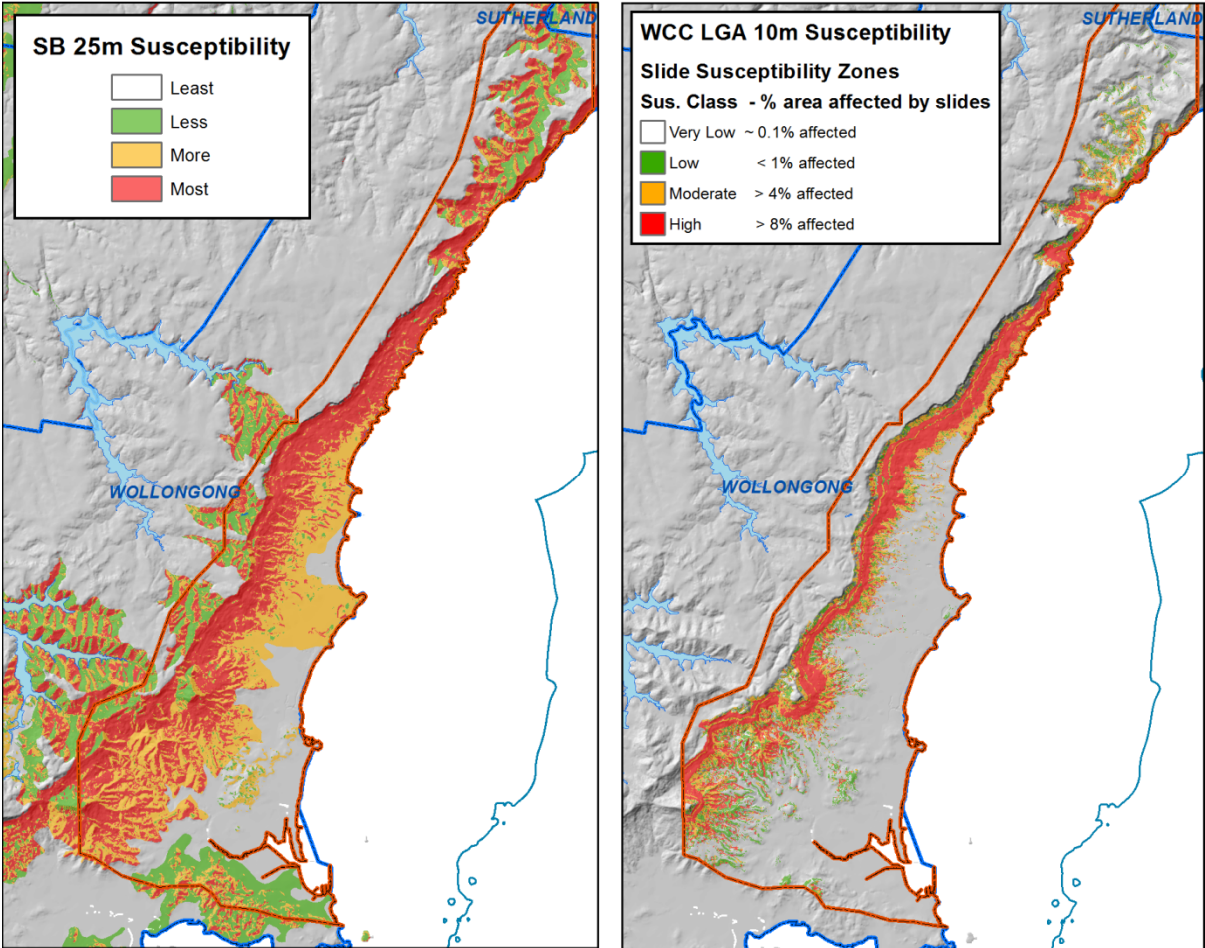


Figure 4. Comparison of the Susceptibility Zoning of the northern Wollongong LGA at 25m pixel resolution and the higher resolution 10m pixel resolution.

8 POTENTIAL DEVELOPMENT OF THE SYDNEY BASIN STUDY

This UoW LRT is trying to source funding to pursue this area of research. The main focus of future work relating to the Sydney Basin project will involve upgrades to the Landslide Inventory. Due to the state based focus of two of the UoW LRT Industry Partners, RTA and RailCorp (the other being Wollongong City Council), the focus of our Landslide Inventory is now NSW wide. Accordingly, over the next few years, the LI is set to be expanded with the inclusion of the current Wollondilly area project work, the 220 odd Pittwater National Disaster Mitigation Programme compiled failures and another 300 or so Southern Highlands/Blue Mountains and Newcastle region landslides. This upgrade will see the inventory grow to in excess of 2000 largely Sydney Basin landslides over the next few years, although this work must be carried out carefully and systematically.

The input geology data set can also readily be enhanced, and 1:100,000 scale ArcGIS compatible shapefiles have already been sourced, although they do not cover the entire Sydney Basin region. So, again enhanced resolution is already available with reduced coverage.

The base DEM is another data source where upgrades can be expected. ALS derived DEMs are becoming more and more common and hence these may be used to enhance both the modelling resolution and also the age of the DEM. An important research question 'what is the optimum resolution at which this modelling should be undertaken?' is quite valid and forms part of the LRT research direction in this field. Whilst there is no correct answer here, the answer lies in the balance between available resources (time, money, data etc) and the desired resolution of the output modelling.

9 RELATIVE REVIEW OF THESE ZONING PROJECTS AND WITH RESPECT TO AGS 2007

With the aid of GIS, it becomes quite simple to compare study areas numerically, as shown in Table 1. Clearly the project areas in Wollongong and the Wollondilly LGA's are relatively small compared with the enormity of the Sydney Basin Region. The relative amount of work that has been put into development of the respective Landslide Inventories of each area can clearly be seen both in the absolute landslide count per region, but even more clearly from the percentage of the Study Areas affected by landslides and the corresponding subjectively assessed 'completeness' of the landslide inventory coverage. The numbers reported as the percentage of the Study Areas affected by landslides (landslide density) highlights an interesting issue. Landslide density will become more often reported with the advent of landslide inventories and GIS-based data management. Clearly the density of landslides within the various study areas reported herein vary considerably, and at present there is no classification system to compare and contrast regions. A simple system is proposed here for discussion as shown in Table 3. On the basis of this proposed classification, for Wollongong, landslides would be considered common and for the Wollondilly study area landslides would be considered abundant. The Wollongong and Wollondilly study area landslide affected areas are considered to be near complete and represent quite realistic coverage's, based on well developed and mature landslide inventories, albeit for relatively small project based study areas. The Sydney Basin landslide inventory is incomplete and is readily acknowledged to include, at best, less than 1% of the total landslides within the study area.

Table 3. Proposed classification of Landslide density

Description	% of the Study Area affected by landslides
rare	< 0.01
occasional	0.01 - < 0.5
common	0.5 - 10
abundant	> 10

The AGS 2007a Guidelines provides two tables that recommend the type and level of zoning and map scales required for landslide zoning purposes (Table 1) and the levels of activity required for susceptibility, hazard and risk zoning purposes. The authors have classified the work undertaken in the projects discussed herein, as summarised in Table 4 below. The most relevant factors in this consideration are the scales of the data used in the modelling (landslide mapping, geology, dem pixel resolution etc) and the intended scale of use for the output zoning data (whether this is as GIS-based data, or in a map format) as this gets all too easily ignored or forgotten with GIS-based usage. In addition to all the challenges associated with the assessment of landslide probability, so well elucidated by Lee (2009), the importance of scale cannot be forgotten.

Table 4. AGS 2007a classification of the inventories and susceptibility zoning projects discussed in this paper.

LGA	Landslide Inventory level AGS 2007a Table 2	Susceptibility Zoning Level AGS 2007a Table 1	Intended Use Scale
Wollongong Study part of LGA	Sophisticated	Local Zoning Advisory	5,000
Picton area within Wollondilly	Sophisticated	Local Zoning Advisory	5,000
Sydney Basin	Not Applicable yet	Not Applicable yet	50,000 - 250,000

10 SUMMARY

Comprehensive, large scale regional GIS-based Landslide Inventories have been used with other GIS-based data and Data Mining techniques to develop transparent, entirely data-driven non-statistical Landslide Susceptibility and Hazard models. The modelling methodology is flexible, quantifiable and non-subjective and readily allows the generation of GIS-based map outputs, the scale of which are determined by input data alone.

The modelling technique is already being applied to other areas and at other scales within Australia (Miner, et. al, 2010). A preliminary 'Proof of Concept' model for the 31,000km² Sydney Basin area is also presented. It is important to note that for the susceptibility zoning, only landslide outlines and landslide classification is required, which simplifies the requirements of the landslide inventory for this level of mapping. The authors look forward to developing the Sydney Basin wide project and reporting more and detailed results of this at a later time. Over the next few years, as the GIS-based data sets are assembled and refined, the Landslide Inventory coverage is developed and refined with external assistance, we feel extremely confident that this wider area regional and now even national scale modelling will be successful. This type of regional modelling, at quite high resolution (large scale) given sufficient resolution input data, are likely to be suitable for use at Local Government Planning levels and or to assist decision makers to determine areas in need of further landslide investigations, as required by the guidelines published in AGS 2007. Furthermore, susceptibility modelling at a national scale to identify preliminary or 'first pass' binary type (i.e., in/out) areas for further assessment is also achievable in the very near future.

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