Digital Elevation Modelling for natural hazard risk assessment

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Introduction

The application of geographic information systems (GISs) to natural hazard risk management is a relatively new and emerging science. Coppock (1995) notes that GIS has made a contribution to various facets of natural hazard risk management since risk is a multi-dimensional and multi-disciplinary phenomenon, which have a spatial component, whatever their initial focus. Hence, the success of GIS implementation for natural hazard risk reduction can be contingent upon the availability of spatial data. The digital elevation model (DEM) is a key form of spatial data . A DEM is a spatially referenced continuous surface representing the topography of an area. A DEM surface may be represented by a grid, where each cell in the grid indicates a ground elevation. DEMs are usually stored as computer files and are key to most GIS spatial databases.

Ground elevations modelled by DEMs are important for a number of natural hazard risk management applications including flood inundation modelling (storm tide and riverine), landslide susceptibility modelling and bushfire risk mapping. Risk management personnel may not be directly responsible for DEM creation but may need to be familiar with the general concepts and key terms. Concepts include DEM *accuracy*, *resolution*, *spatial extent*, *currency* and *fitness-of-use*. Presenting the basic theory of DEM creation, and DEM characteristics may help risk managers understand and better utilise this important, and increasingly common, model of spatial data.

Spatial data issues associated with DEMs including error, accuracy, resolution and scale are also critical to other spatial data used in GIS-based natural hazard risk management. Data themes can include physical hazard zonations, building and lifeline databases, and census data. Examining these issues should also be a first step when organisations integrate GIS with risk management processes such as AS/NZS 4360 (1995). For example, the first stage of AS/NZS 4360 is titled 'Establishing the Context' and focuses on institutional issues surrounding the implementation of the standard. This stage is important since it identifies the aims, objectives and GIS modelling limitations of the project. Similarly, issues of error, accuracy, resolution, scale and spatial extent should be considered. DEMs are examined as a case-study of these issues.

Cairns in Far North Queensland is the study site, and reference is made to storm tide inundation modelling. Issues associated with riverine flooding are similar, and the general concepts are applicable to other natural hazard risk assessments. In Queensland, DEMs have recently been used for developing inundation evacuation plans, and therefore, issues of accuracy and error are critical for decision making. Issues to be discussed also include, DEM availability in Australia, surface interpolation procedures and DEM input data sources. Since risk results derived from DEMs are as accurate as the input data used to derive them, attention is given to DEM error assessment. End-users of DEMs perceive levels of accuracy in the elevation data that are optimistic. Exploratory spatial data error analysis is shown to be a critical aspect of DEM creation, and for determining the *fitness-of-use* of spatial data.

DEM components

A DEM is described by three components: the DEM resolution (grid cell), DEM accuracy, and DEM spatial extent (Figure 1). The spatial extent is a relatively simple concept describing the area on the ground that the DEM covers. The spatial extent is determined by the area of interest, and by the availability of input data sources such as contours or spot elevations. Grid resolution and grid error are the more complex components of a DEM. The grid resolution is similar to the minimum mapping unit concept common in cartography, and is the areal size of each grid cell in the DEM. Selecting an appropriate DEM cell resolution is a choice between adequate surface representation, the availability of input data, and the allowable DEM file size. Priority is given to maximising the DEMs ability to represent terrain variation for a modelling application since computing issues can be overcome with faster processors, and larger storage capacities.

DEM cell sizes range from 250 metres (where each cell represents an area of 250 x 250 metres on the ground) for continental/regional scale mapping, to 20 metres for more local mapping. Where the terrain is less homogenous, a smaller cell size is chosen. One guide for selecting a suitable DEM cell size is the desired level of modelling detail required. However, the areal density of the input topographic can also determine suitable cell sizes. A DEM is a model of a real world phenomenon and hence will contain inherent errors. Error is defined as the deviation of the modelled attribute from the true value. By definition, DEMs will always contain horizontal and vertical errors and this can undermine the results obtained from hazard risk models. For example, the vertical error in the DEM may be greater than a predicted inundation level. DEM vertical error is discussed in further detail as it has important implications for natural hazard risk modelling.

Commercially available DEMs

In Australia, DEMs that cover the entire country are rare. Such continental scale DEMs have accuracy's which make them unsuitable for many local scale hazard risk assessment projects. Of note is the Australian Surveying and Land Information Group (AUSLIG) 1:250,000 scale DEM (1/40 degree, 250 metre grid resolution) for all of Australia. The suitability of small to

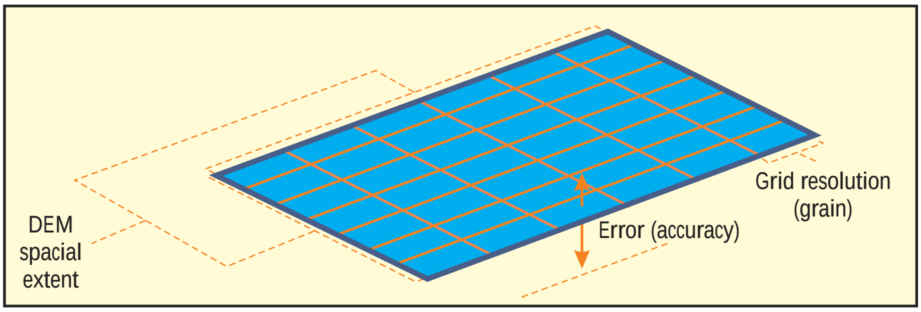

Figure 1: Key components for describing a DEM

medium continental scale DEMs (1:250,000) for storm tide risk management is discussed later in the paper. Since high vertical accuracy continental scale DEMs are not available, it is more common for DEMs to be created from local topographic data including topographic maps, spot elevations from survey control points, spot elevations from global positioning systems (GPS), levelling data from utilities including sewerage networks or road networks, spot elevations from orthophoto maps, existing digital elevation models and satellite image pairs that allow for elevation data extraction (e.g. SPOT images).

Digital contour and spot elevation data are commonly available from mapping agencies, such as AUSLIG, for most of Australia. The national coverage at larger scales (1:25,000) is far from complete. Other potential sources of elevation data include local government engineering departments; State geodesy, surveying or mapping agencies; State land management agencies; State utility management agencies; and private engineering consulting and surveying companies.

As GIS and spatial analysis becomes more common, it is likely that large scale DEMs will become available from private and public agencies. Risk managers can then avoid the costs and effort associated with primary elevation data capture by purchasing existing DEMs. A recent development that is useful for risk managers is the establishment of the Australian Spatial Data Directory, which provides a web-based interface to search for spatial data, including DEMs, in Australia.

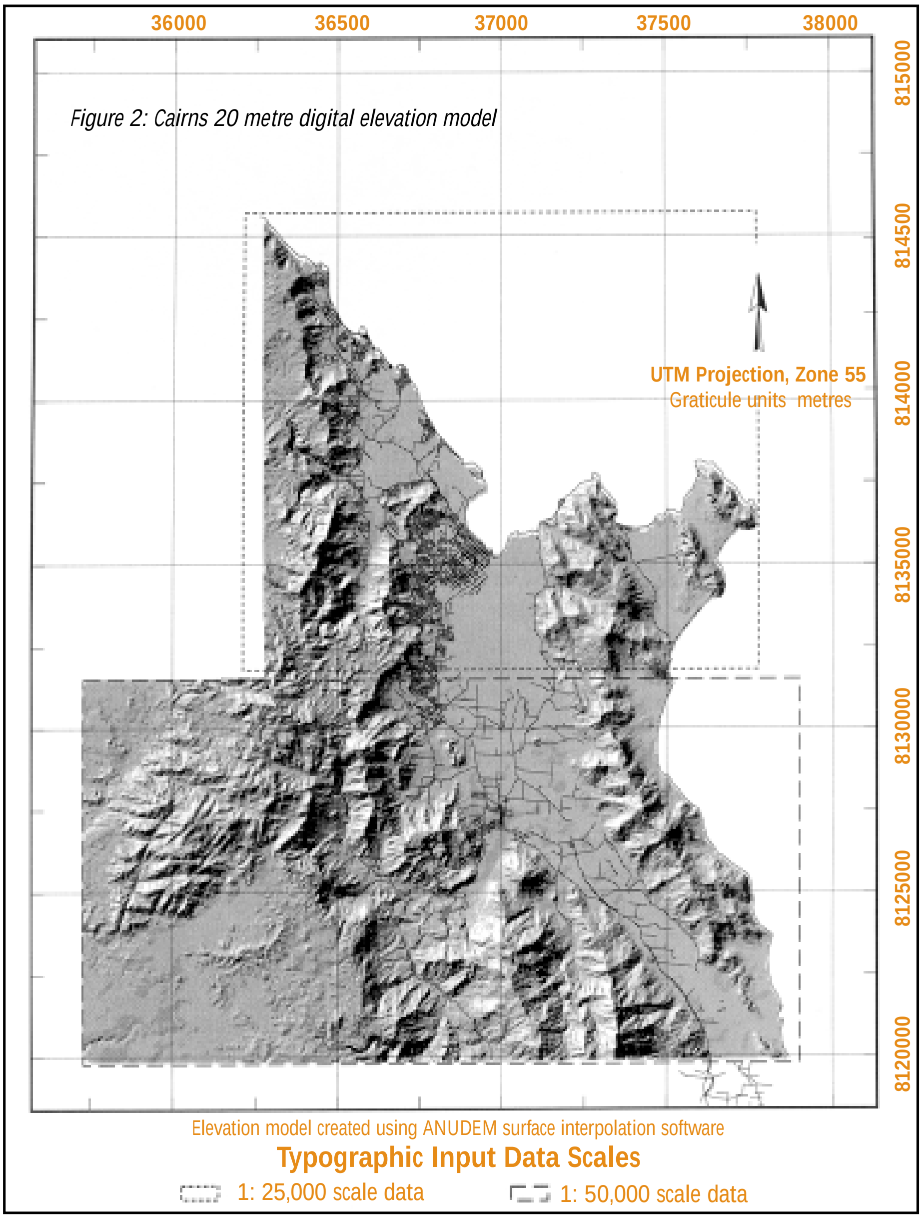

Figure 2: Cairns 20 metre digital elevation model

Creating DEMs from sparse elevation data

Since elevation data usually consist of discrete sample points such as contour lines or spot elevations, a DEM is created by interpolating these to regions without elevation data. A range of surface interpolation algorithms exist for transforming discrete elevation data (contours and spot elevations) to a continuous DEM surface. Algorithms include techniques such as weighted moving averages, bi-cubic splines, kriging, and finite elements (Carrara et al. 1997). More commonly, DEMs have been generated using Triangular Irregular Networks (TINs) from contour data within a commercial GIS such as ARC/INFO or Intergraph MGE.

Recently, commercial software designed specifically for elevation modelling, such as ANUDEM (Hutchinson 1996), has become available. The DEM creation process will be highly iterative, with a number of intermediate DEMs created before the final product is complete. For each successive DEM realisation, error assessment should verify DEM quality. Error assessment includes examining the number and location of data 'sink points', creating three dimensional plots to identify anomalous peaks or troughs, and comparison against known high accuracy control elevations. Since the process of DEM creation is fundamentally a technical issue, a detailed discussion is omitted here. Further discussion of DEM creation algorithms and procedures is available in Gao (1997). Of greater concern are the broader issues associated with DEM creation, use, and consequences for natural hazard risk management.

Input Elevation Data	*Scale*	*Source*
Contours (20 metre interval)	1:50,000	Dept. of Natural Resources
Contours (5m interval, 2.5m in low relief)	1:25,000	Dept. of Natural Resources
Spot elevations	1:50,000	Dept. of Natural Resources
Spot elevations	1:25,000	Dept. of Natural Resources
Stream networks	1:50,000	Dept. of Natural Resources
Stream networks	1:25,000	Dept. of Natural Resources
560 Permanent Survey Markers (PSM)	n/a	Cairns City Council

Table 1: Input data, scales, and data sources for the Cairns DEM

Cairns case study

Input data sources: DEM modelling

To illustrate the issues associated with DEMs, the objective was to develop the highest accuracy DEM possible for Cairns from existing elevation data. The DEM will be used for storm tide and riverine flood inundation modelling, and building damage assessment. Contour and spot elevation data was obtained from the Queensland Department of Natural Resources (DNR) in GIS format at two scales: 1:25,000 and 1:50,000. Commercial elevation data should always come with a data accuracy statement. The accuracy standard for the 1:25,000 scale data states that 90 % of the elevations are correct to within 5 metres. For the 1:50,000 scale data, 90 % of the elevations are correct to within 10 metres (i.e. half the contour interval).

These statistics are termed root mean square errors (RMSEs), and represent the average deviation from the true ground elevation. Stream networks were also included in the ANUDEM DEM interpolation since they provide a more accurate representation of hydrologic features. Both datasets were combined and the smaller scale (1:50,000) was treated as the minimum mapping scale for the entire region. Since DEM input data for Cairns was derived from common commercially available contour data, results and conclusions are applicable for other natural hazard risk management projects in Australia.

Elevation data pre-processing

Pre-processing included identifying spurious contour and spot elevations. Spurious elevations occur as a relic of the data capture process, including the digital conversion of paper maps to digital format. For instance, the misplacement of a decimal point on an elevation contour during manual digitising can introduce gross errors to the final DEM. Another example is the case of a Permanent Survey Marker (PSM) in Cairns located atop a five story building providing an elevation 20 metres greater than ground height. And finally, the presence of decimetre contours in the source contour data can cause problems. These elevations appeared as 25 metres in the final DEM resulting in incorrect elevations along the coast. Errors are visible when the DEM is plotted in the GIS. Errors are indicated as exaggerated 'peaks' and 'troughs' in the study domain.

DEM surface interpolation

ANUDEM surface interpolation software was used to create the final DEM from topographic data (*Table 1*). Further details of ANUDEM based elevation modelling are available in Hutchinson (1988, 1996). The final Cairns DEM is shown in *Figure 2*, shaded using analytical hill shading with 256 grey levels to accentuate the relief. 560 permanent survey mark (PSM) elevations were obtained from the Cairns City Council and were withheld from the DEM interpolation, to be used for DEM error assessment. *Figure 3* shows the elevation frequency histogram for the Cairns study area.

Map scale	Contour interval	Vertical accuracy	Provider
1:25 000	10 metre	5 metres	State Mapping Agencies
1:50 000	20 metre	10 metres	State Mapping Agencies
1:100 000	20 metre	10 metres	AUSLIG
1:250 000	50 metre	25 metres	AUSLIG

Table 2: Scale, contour interval, and accuracy for selected topographic maps

Vertical accuracy is valid for 90% of the area in areas of light to medium vegetation. Where dense vegetation is found the accuracy is less. These values are representative of most maps in each map series although some variation exists where limited data are available, in areas of low relief, and other special cases which are noted on each map.

DEM error – background

Although DEMs are critical to many natural hazard risk modelling applications, they contain inherent *source* and *processing* errors. Source errors are present in the input data, including the horizontal and vertical accuracy of contours or spot elevations. Processing errors are introduced at the interpolation stage where a continuous elevation surface is derived from discrete data (ANUDEM modelling for instance). DEM *accuracy* is the amount of error present in a DEM. Topographic maps commonly contain accuracy measures that vary depending on the scale of data capture (*Table 2*). Accuracy measures commonly used for spatial data include root mean square errors (RMSE) (Sasowsky et al. 1992), epsilon bands (Dunn et al. 1990), probability surfaces (Lowell 1992), and classification error matrices (Walsh et al. 1987; Veregin 1995).

RMSE statistics are the most common measures of vertical accuracy in topographic data. An RMSE statistic is a summary for the average vertical error in the entire DEM. Sub-centimetre accuracy PSM points are used to obtain RMSE statistics for the Cairns DEM. The elevation at each PSM is compared against the elevation found at the same location in the DEM, absolute differences are obtained, and frequency histograms, and cumulative frequency histograms plotted to show the *global* error for a DEM. The mean of these values is the RMSE estimate or *standard error* for the DEM. The cumulative frequency histogram provides a *confidence interval* for DEM error. The term *global* means that the error measure is for the entire DEM. This is critical because DEM error may vary throughout the study area. For example, vertical errors are usually greater in mountainous terrain. DEM accuracies such as those shown in *Table 2* are conservative estimates, and may be of limited use to risk managers. Therefore a detailed error assessment as presented below should be used.

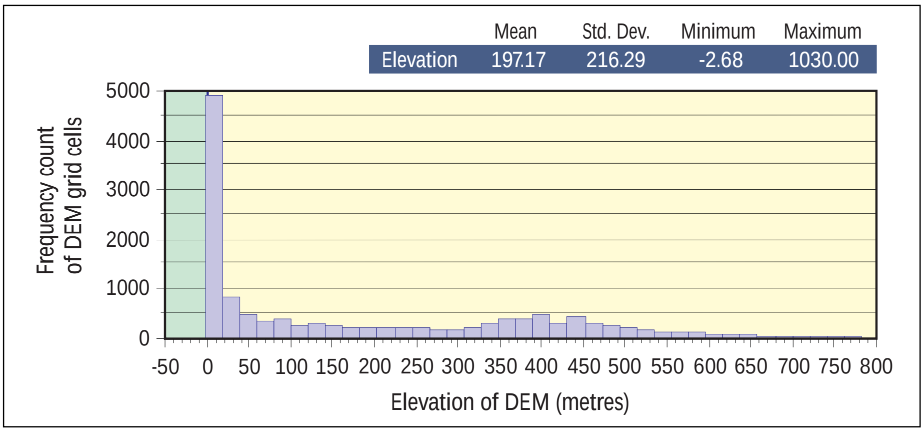

Figure 3: Frequency histogram and statistics for all grid cells in the Cairns 20 metre DEM

DEM error results

Figure 4 shows the error frequency histogram, and cumulative frequency histogram, for the vertical difference between the PSM elevations and the final 20 metre grid cell resolution Cairns DEM based on 1:25,000 scale contour and spot elevations. The RMSE statistic states that elevations in the DEM are correct on average to within 1.98 metres. At the 90% confidence interval the elevations are correct to within 4.5 metres 90 % of the time. This is a 0.5 metre improvement over the published accuracy standard of 5 metres accuracy, 90 % of the time. RMSE statistics indicate that interpolated DEM elevations deviate from the 'truth', indicating that source errors exist as a relic of the scale of data capture. A closer approximation of the PSM elevations would be impossible with topographic data captured at this scale (1:25,000). Risk managers need to ask 'what implications does this have for risk modelling?'

Risk managers should consider the study domain closely. In Cairns, the elevation range of occupied buildings has important implications for DEM error assessment, and hence for inundation modelling. For example, global error estimates (RMSE statistics) and confidence interval errors based on the entire DEM may not be relevant since occupied buildings are distributed in the lower elevations. The following section examines the variation of elevation error within the Cairns study site.

Spatial variation of error

The Cairns DEM was partitioned into three elevation zones in the ranges 0 to 2.5, 2.5 to 5, and 5 to 10 metres, and RMSE statis-

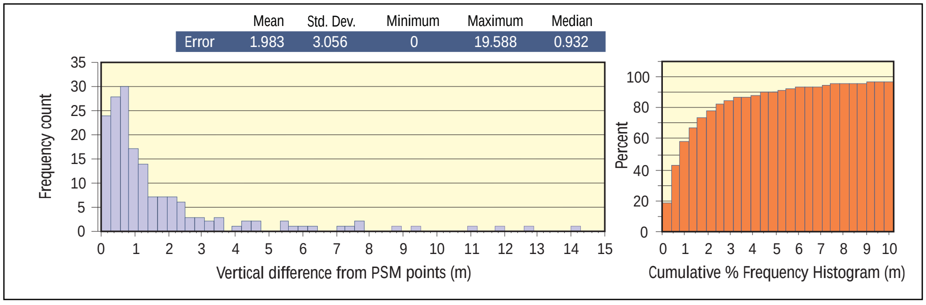

Figure 4: Error frequency histograms and cumulative frequency histogram for 20 metre Cairns DEM. Histograms show the difference between observed elevations in the DEM and elevations from PSM points.

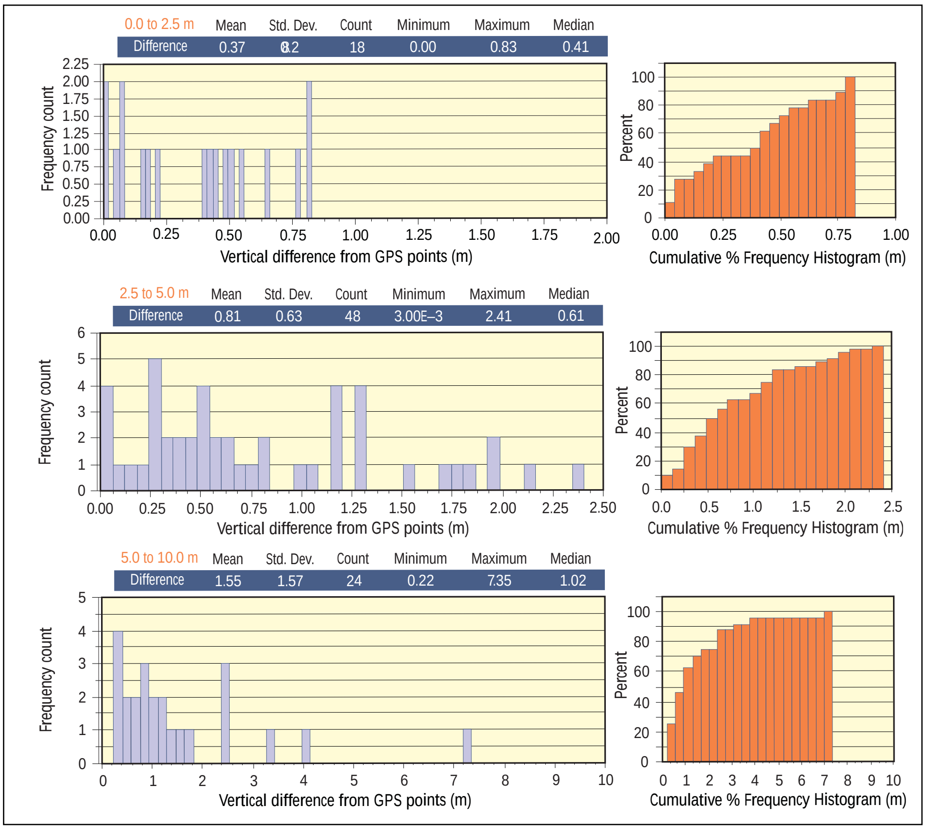

Figure 5 (a, b, c): Error frequency histograms for varying elevation zones in Cairns.

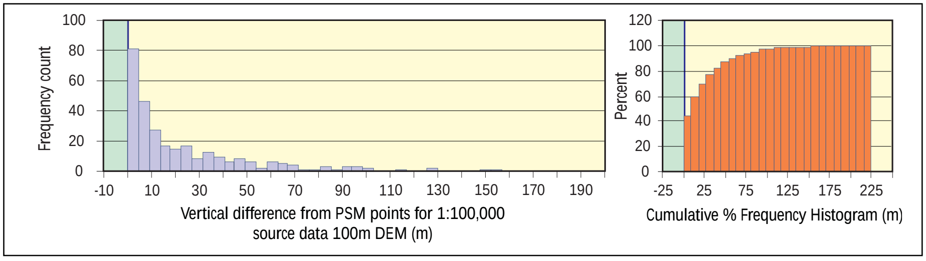

Figure 6: Error frequency histogram for 100 metre Cairns DEM.

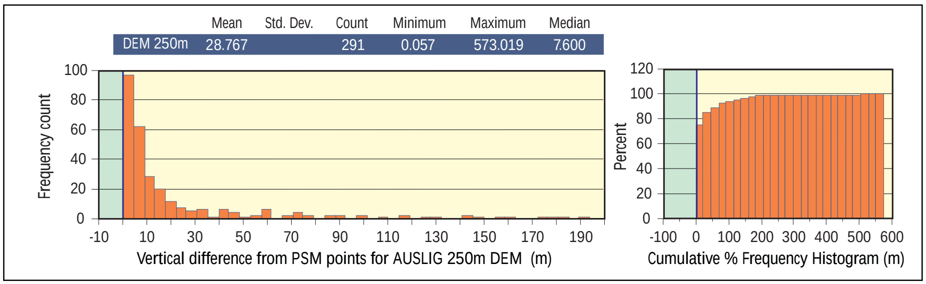

Figure 7: Error frequency histogram for 250 metre Cairns DEM.

tics calculated for each zone. This is significant for Cairns since most buildings are located on elevations less than 5 metres, and hence global RMSE statistics may be irrelevant for a hazard risk assessment such, as storm tide inundation. *Figure 5* shows error histograms for these three elevation zones. The RMSE is 0.37 metres, 0.81 metres, and 1.55 metres for each elevation zone, respectively. An approximate doubling of error is observed as the elevations become higher. Therefore, the DEM is more accurate in flat terrain and less accurate in higher relief regions which has important implications when urbanisation patterns are considered in Australia.

For flood inundation risk assessment, the spatial pattern of DEM error has important implications for evacuation planning. The concern is that DEM RMSE may vary through the study domain, making evacuation zones difficult to define. Results have shown that DEM error does vary spatially but within the areas of interest, or where people live, it remains relatively constant. Evacuation zones based on elevation can be used to prioritise regions to be evacuated. Therefore the Cairns DEM is suitable for developing flood inundation 'relative risk' zones.

Cumulative frequency histograms and summary statistics showing the variation in DEM error for varying elevation zones for the 20 metre Cairns DEM are also shown. Error results are shown for 3 elevation zones: *0–2.5, 2.5–5.0 and 5.0–10.0 metres (GPS points = PSM points).*

Alternate topographic data for elevation modelling.

The objective of elevation modelling is to create the highest accuracy DEM possible, from existing contour and spot elevation data. The previous discussion examined the error associated with elevation data in Cairns and the implications for risk modelling. For other areas in Australia, topographic data may not be commercially available, and existing smaller scale, and less vertically accurate data may provide a solution. This section examines the error associated with applying smaller scale, commercially available, topographic data for risk modelling. Two small scale, and less vertically accurate, topographic data sources are compared against existing fine scale, high accuracy DEMs. These data are representative of the scale and accuracy of commercially available topographic data in Australia. The first is a 100 metre grid resolution DEM developed using ANUDEM from spot elevations and stream networks derived from AUSLIG 1:100,000 scale topographic maps. The second is a continental wide, 250 metre grid resolution DEM which is commercially available through AUSLIG. The 250 metre Australian continental wide DEM has been developed from input date listed below.

- Bureau of Mineral Resources ground survey points (7 metre RMSE).
- Trigonometric Points (1 metre RMSE).
- 1:2,500,00 and 1:250,000 scale stream networks.
- 1:250,000 scale sink points (10 metre RMSE).

The methodology applied in Section 5.5 was used to quantify the error in these DEMs for Cairns. Figure 6 & 7 show error histograms for both small scale DEMs for Cairns. The 100 metre grid cell resolution DEM is accurate to within 75 metres, 90 % of the time. The 250 metre grid cell resolution DEM is accurate to within 100 metres 90 % of the time. The RMSE for the 100 metre grid cell DEM is 24.6 metres, and a higher 28.7 metres for the 250 metre DEM. Results also show that there is difference between standard error accuracy measures (RMSEs) and accuracy's based on confidence intervals. Hence, risk managers should be aware of these differences. The final error estimate for the 20 metre Cairns DEM found that 90 % of the elevations are correct to within 4.5 metres. Large RMSEs for the small scale DEMs make them unsuitable for local scale natural hazard inundation modelling. 1:50,000 scale topographic data are the minimum scale required, but preferably 1:25,000 scale data, or larger, should be used. This rule may vary in areas of high relief, or where less input data is available.

Conclusion

The exploratory spatial data analysis has identified the error that can be expected from commercially available elevation data in Australia. If resources allow, high accuracy DEMs can be built from high vertical accuracy spot elevations and contours. The latest generation of commercial satellite imagery can be obtained as overlapping pairs which can be used for elevation modelling, although costs can be prohibitive. For natural hazard risk assessment, end-users should first determine the *fitness-of-use* of any DEM for their application. A bushfire risk mapping project may have a lesser need for high accuracy elevation data, than a flood mitigation cost-benefit analysis. Agencies charged with national risk management assessments such as climate modelling, may find continental scale DEMs adequate for risk assessment. Regardless of the risk modelling application, guidelines will be useful for any applications that utilise DEMs for natural hazard risk management. The guidelines are listed below.

- Risk managers should identify the level of accuracy required of the DEM before creating or purchasing them. A user needs assessment can detail the spatial extent of the required DEM and its other characteristics (cell size, accuracy).
- Where possible, risk managers should attempt to use existing DEMs that may be obtained from private companies, government agencies, or local councils.
- When DEMs are obtained, risk managers should receive detailed metadata. Metadata are information about data. The Australian New Zealand Land Information Council (ANZLIC) has recently drafted metadata guidelines for the use and transfer of spatial data. Metadata defines the features and lineage of spatial data, including the scale, accuracy and source of the input data, date of last update, and data custodianship. Some organisations have already implemented this standard for their spatial data management. Further information is available at http://www.anzlic.org.au/index.html. The guidelines are useful because they summarise the key issues risk managers should consider when purchasing and using spatial data.
- A DEM error statement should accompany any DEM. The error statement will provide a global estimate of vertical accuracy, commonly as an RMSE statistic. The error statement should note whether it is a standard error (RMSE) or an accuracy based on a confidence interval (i.e. 90 % of the time). This difference can result in different error statements. Error statements for DEMs are commonly omitted, and can lead end users to assumptions of elevation accuracy that are false.
- If global error estimates are inadequate —for example for a very large study site with large terrain variations—a detailed error assessment may be necessary. High accuracy PSM control points for the study site can be compared against the DEM. An error assessment can provide risk managers with an indication of the suitability of a DEM.
- DEM users are commonly concerned with DEM grid cell resolution. DEM vertical accuracy is a better indicator of DEM suitability, particularly in flat coastal areas where the terrain is relatively homogenous.

The limitations associated with DEMs are common to other spatial data in a GIS. The problems of accuracy, error and fitness-of-use, ultimately stem from the desire to adapt data which was designed originally for analogue cartography. Often, such data are adapted for modelling applications beyond the scope of their original purpose. This is a major reason for some of the limitations outlined, and risk managers need to be aware of these. Secondly, risk managers can influence the processes developing national, state, and local government spatial data specifications and standards so as to better accommodate natural hazard risk management, and risk modelling requirements.

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