University of Southern Queensland

Faculty of Health, Engineering and Sciences

LiDAR Data for DEM Generation and Flood Plain Mapping

A dissertation submitted by

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Abstract

High-resolution Digital Elevation Model (DEM) is a key spatial dataset for flood plain mapping and catchment management. On the 10th of January 2011, heavy rainfall caused flash flooding through Toowoomba city and central business district resulting in loss of life and significant damage to public and private property. Effective flash flood forecasting is a big challenge that requires accurate catchment spatial information. Much research has been undertaken on the use of airborne LiDAR data to generate high-resolution DEM.

The aim of this report is to determine the suitability of using airborne LiDAR data for flood plain mapping and catchment management. Airborne LiDAR data will be used to generate a high resolution DEM for a section of West Creek, part of the Gowrie Creek catchment, Toowoomba, Queensland. Accuracy of this high-resolution DEM was verified using GPS survey equipment to gather point data over the study area. Flood zone, inundation depth and water volume was extracted from the LiDAR derived DEM for flood surface levels indicative of the 2011 floods. These datasets were verified using the GPD derived DEM.

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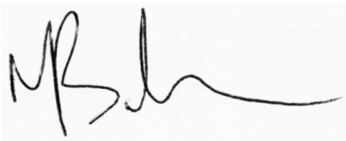

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Chapter 1 – Introduction

1.1 Introduction

Around lunch time on Monday the 10th of January 2011, without warning, intense rainfall over the Gowrie Creek Catchment caused severe flash flooding through the Toowoomba CBD (Central Business District) resulting in loss of life and great damage to property. Heavy rainfall lasted not much longer than an hour and flood waters peaked only 1.5 to 2 hours after the rainfall began giving little warning time. Accurate flash flood forecasting for specific locations is challenging but necessary for the design of flood mitigation measures to avoid repeats of the damage explained above.

Figure 1 Flooded Toowoomba CBD [Source: Sydney Morning Herald]

High-resolution digital elevation model (DEM) is an important data set for catchment management and flood plain mapping. The DEM is the base dataset for many outputs used for flood plain mapping and flood modelling. Therefore the accuracy of the DEM has direct influence on these output models. Airborne light detection and ranging (LiDAR) can capture data to generate DEMs in short amount of time in comparison to traditional GPS and ground survey methods. Therefore there is great potential for airborne LiDAR data to provide accurate data across large areas of catchments that can be useful for accurate flash flood prediction.

1.2 Aim of this Research

The aim of this research is to determine the suitability of airborne LiDAR data for high-resolution DEM generation and flood plain mapping. LiDAR output will be verified using GPS. This aim is broken into the following research objectives:

a) Use airborne LiDAR point data to generate a high resolution DEM over specified study area.
b) Verify accuracy of LiDAR generated DEM by GPS data acquisition.
c) Use LiDAR generated high-resolution DEM to delineate flood zone for typical flash flood water levels.
d) Verify accuracy of flood zone delineation by GPS.
e) Use LiDAR generated high-resolution DEM for flood inundation depth and water volume calculations.
f) Verify flood inundation depth and water volume by GPS.

1.3 Expected Benefits

There are a number of perceived benefits from the research. Firstly, this research will compliment other studies in assessing error of airborne LiDAR data. This will increase awareness of the performance of LiDAR over different terrain and thereby help others assess whether an application would benefit from airborne LiDAR, as potential users understand its capabilities and limitations. Secondly, this research will be of benefit in understanding the potential of airborne LiDAR data for use in flood plain mapping and catchment management. LiDAR has the ability to provide large amounts of data relatively quickly when compared to traditional ground survey methods. Being able to use airborne LiDAR data for these applications would be of great benefit in the increase of accurate spatial data over catchment areas resulting in increased accuracies for flood modelling and catchment management.

1.4 Dissertation Overview

This dissertation contains five main chapters. These chapters are given a brief description below:

Chapter 1 Introduction – Gives an introduction to the topic of research. The aims of the research are provided. Background information regarding the topic is discussed as well as perceived benefits of the research.

Chapter 2 Literature Review – Provides a summary of the literature review undertaken for this dissertation. It is broken into three topic areas; flood plain mapping, LiDAR technology and DEM generation and accuracy.

Chapter 3 Methodology – This chapter discusses the methods used to fulfil the aims of the research. Discussion is included regarding the study area, data acquisition, DEM generation and analysis, flood zone delineation and flood inundation depth and volume analysis.

Chapter 4 Results and Discussion – Provides output data from the methodology and discussion of prevalent trends and relationships between airborne LiDAR accuracy and high-resolution DEM applications in flood plain mapping.

Chapter 5 – Provides a conclusion to the dissertation

Chapter 2 – Literature Review

2.1 Introduction

A literature review was undertaken in regard to three key areas consisting of, flood plain mapping, LiDAR technology and DEM generation and accuracy. This chapter aims to give insight into previous research and findings in this area as well as explaining some key concepts of this area of study.

2.2 Flood plain mapping

Flood plain mapping involves the formation of a number of models for analysis and management such as topographic surface models, two-dimensional hydraulic surface flow models and thematic land cover maps (Hollaus, et al., 2005). The DEM and its derived parameters such as slope, aspect and drainage network forms the base input data for these models and therefore the accuracy of the input DEM will have direct influences on the output models. Increased accuracy of the input DEM is crucial in minimizing the uncertainties of flood modeling and simulation results (Hollaus, et al., 2005).

McDougall, et al. (2008) reports on the accuracy requirements of DEMs for catchment management. Coverage and accuracy requirements for different applications of catchment management were determined in 2007 by a workshop of 18 participants representing key stakeholders, for Queensland. The coverage and accuracy requirements for the application of "Disaster planning and management (flood and fire)" is defined as +/-1m. However, other applications that may be applicable to flash flood prediction have coverage accuracy requirements of <0.5m including, "Hydrological modelling", "Insurance risk and assessment" and "Land and water management plans" (McDougall, et al., 2008).

A key application of flood plain mapping is the estimation of flood damage. Various hydrological factors affect the magnitude of flood damage including flood extent, inundation depth, flow velocity, duration and timing of the flood (Moel and Aerts, 2010). For flood damages, inundation depth is regarded as the most important parameter (Merz et al., 2007; Wind et al., 1999). However, flood extent and flood depth are usually calculated for a flood event with a specific return period (de Moel et al., 2009). Moel and Aerts (2010) conducted research into the effects of uncertainty in land use, damage models and inundation depth on flood damage estimates. Results of the research indicate that when an uncertainty of 250 cm is assumed for inundation depth, a total uncertainty surrounding the final damage estimate in the case study area can vary up to a factor 5-6. In other words, the lowest estimate for flood damage is 5-6 times lower than the highest estimate of damage (Moel and Aerts, 2010). Accuracy of inundation depth is clearly critical in estimating flood damage.

2.3 LiDAR technology

LiDAR, also referred to as airborne laser scanning, light detection and ranging, or laser altimetry, is an active remote sensing technique, which was originally designed to measure the topography of the Earth's surface (Hollaus, et al., 2005). A laser emits short infrared pulses towards the Earth's surface and a photodiode measures the backscattered echoes (Hollaus, et al., 2005). LiDAR technology has been studied for a considerable time period since as early as the 1960's and continues to be an area of active research and development (Flood, 2001). Though airborne LiDAR data has been commercially in use since the mid 1990's it is still developing rapidly in regards to sensor technology and data processing. Developments in LiDAR technology allow high-density point data to be captured for more affordable prices. High-density point data allows terrain to be represented in much detail (Liu, 2008). As a result of these developments LiDAR data has become a major source of digital terrain information for a variety of applications including hydraulic modelling and flood plain mapping (Raber, et al., 2007).

Through the initial years of extensive LiDAR use (1995-2000) the accuracy of airborne LiDAR data was generally known and was routinely quoted by aerospace companies as 15cm (Hodgson and Bresnahan, 2004). In order to empirically assess airborne LiDAR data, Hodgson and Bresnahan (2004) performed a study on the accuracy of airborne LiDAR-derived elevations. As oppose to testing elevations interpolated by a DEM, this study validated LiDAR data by locating the x-y coordinates of LiDAR points and taking measurements at these points with either GPS or total station survey technology.

Elevation error of LiDAR was shown to be the function of a number of variables including LiDAR system measurements, horizontal displacement, interpolation error and surveyor error. Analysis of elevation error was undertaken across a number of land cover and grade classes. The results of the study show that elevation root mean square errors for LiDAR data were 17 to 26 cm. The highest errors were shown to occur over steep land as the horizontal error in this land type introduced further elevation error. LiDAR measurement over land of steep slopes with grades approximately 25 degrees were shown to contain elevation errors twice as large as data collected over slopes of 1.5 degrees. Errors over flat surfaces, even forested ones, were shown to be very low compared to other sources of digital elevation data such as photogrammetry (Hodgson and Bresnahan, 2004).

There have been a number of other studies that assess the accuracy of LiDAR derived elevations for various study areas. Adams and Chandler (2002) found a LiDAR derived elevation accuracy of 26 cm and found improved results over sloping terrain compared to DEMs derived from digital photogrammetry. Bowen and Waltermine (2002) found an overall elevation accuracy of 43 cm. Cobby et al. (2000) found an LiDAR elevation accuracy of 17 cm for data gathered over grass and cereal crop land cover.

2.4 DEM generation and accuracy

Liu (2008) provides a study into the effective processing of raw LiDAR data and the generation of high resolution DEM. Methods regarding DEM generation, LiDAR data reduction, LiDAR data filters, and interpolation are discussed. These will be of great importance to the aims of this report as reducing redundant information and generating an accurate DEM efficiently is of importance. Liu (2008) concludes that the filtering of ground and non-ground data is the most critical step in generation of an accurate DEM from LiDAR data. Also of worth is the extraction and inclusion of critical elements, such as breaklines, in maintaining accuracy without excessive redundancies (Liu, 2008).

Airborne LiDAR measures backscattered signals from any surface. Many of these surfaces are not bare earth readings, but rather tops of buildings, trees or other vegetation. While these non-ground points have use in applications of forestry or land use studies, they introduce significant errors into a DEM if not filtered. Dowman and Fischer (2001) conducted research into the elevation errors of airborne LiDAR derived DEM using multiple returns. These authors found significant errors of up to 4m RMSE over flat ground when no filtering was applied (Downman and Fischer, 2001). Zhang, et al. (2003) provides a study on a progressive morphological filter to remove non-ground points from airborne LiDAR data. The filter is developed and tested on mountainous and flat urbanized areas with apparent success. An effective and accurate method of removing non-ground data from LiDAR data is critical in generation accurate high resolution DEMs (Zhang, et al., 2003).

Liu and Zhang (2010) provide a study into the automated delineation of drainage networks from high resolution DEM. As the drainage network is one of main factors in flood prediction, accurate means of extracting it are paramount. Liu and Zhang (2010) assess existing methods for drainage network extraction and focus on extraction using the Arc Hydro extension of ArcGIS with different threshold limits (the minimum upstream drainage area). The study concludes with the evidence that high resolution DEMs are required for detailed drainage networks as they can provide adequate data for drainage network extraction using smaller threshold values.

Assessing the accuracy of LiDAR derived DEM is a key outcome of this research project. A commonly accepted method to perform an empirical assessment of LiDAR generated DEM accuracy is to use the root mean square error (RMSE) statistic based on survey spot levels (Raber et al., 2007). The RMSE formula is as follows:

$$RMSE_{LiDAR\ Observations} = \sqrt{\frac{\Sigma(Z_{LiDAR} - Z_{Survey})^2}{n}}$$

Where:

Z_{LiDAR} = Elevation of LiDAR point (m)

Z_{Survey} = Elevation of surveyed point (m)

n = number of points surveyed

The RMSE value provides a tangible and realistic estimate of errors most likely to be encountered for LiDAR observations. This will be used in analysing the elevation errors of airborne LiDAR generated high resolution DEM.

2.5 Conclusion

This chapter has discussed key concepts of the study area as well as reviewing research and findings of relevant literature. Flood plain mapping was the first topic researched. Data requirements for flood plain mapping were identified and the importance of an accurate DEM was noted as many output models are based of this key data set. Accuracy requirements of DEMs for flood plain mapping were defined and the application of flood plain mapping in regards to damage estimates was discussed. Secondly, LiDAR technology was researched. Background information on this technology was provided including history of use and expected error sources. Thirdly, DEM generation and accuracy was researched. Research regarding filtering of non-ground points and accurate DEM generation was presented. Use of DEM for flood plain modelling was discussed as well as statistical methods to analyse DEM elevation accuracy.

Chapter 3 – Methodology

3.1 Introduction

This chapter will present the different stages of planning, resources, data acquisition, data processing and analysis in order to meet the aims of the research. It will cover:

- Study Area
- Data Acquisition
- DEM Generation
- Validation of GPS Data Acquisition
- Elevation Accuracy of Airborne LiDAR Derived DEM
- Flood Zone Delineation
- Flood Inundation Depth and Volume

3.2 Study Area

The study area selected was an approximately 9.5ha section of West Creek, Toowoomba, which forms part of the Gowrie Creek catchment. The area consisted largely of undulating grassland of varying grades. The area consisted of features of interest such as tree cover of varying thickness, sharp changes in grade in form of retaining walls, areas of low scrub/long grass and four detention ponds. This study area was chosen as a typical example of an urban catchment area and also because of the varying land covers.

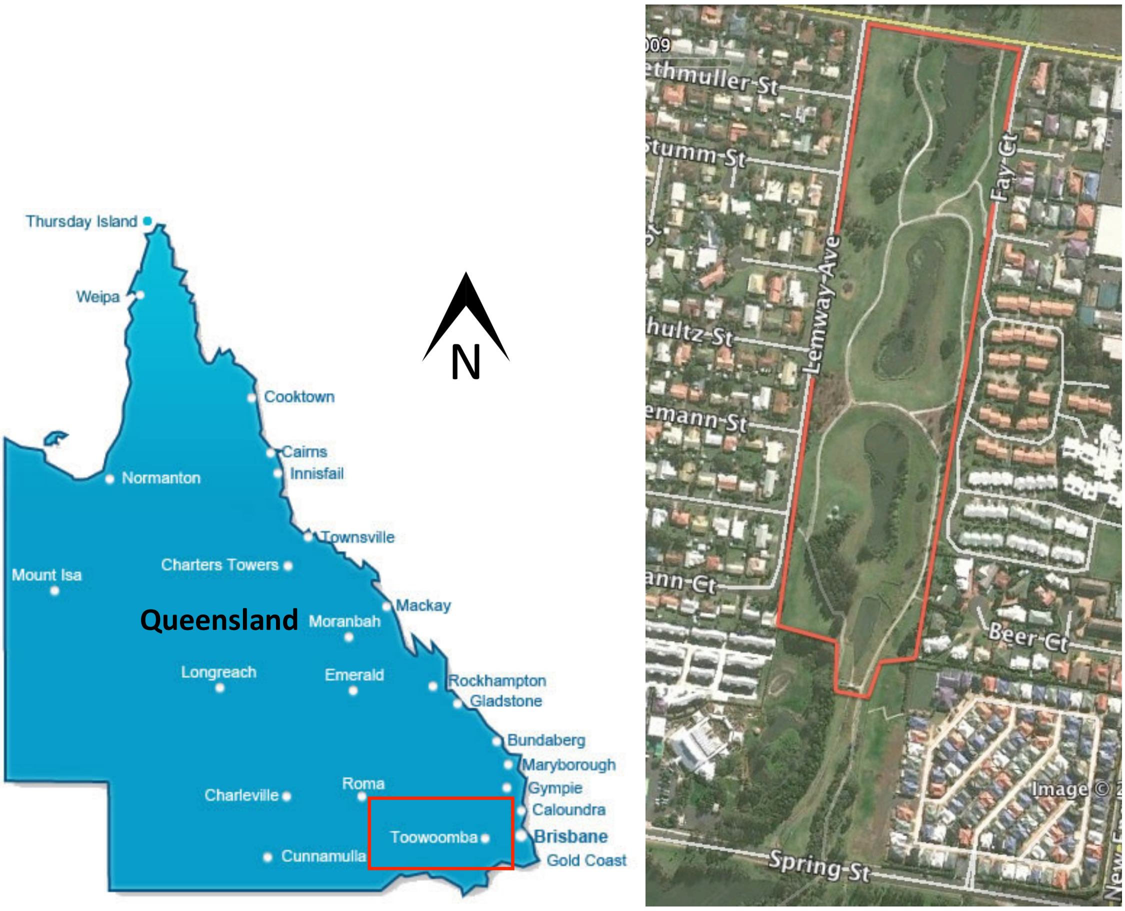

Figure 2 Study area – Toowoomba, Queensland

Figure 2 shows the study area outlined in red. It extends south from Stennar Street, bounded by Lemway Avenue to the west and Fay Court to the east, until past the fourth detention pond as shown.

3.3 Data Acquisition

Two types of data were required for this research project. First, LiDAR point data was obtained to generate a high-resolution DEM. Second, fieldwork was undertaken to collect point data over the study area using GPS survey equipment.

Figure 3 displays the point data acquired for both LiDAR and GPS surveys across the study area.

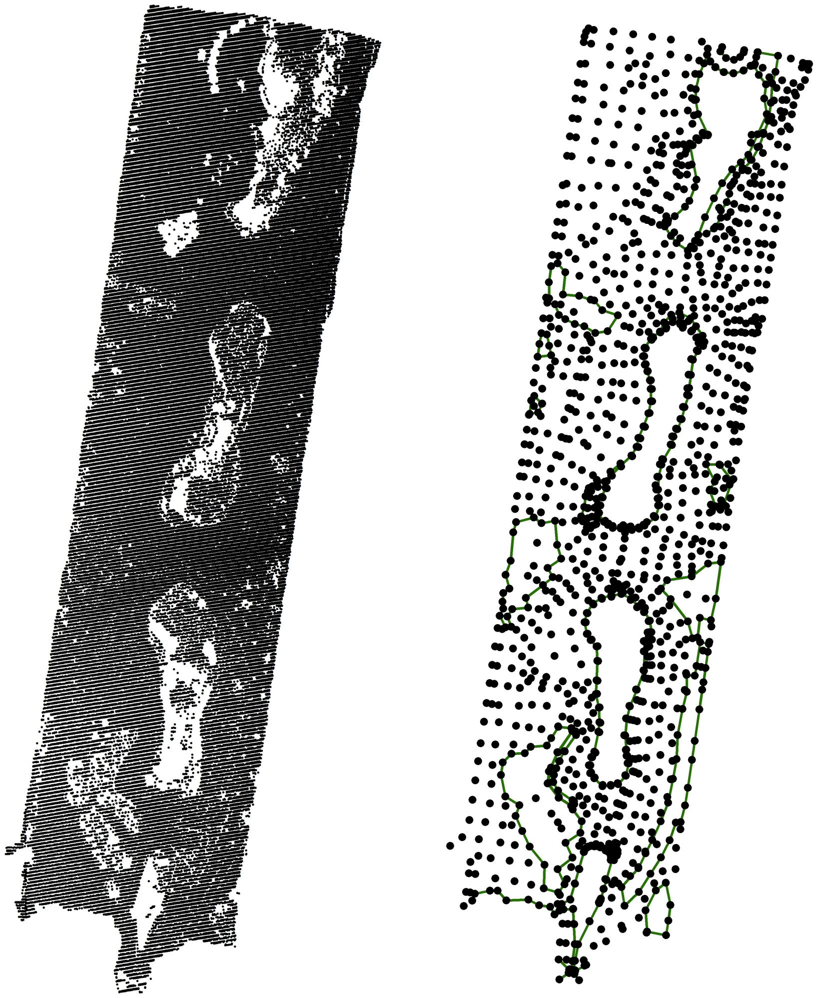

Figure 3 Data points across study area. LiDAR points are shown on the left and GPS points on the right

The LiDAR data was sourced from a Toowoomba wide LiDAR survey conducted in 2010 by Schlencker Mapping Pty Ltd for Toowoomba City Council. The survey covered an area of more than 2760 square kilometres across the Toowoomba Local Government Area (Schlencker Mapping Pty Ltd, 2010). Schlencker Mapping provided the data to Toowoomba City Council in separated layers of ground and non-ground points. The method used to separate the point data into ground and non-ground is unknown. As can be seen in the above images, the density of LiDAR observations is very high – one of the characteristics of LiDAR data. The average point separation is 1m (Schlencker Mapping Pty Ltd, 2010). The data for this research was cropped from the two adjoin 1km square tiles to cover the West Creek study area.

Table 1 shows the meta-data of the LiDAR survey was provided by Schlencker Mapping (2010).

Acquisition Start Date	29th June 2010
Acquisition End Date	16th July 3010
Device Name	Optech 'ALTM Gemini'
IMU	Applanix 'Litton 510'
Flying Height (AGL)	1200m
No. of Runs	242
Swath Width	1000m
Side Overlap	30 %
Horizontal Datum	GDA94
Vertical Datum	AHD
Map Projection	MGA Zone56
Control	302 surveyed GPS control points
Vertical Accuracy	±0.15m @ 1σ
Horizontal Accuracy	±0.22m @ 1σ
Surface Type	Ground and DTM
Average Point Separation	1.0m
Laser Return Types	1st through to 4th

Table 1 LiDAR meta-data (Schlencker Mapping Pty Ltd, 2010, p4)

Of note are the quoted horizontal and vertical accuracies of the data. The results were validated by use of a vehicle mounted GPS rover travelling over 218 kilometres of roads through the survey area, which achieved measurements to an accuracy of +/-.05 metres (Schlencker Mapping Pty Ltd, 2010). It is worth noting that this validation was only conducted over bitumen and gravel roads and therefore would not be a complete validation of the LiDAR data across different ground covers.

GPS points were collected over a three-day survey of the study area in June 2013 using a Trimble R8 rover and base station. Prior to undertaking field data collection a risk assessment matrix was completed to ensure all risks were identified, rated and appropriately managed (refer Appendix B – Risk Assessment Matrix). Points were collected to best represent the ground surface of the study area, by generally following a 10m grid while prioritising accurate location of changes in grade whether along banks, retaining walls, etc. Areas of differing ground cover where delineated to provide insight into the performance of LiDAR across cut grass, long grass, and forested land covers. The study area also consisted of areas of steep grade that would provide validation of LiDAR accuracy over such terrain. It must be noted that elevation data for the water bodies was interpolated and not collected. It was considered too high a risk to enter the water bodies as a single person party undertook fieldwork and expensive equipment used was borrowed from the University of Southern Queensland. In total, 1460 data points were collected across the study area.

3.4 DEM Generation

High resolution DEMs were generated for each data set using ESRI ArcMap 10.1 software. Figure 4 shows the two DEMs.

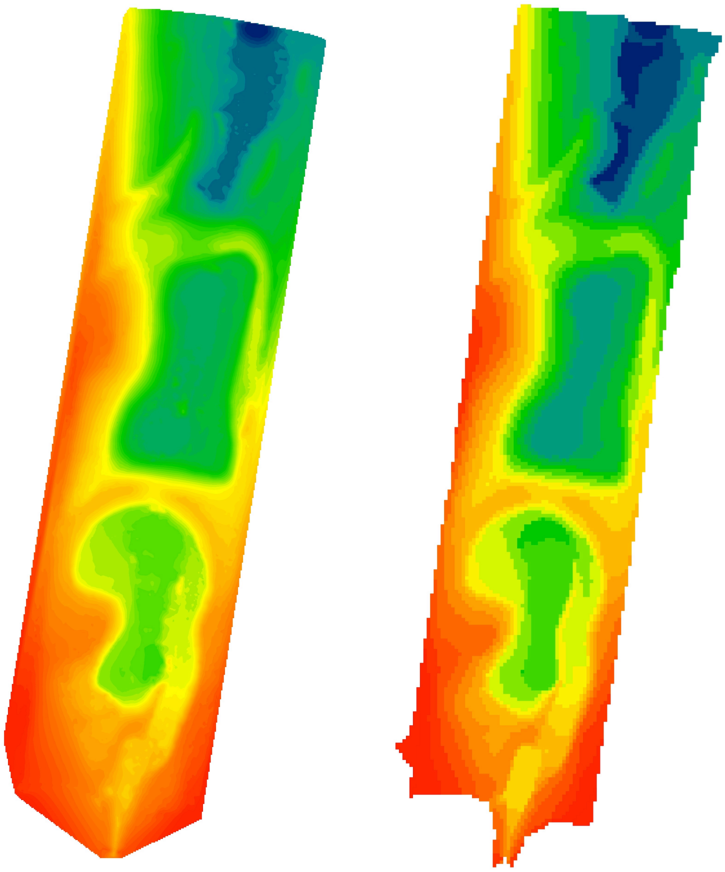

Figure 4 High resolution DEMs. LiDAR generated DEM is shown on the left and GPS generated DEM is shown on right.

As the LiDAR data was already separated into ground and non-ground points, the DEM was generated straight from the ground only points.

In order to generate a correct three-dimensional surface, a TIN (Triangular Irregular Network) surface was first generated over the GPS data points. This allowed manipulation of triangles to ensure correct surface modelling along banks, retaining walls and other hard breaklines. A high resolution DEM was then generated from this TIN surface.

3.5 Validation of GPS Data Acquisition

In order for useful comparison and analysis of LiDAR generated DEM, the GPS generated DEM would need to be validated as an accurate representation of the catchment area. Validation of the GPS survey was accomplished by re-surveying two separate areas of the study area on the final day of data acquisition. These surveys covered an area of approximately 4125m2, and consisted of 101 points. Similar to initial GPS processing, TIN surfaces were first generated across each validation area to ensure correct three-dimensional surface modelling. DEMs were then generated from these TIN surfaces.

Figure 5 below shows the approximate position of the two validation surveys. The locations were selected in order to cover a variety of the land covers and grades present in the study area. The Northern validation area consisted of a steep bank, flat grade and retaining wall with land cover being majority cut grass. The Southern validation area consisted of two steep to medium grade banks falling to an undulating to flat drainage channel, the majority of which was covered in long grass and shrubs, and partly covered by trees.

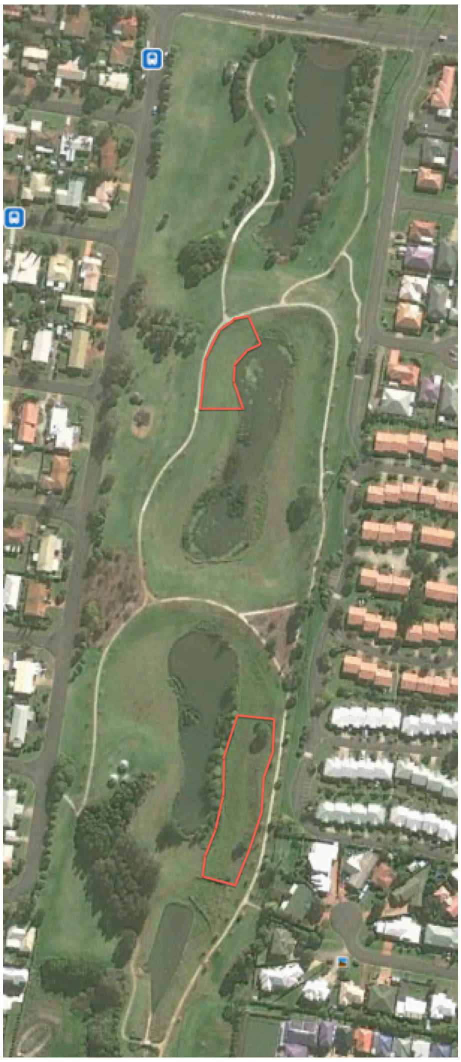

Figure 5 Site map showing approximate positions of GPS validation surveys in red.

3.6 Elevation Accuracy of Airborne LiDAR Derived DEM

The central objective of this research project is to analyse the vertical accuracy of airborne LiDAR. This was achieved by comparison of the LiDAR generated DEM and the GPS generated DEM to determine the difference in elevation between the models. This was undertaken for the entire data set, but also for sub-sets of the data to determine any relationships between vertical accuracy and grade or vertical accuracy and land cover.

To determine the relationship between vertical error in the LiDAR generated DEM and grade, a slope map was generated in ESRI ArcMap 10.1 software from the GPS generated DEM (Figure 6). The map was categorised into the following four classes of grades for analysis: 0-5%, 5-10%, 10-20% and grades greater than 20%. This would allow appropriate analysis to determine the influence of grade on vertical error in the LiDAR generated DEM. To achieve this, the GPS generated DEM was copied and cropped so as to only cover the grade of interest. Elevation comparison between the cropped GPS generated DEM and LiDAR DEM was then completed. This process was then repeated for each grade class. It is expected that as grade increases, the elevation error will increase (Hodgson and Bresnahan, 2004).

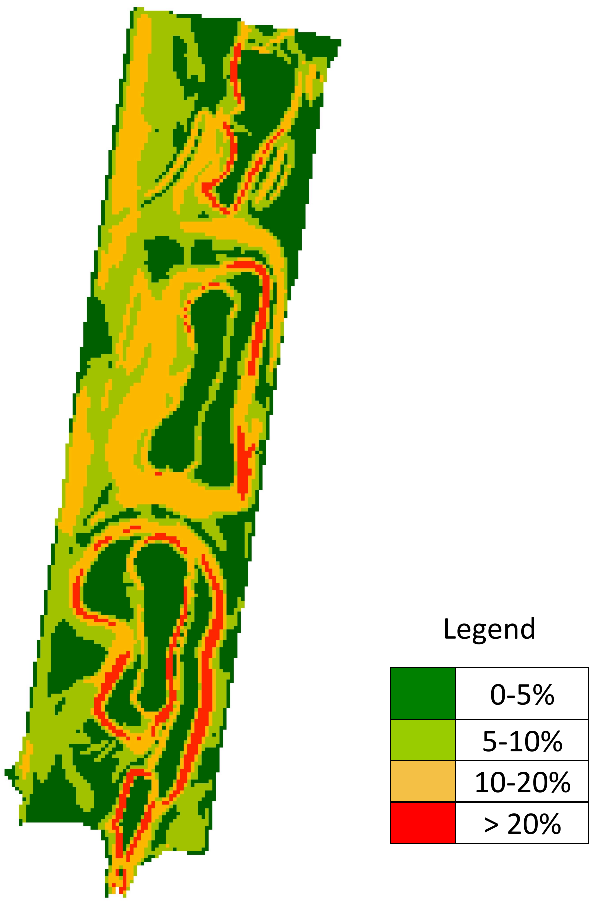

Figure 6 Slope map

Analysis of vertical error in the LiDAR generated DEM across differing land cover was also undertaken. During GPS data collection, measurements were taken to delineate areas of trees, water bodies, cut grass (including concrete paths), and long grass and shrubs. For purposes of analysis, three land cover classes were selected; grass (including concrete paths), long grass/shrubs, and trees. Table 2 shows typical examples of these areas throughout the study area categorised into the land cover classes used for vertical accuracy analysis.

Class and Description	Sample picture
Grass Cut grass ≤0.3m in height and paved surfaces.	
Long grass/Shrub Thick grass >0.3m in height or thick shrub vegetation <3m high.	
Forested Deciduous and non-deciduous areas of trees with majority closed canopy.	

Table 2 Land cover classes used in vertical accuracy analysis with descriptions

Analysis over water bodies was not undertaken due to the absence of data collection through water bodies as stated in section 3.3. Similar to analysis over different grade classes, the GPS generated DEM was copied and cropped so as to only cover the land cover of interest. This cropped DEM was used as the base for analysis in elevation difference of LiDAR generated DEM over the area. This method was repeated for each land cover class. It is expected that there will be little difference between vertical errors across grass and tree land covers (Hodgson and Bresnahan, 2004).

In order to provide useable data on the expected vertical accuracies of LiDAR data the root mean square error (RMSE) for elevation values will be calculated for the entire study area as well as each grade and land cover class. This statistical analysis is useful in that it returns values in the units of the variable being analysed. In this way the elevation RMSE could be thought of as the expected elevation error for a LiDAR generated DEM. The formula used for RMSE calculations was as follows:

$$RMSE_{LiDAR\ Observations} = \sqrt{\frac{\Sigma(Z_{LiDAR} - Z_{GPS})^2}{n}} \tag{1}$$

Where:

Z_{LiDAR} = Elevation of LiDAR generated DEM raster cell (m)

Z_{GPS} = Elevation of GPS generated DEM raster cell (m)

n = number of raster cells used for calculation

The square of the difference in elevations between LiDAR generated DEM and GPS DEM will be calculated using ESRI ArcMap 10.1 functions that return the square difference between the raster images as well as the number of corresponding cells of both raster images (n). This data will be analysed and compared to previous studies that calculated RMSE values across similar land covers and grades. Comparison against quoted vertical accuracies provided in the LiDAR metadata by Schlencker Mapping Pty Ltd (Table 1) will also be undertaken.

3.7 Flood Zone Delineation

Basic floodplain mapping applications will be performed on each DEM surface in order to meet the other key objective of this research.

The influence of DEM errors on flood zone delineation will be determined by creation of an indicative water surface level for a flood event in the ESRI ArcMap 10.1 software package. The volumetric difference between this surface and the GPS generated DEM will be calculated using ArcMap 'Surface Difference' function. A polygon feature class is returned where each polygon is classified as either 'above', 'below', or 'equal'. In this way the line at which the indicative flood water surface level is equal to the ground surface is defined as the flood zone extent. All areas where the water surface is greater than the ground surface would be classified as the flood zone. The same calculations will be repeated for the LiDAR generated DEM. Analysis of the flood zone line for each DEM and surface area of the flood zone will be undertaken to determine how flood zone location and area across the surface are influenced by any errors in the LiDAR generated DEM.

The indicative water surface level for a flood event over the study area is based on the Insurance Council of Australia Hydrology Panel (2011) report on the January 2011 flooding in Toowoomba. The report provides Gowrie Creek water levels as measured at Cranley Stream gauge (422326A), 10 January 2011, which lies approximately 6km north of the study area. The maximum water level recorded was approximately 4.6 metres during the flood event as shown in Table 3. For the purpose of this assessment a water level of 4.5m was selected to represent a similar flood event. A water surface was created so that the surface was approximately 4.5 metres above the invert levels of the four detention ponds across the study area. This surface was created by setting water surface profiles at the ends of each detention pond at constant elevations equal to 4.5 metres plus the average depth of the detention pond at the profile location. The same calculations were performed for a water level of 3.5 metres for comparison of any relationships between DEM accuracy and flood zone delineation.

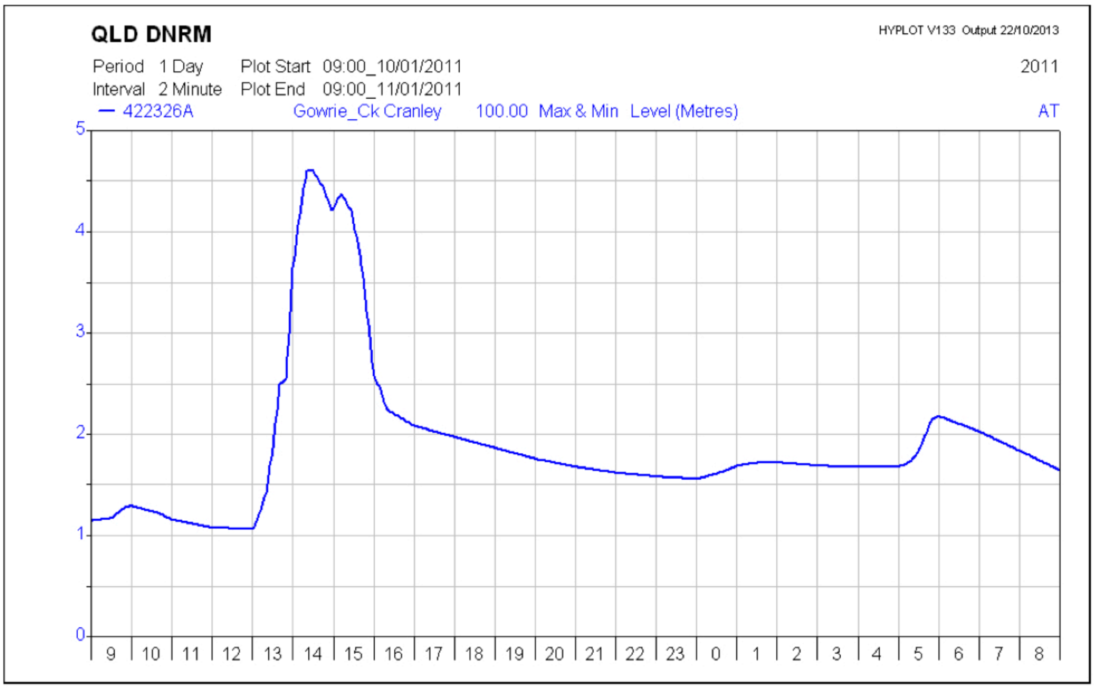

Table 3 Stream water levels (metres), Canley stream gauge, Gowrie Creek (QLD DNRM, 2012).

It must be noted that the surface would most likely be an inaccurate representation of an actual flood event across the study. However, for the purpose of analysing the relationship between the different DEMs and the same water level surface, the actual value of the water surface is in some ways irrelevant, as it remains constant. Delineation of actual flood zones across the study area for a specified flood event would require much more site-specific information to predict a water surface for the flood event.

3.8 Flood Inundation Depth and Volume

Analysis of the influence of error in LiDAR generated DEM on flood inundation depth and volume will completed. As discussed in section 2.2 flood inundation depth is a critical data set for flood plain mapping in the application of flood damage estimation. Relatively low uncertainties between 0.1 -0.25m can introduce large uncertainties in damage estimates (Moel and Aerts, 2010).

Raster functions provided with ESRI ArcMap 10.1 will be used to determine the volume of flood water above the GPS generated ground surface up to the flood water surface level. Depth of flood water across the flood zone will also be calculated. The same calculations will be undertaken for the LiDAR generated DEM. The RMSE value will be calculated in order to analyse the expected error in flood inundation depth when using LiDAR generated DEM for flood plain mapping.

3.9 Conclusion

This chapter discussed what methods would be employed to fulfil the aims of this research. The study area was identified. Data acquisition methods were discussed. Generation of DEMs and analysis methods were discussed. The methodology discussed above provides a framework for the presentation of results and discussion.

Chapter 4 – Results and Discussion

4.1 Introduction

In this chapter the results of the research will be presented and discussed. Output from ESRI ArcMap of histograms and raster images will be presented and discussed in regards to:

- Elevation accuracy of GPS under the heading Validation of GPS
- Elevation accuracy of Airborne LiDAR Derived DEM
- Flood Zone Delineation
- Flood Inundation Depth and Volume

4.2 Validation of GPS Data Acquisition

It is important to validate the original GPS survey as explained in section 3.5. To validate the elevation of the original GPS survey, the elevations of the DEMs generated from the validation surveys were each subtracted from the elevations of the DEM generated by the original GPS survey. Figure 7 shows the resultant raster images for these calculations with elevation differences in metres represented by the different colours.

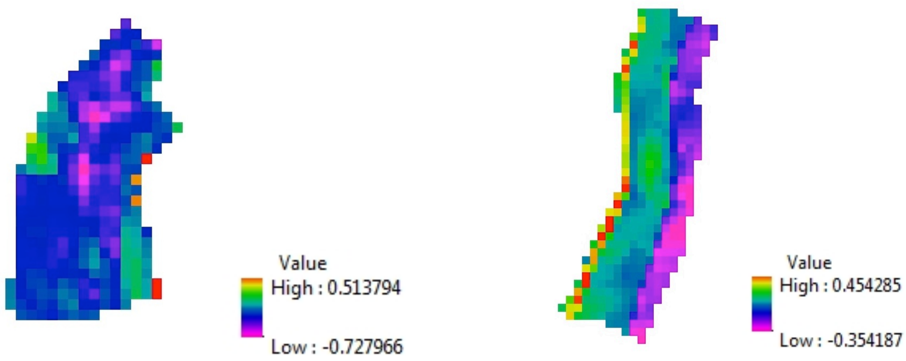

Figure 7 Raster image generated by GPS generated DEM minus validation DEMs. The Northern validation survey is shown on the left and the Southern validation survey on the right.

Figure 8 and Figure 9 show the ArcMap output from the calculation of the two validation DEMs and the original GPS generated DEMs. Ideally the difference would zero, indicating that the original GPS survey was completely accurate and free from error. As can be seen below in the below figures, this has not been achieved; however the validation surveys still have value in this research. Figure 8 and Figure 9 show the ArcMap output of the elevation differences between each DEM generated by the validation surveys and the DEM generated by the original survey. ArcMap was used to generate a raster image of the squared differences of the elevations across corresponding raster cells. These values were used to calculate RMSE values for the validation surveys as seen in Table 4. The RMSE values are high at 0.089m and 0.128m for the North and Southern surveys respectively, although the mean differences are more acceptable at -0.037m and -0.032m for the Northern and Southern surveys respectively.

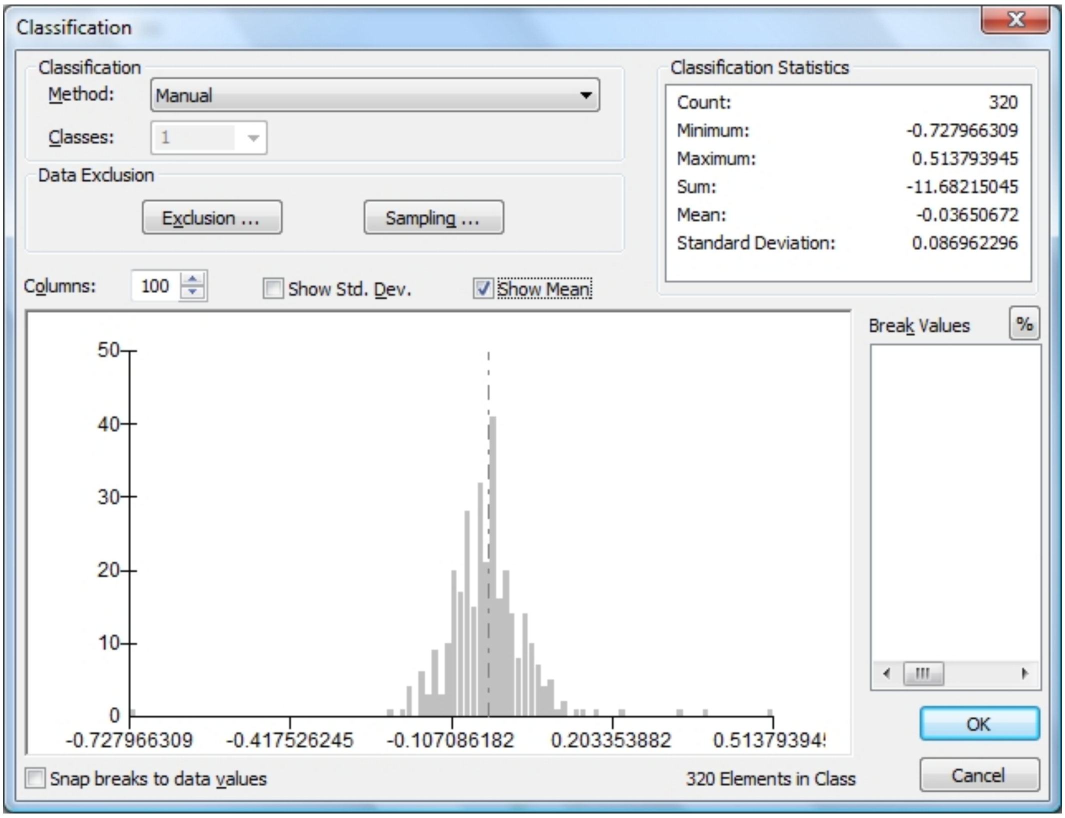

Figure 8 ArcMap 10.1 output of elevation difference in metres between Northern validation survey and original GPS survey.

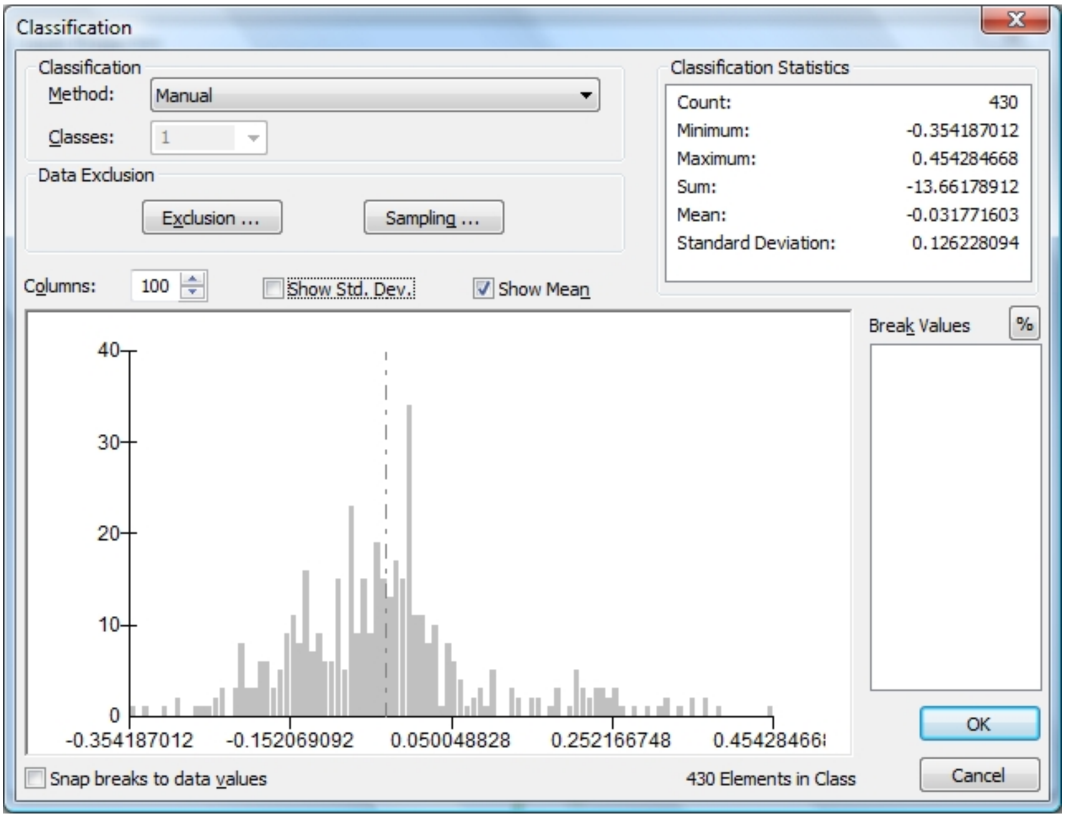

Figure 9 ArcMap 10.1 output of elevation difference in metres between Southern validation survey and original GPS survey.

Survey	Mean	Standard deviation	Raster cell count (n)	Sum square ΔV	RMSE
North	-0.037	0.087	320	2.509	0.089
South	-0.032	0.126	430	7.055	0.128

Table 4 Elevation errors in validation surveys in metres.

There are some perceived reasons as to why the DEMs from the validation surveys show elevation differences to the original GPS derived DEM. The differences could largely be attributed to the differing location of actual point measurements. The location of point measurements were chosen to best represent the natural ground surface at the discretion of the surveyor, rather than at pre-determined, unique and identifiable locations. Across a majority of ground surfaces, the difference in point location would not contribute to a large difference in the DEM. However, across situations such as curved retaining walls, or steep banks, this different location of point measurement would contribute to larger DEM differences. The DEM is formed from a TIN surface, which joins straight, not curved, lines between the point measurements.

These lines are calculated as having continuous elevations of constant grade between the nodes. A significant vertical error is therefore generated for these situations, as the straight line of constant grade will 'skip' measured points from another data set along the curved retaining wall.

To demonstrate this added error source along curved retaining walls, a TIN surface for the Northern validation survey was generated excluding measured points along the curved retaining wall. A new DEM was generated from this cropped surface and analysed against the original GPS DEM across the corresponding area. Table 5 demonstrates an improvement of this cropped area in terms of vertical accuracy by removing the surface over the curved retaining wall.

Survey	Mean	Standard deviation	Raster cell count (n)	Sum square ΔV	RMSE
North	-0.037	0.087	320	2.509	0.089
Crop North	-0.032	0.056	277	1.142	0.064

Table 5 Elevation errors in validation survey in metres, with and without retaining wall.

Another error source in elevation differences between the GPS surveys is the inherent vertical errors in the equipment and processes used for data collection. The GPS was used in a rapid real time kinetic (RTK) mode taking three-second observations with vertical precisions of approximately 12-35mm. Difficulties were encountered across forested areas of the site as the GPS struggled to gain high vertical precisions and would regularly lose position fix when in these areas. Vertical precision through these areas was therefore limited.

Despite these errors, the validation surveys do provide important information for this research. At a basic level, the mean elevation differences are close to zero (both around -0.035m), validating that there was no major systematic error in the data collection process. If the elevation errors were both significantly in a positive or negative direction, it would be an indication that systematic errors in data collection were present such as GPS antennae height or vertical projection or datum errors. It could be argued that there is a general shift as the mean elevation errors are both very close to -0.035m, however for the purposes of flood and catchment applications, and the quoted vertical errors of +/-0.15m of the provided LiDAR data as seen in figure 3, this shift would be negligible.

In regards to the spread of vertical differences as discussed above, it would be recommended for future studies to increase point spacing, especially across curved and steep changes of grades, to better represent the surface and create a more accurate DEM. The elevation errors across the validation surveys do present the need for higher accuracy point acquisition across the study area. This could be achieved by longer point observation times or combined use of total station survey equipment for forested areas.

4.3 Elevation Accuracy of Airborne LiDAR Derived DEM

Figure 10 shows the resultant raster image produced by subtracting the elevations of the airborne LiDAR generated DEM from the elevations of the GPS generated DEM. The colours represent the calculated elevation difference in meters as shown. This visual representation shows that the majority of the study are (not including the water bodies) returned differences in height between +0.25m and -0.25m which is within determined accuracy requirements for flood plain mapping and catchment management of <0.5m (McDougall, et al., 2008).

Returns across water bodies are significantly higher being shown as approximately between -0.25m and -2.0m. That is, the LiDAR generated DEM is *above* the GPS generated GPS DEM by these values. It must be stated, as explained in section 3.3, that the elevations across water bodies were interpolated based on point data acquired around the edges and approximately 0.5-1m into the water bodies. However, it can still be deduced that the LiDAR DEM is generally inaccurate in elevation results across water bodies.

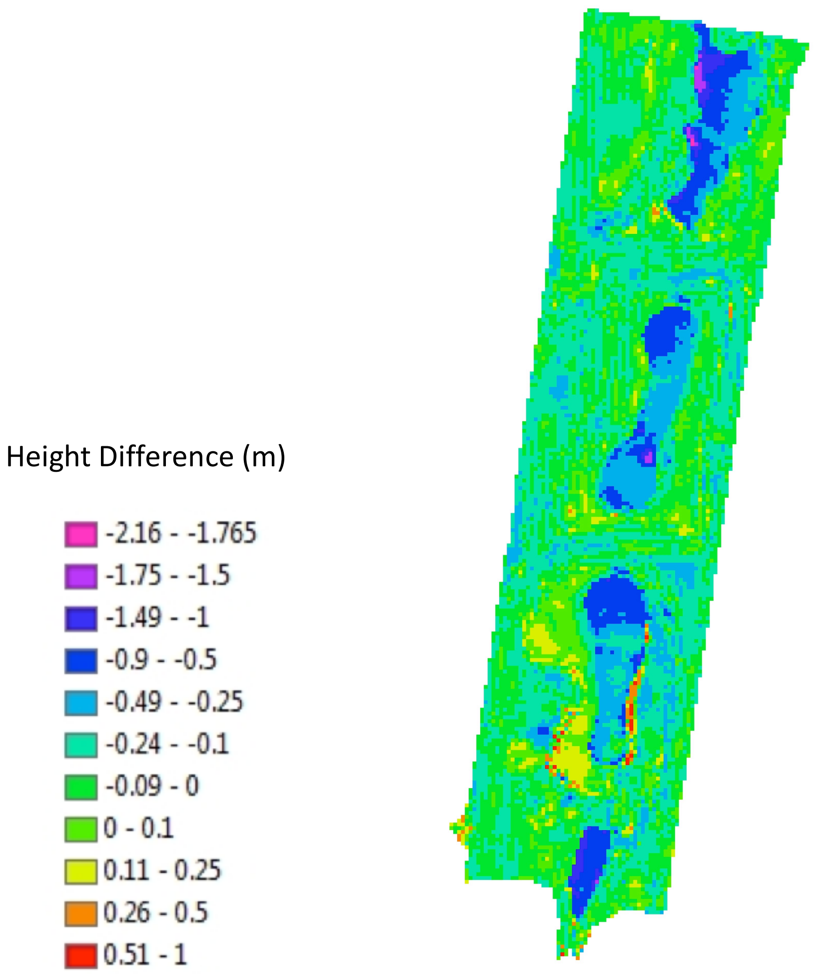

Figure 10 Raster image of GPS generated DEM minus LiDAR generated DEM

Figure 11 shows the output statistics for the above raster calculation. ArcMap software was used to calculate the square elevation difference between the LiDAR generated DEM and the GPS DEM. This data was used to calculate the RMSE value of the LiDAR elevations according to equation (1). Table 6 provides a summary of these statistics. The RMSE for LiDAR elevation across the entire study area is calculated to be 0.260m. This value is higher than the quoted vertical accuracy of 0.15m in Table 1, although this is not surprising as the means of validation of the LiDAR were conducted along bitumen and gravel roads with minimal steep grades as discussed in section 3.3. We can see that the mean for the entire dataset is -0.159m with standard deviation of 0.226m, which confirms the deductions from the raster image discussed above. The mean elevation error and larger histogram area to the left, suggest that the LiDAR DEM elevations generally above the GPS generated DEM elevations as the calculation was ordered as GPS DEM minus LiDAR DEM. These results agree with other empirical studies that have been conducted to date, that suggest accuracies of 26 cm to 153 cm RMSE for large-scale mapping applications (Adams and Chandler, 2002; Bowen and Waltermine, 2002; Hodgson *et al.,* 2003).

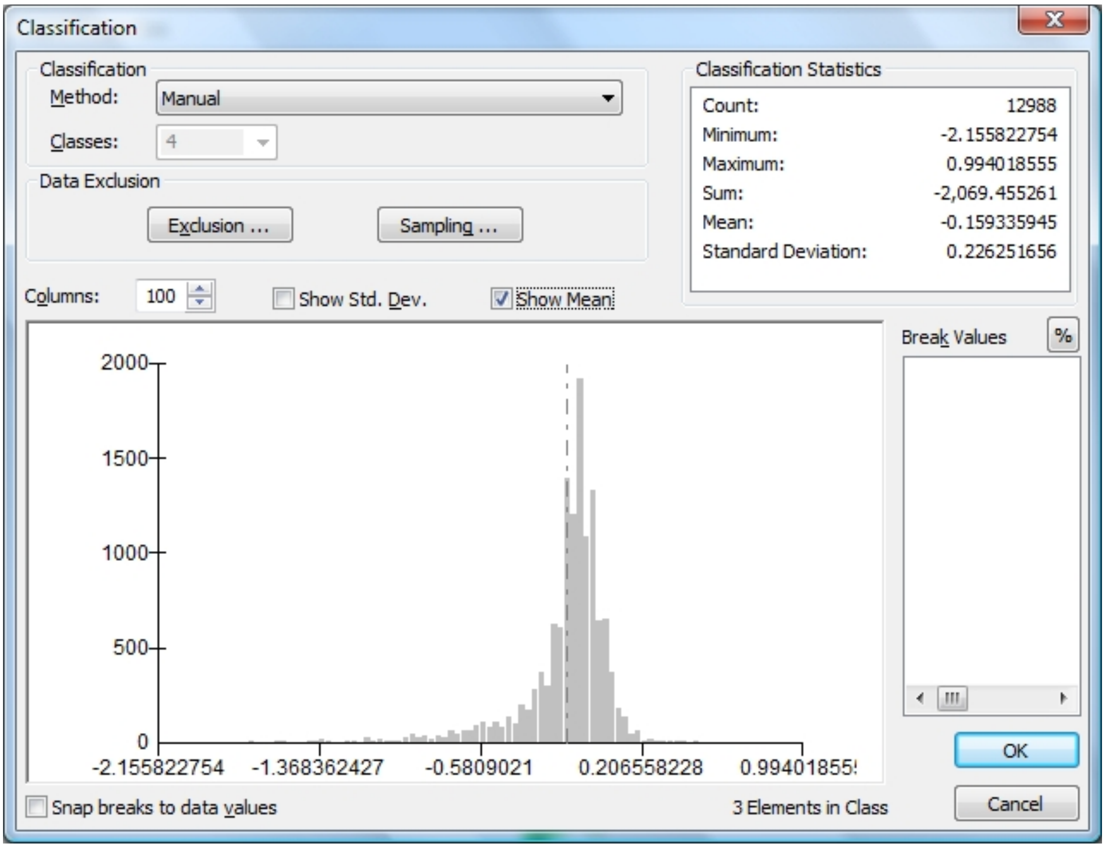

Figure 11 ArcMap 10.1 output of elevation differences in metres between entire LiDAR generated DEM and GPS generated DEM

	Mean	Standard Deviation	Minimum	Maximum	RMSE
Total DEM	-0.159	0.226	-2.156	0.994	0.260

Table 6 Elevation error (m) of LiDAR generated DEM.

To further understand these elevation errors in the LiDAR generated DEM, the above calculations were repeated for the different grade classes. Figure 12 shows the statistical output for the calculation of LiDAR generated DEM minus GPS generated DEM for each grade class. RMSE values were also calculated for each grade class. Table 7 summarises these results.

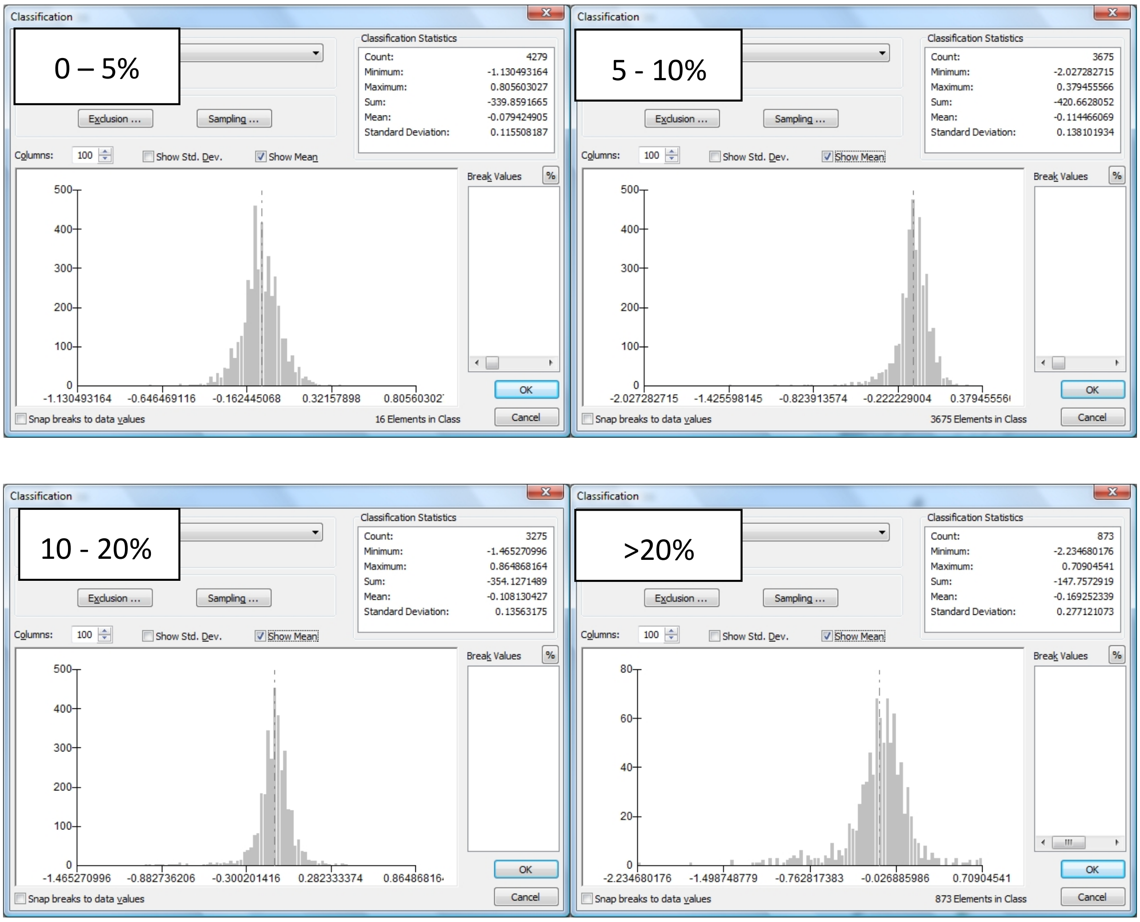

Figure 12 ArcMap 10.1 output for elevation differences in metres between LiDAR generated DEM and GPS generated DEM across each grade class.

	Mean	Standard Deviation	Minimum	Maximum	RMSE
Total DEM	-0.159	0.226	-2.156	0.994	0.260
Grade Classes					
0-5%	-0.079	0.116	-1.130	0.806	0.130
5-10%	-0.114	0.138	-2.027	0.379	0.158
10-20%	-0.108	0.136	-1.465	0.865	0.160
> 20%	-0.169	0.277	-2.235	0.709	0.309

Table 7 Elevation error (m) of LiDAR generated DEM across grade classes.

The results from elevation comparison of DEMs across the grade classes confirm previous research that one of the sources for vertical error in airborne LiDAR data is steep grades (Hodgson and Bresnahan, 2004). This relationship is apparent in Table 7 were we see increased mean, standard deviation and range of errors from grade class 0-5% to grade class >20%. There is little difference in elevation error between grades classes 5-10% and 10-20%, however the elevation errors for these two classes are larger than those in grade class 0-5% and smaller than those in grade class >20%. So while the relationship of increasing grade equalling increasing elevation error for airborne LiDAR data is not apparent across grades 5-20%, it is evident for grades 0->20%.

In addition, the above calculations were repeated for the different land cover classes. Figure 13 shows the statistical output for the calculation of LiDAR generated DEM minus GPS generated DEM for each land class. Table 8 summarises these results.

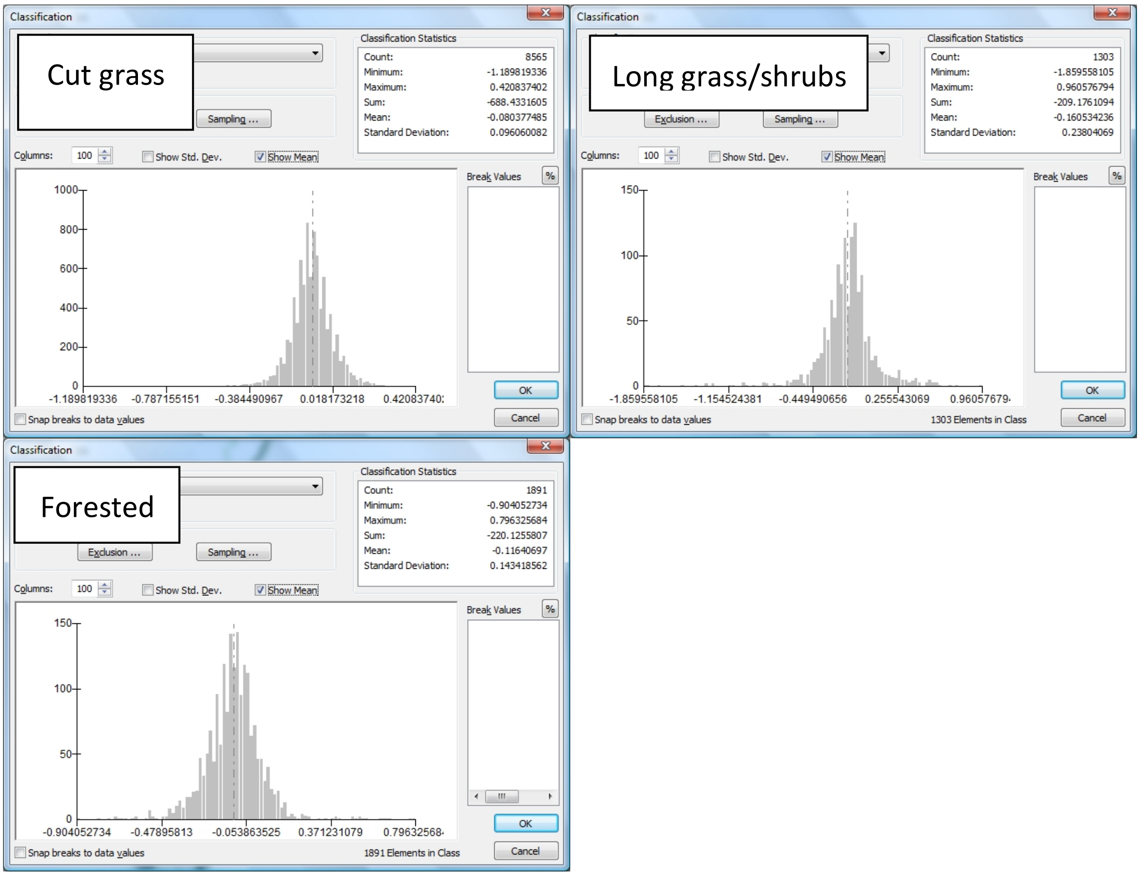

Figure 13 ArcMap 10.1 output for elevation differences in metres between LiDAR generated DEM and GPS generated DEM across each land cover class.

	Mean	Standard Deviation	Minimum	Maximum	RMSE
Total DEM	-0.159	0.226	-2.156	0.994	0.260
Land Cover					
Cut grass	-0.080	0.096	-1.190	0.421	0.113
Long grass/shrubs	-0.161	0.238	-1.860	0.961	0.273
Forested	-0.116	0.143	-0.904	0.796	0.178

Table 8 Elevation error (m) of LiDAR generated DEM across land cover classes.

These results show that airborne LiDAR data will return elevation data of best accuracy across areas of cut grass and pavement with an RMSE of 0.113m, under half of the RMSE for the entire study area. The elevation RMSE was also low across forested land covers at 0.178m in comparison to elevation errors of the entire site. These results confirm by past research that shows errors over flat surfaces, even forested ones, are very low compared to other sources of digital elevation data such as photogrammetry (Hodgson and Bresnahan, 2004). These results reflect the characteristics of forested areas of the site. Forested areas consisted of tall trees with closed to majority-closed canopies with little to no other ground cover in the form of long grass or shrubs. This allows any LiDAR signals that penetrate the canopy acquire a bare earth elevation with ease. Across forested areas the difference between ground and no-ground points would be large as most trees were in a height range of 5-15m. This situation would allow for accurate filtering of non-ground points from the data set when compared to land covers of dense undergrowth close to the bare earth surface. These land cover types best represent the vertical accuracy of the provided airborne LiDAR data as quoted in Table 1.

It is evident that airborne LiDAR will experience greatest elevation errors across land cover types of long grass and shrubs. Table 8 shows that the mean and standard deviation of elevation errors of the DEM over this land cover type, being -0.161 and 0.238 respectively, are higher than the entire data set. This is also true for the elevation RMSE with the RMSE over this land cover class being 0.273m – higher than the entire study area elevation RMSE of 0.260m. These larger elevation errors would be expected, as penetration of such homogenous thick land cover by airborne LiDAR scanners would be difficult. Separation of ground and non ground points would prove to be a further source of error over these land covers as the elevation difference between the bare earth and the top of the grass or shrub would not be as extreme as those differences in forested areas. These inaccuracies have been evident in other studies that returned greatest elevation errors over homogenous meadows with high grass and shrubs (Hollaus, et al. 2005).

4.4 Flood Zone Delineation

Flood zones were calculated for each DEM surface for flood surfaces of 3.5 metres and 4.5 metres above the invert levels of each detention basin across the study area. Figure 14 is an output polygon map from ArcMap depicting areas where the 4.5 metre flood surface is above the ground surface (blue polygon) and areas where the 4.5 metre flood surface is below the ground surface (green polygon). Areas where the flood surface is above the ground surface are classified as the flood zone for this indicative flood event. Figure 15 displays the flood zone delineation for the 4.5 metre flood surface overlaid onto the GPS generated TIN surface. The area of the flood zone for the GPS generated DEM was calculated and compared to the surface area of the flood zone for the LiDAR generated DEM. Table 9 shows these areas.

The flood zone surface area calculated for the GPS generated DEM is 1,135.2m^2 larger than the flood zone surface area calculated for the LiDAR generated DEM. As the flood surface was held as constant for the calculations, this decreased flood zone area for the LiDAR generated DEM indicates that the LiDAR generated DEM is generally higher in elevation than the GPS generated DEM. In percentage terms, the LiDAR generated DEM under-estimates the flood zone area by approximately 1.64%.

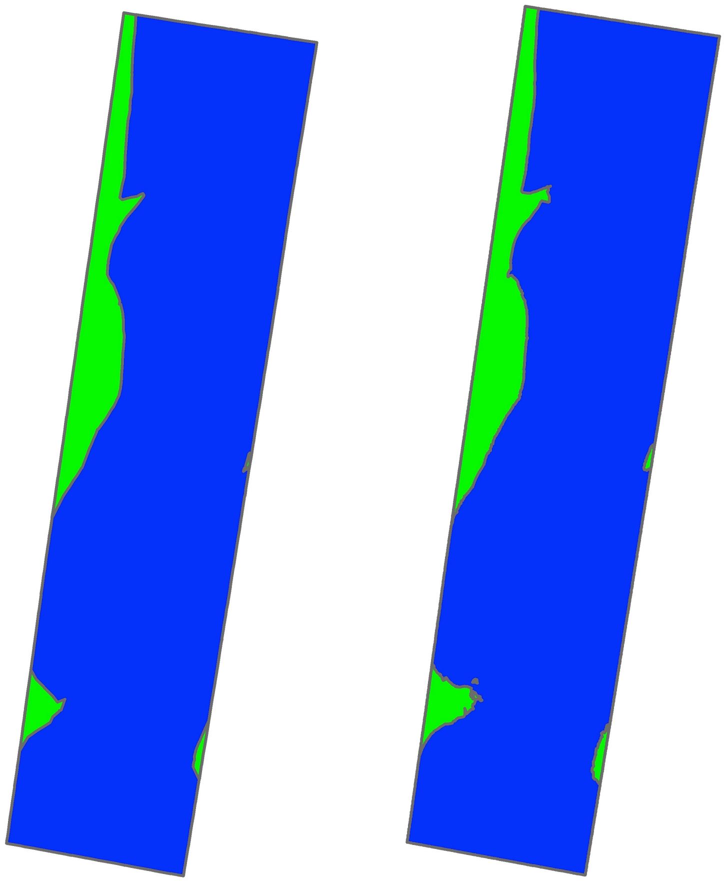

Figure 14 Surface differences for 4.5m flood level. GPS is shown on left and LiDAR on right.

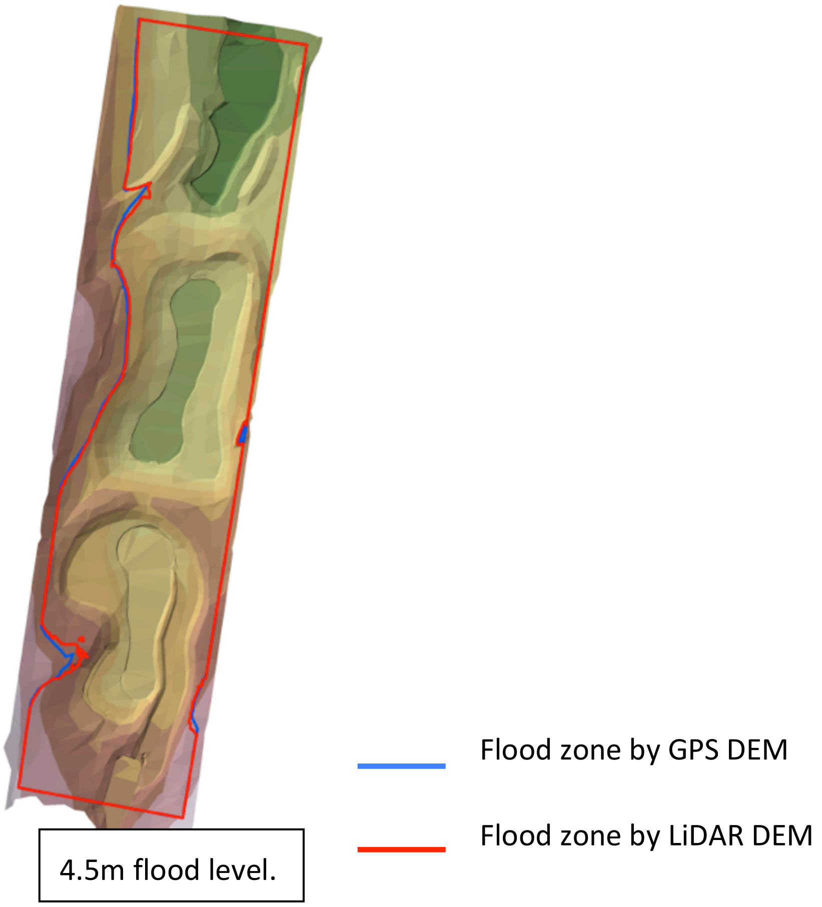

Figure 15 Flood zone delineation produced from GPS DEM and LiDAR DEM for 4.5 metre flood level.

Analysis of Figure 15 is limited as the flood surface exceeded the elevations at the northern and southern limits of the ground surfaces as well as majority of the eastern limit and section of the western limit. This is evident in the straight lines of the flood zones along these edges of the study area where the flood zones generated from each DEM are shown as equal. These areas should not be considered the flood zone, as the flood zone would in fact continue past the edges of the study area until reaching higher ground. To provide a complete flood zone for this section of the catchment, two options are available. Firstly, increase size of study area in an easterly and westerly direction to acquire data until the ground surface is above the flood surface level. Secondly, reduce the elevation of the flood surface level to ensure that it will be lower than the extent of the existing ground surface models. This first option would be most desirable so as to increase the study area for more accurate analysis and to maintain a fairly realistic estimate of the flood surface. However, due to time and resource constraints, this was not undertaken. The second option was therefore investigated. A flood water level of 3 metres above the invert of the detention basins was tested, however the area of the flood zone was significantly reduced due to the embankments separating the detentions being higher than the flood water level. While there are areas downstream of the embankments that are still under the flood water level surface, any areas not connected to upstream areas would not actually be reachable by upstream flood waters due to intervening embankments. Disappointingly, the 3 metre flood water level still reached limits along the western boundary of the study area. Selection of the 3.5 metre flood water level was therefore selected to ensure continuity of flood zone through study area, and even though sections were limited along borders of the study area, as seen in Figure 17, the result is an improvement on the 4.5 metre flood water level.

Similar analysis to the 4.5 metre flood water level was conducted for the 3.5 metre flood water level Figure 16 is an output polygon map from ArcMap depicting areas where the 3.5 metre flood surface is above the ground surface (blue polygon) and areas where the 3.5 metre flood surface is below the ground surface (green polygon). Figure 17 displays the flood zone delineation for the 3.5 metre flood surface overlaid onto the GPS generated TIN surface, as computed by the extent of area where the flood surface is above the ground surface. The area of the flood zone for the GPS generated DEM was calculated and compared to the surface area of the flood zone for the LiDAR generated DEM. Table 9 shows these areas.

DEM source	Flood Level (m)	Flood zone surface area (m^2)	Flood zone surface difference (m^2)	Percentage underestimated
GPS	4.5	69339.8		
LiDAR	4.5	68204.6	1135.2	1.64%
GPS	3.5	60105.2		
LiDAR	3.5	57883.6	2221.6	3.7%

Table 9 Flood zone surface areas for each flood water level surface across GPS generated DEM and LiDAR generated DEM

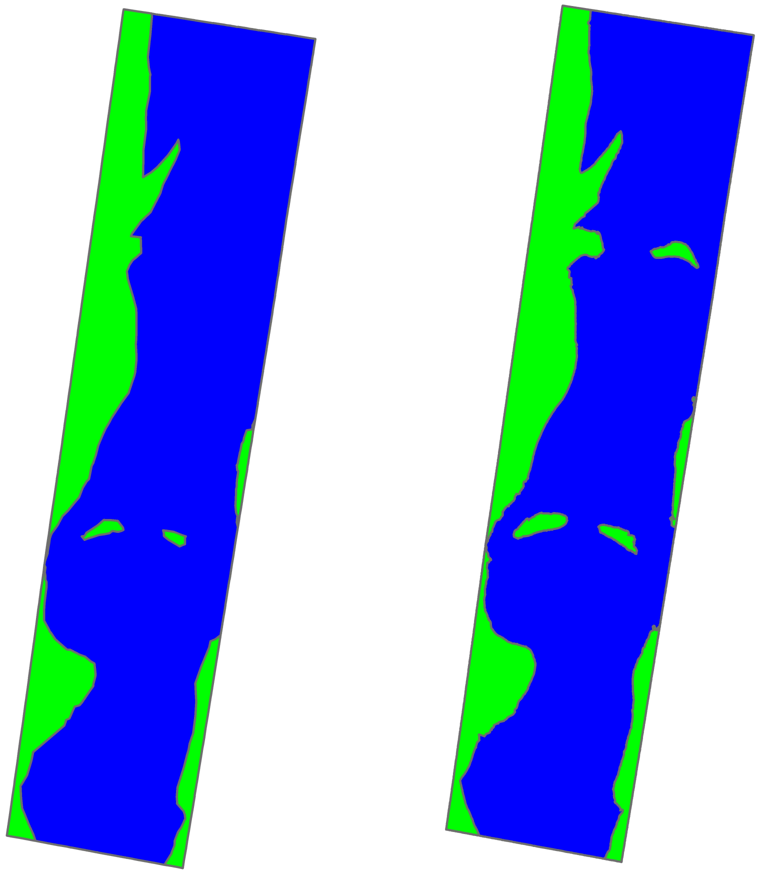

Figure 16 Surface differences for 3.5m flood level. GPS is shown on left and LiDAR on right.

The flood zone surface area calculated for the GPS generated DEM is 2,221.6m^2 larger than the flood zone surface area calculated for the LiDAR generated DEM. As the flood surface was held as constant for the calculations, this decreased flood zone area for the LiDAR generated DEM indicates that the LiDAR generated DEM is generally higher in elevation than the GPS generated DEM. In percentage terms, the LiDAR generated DEM under-estimates the flood zone area by approximately 3.7%.

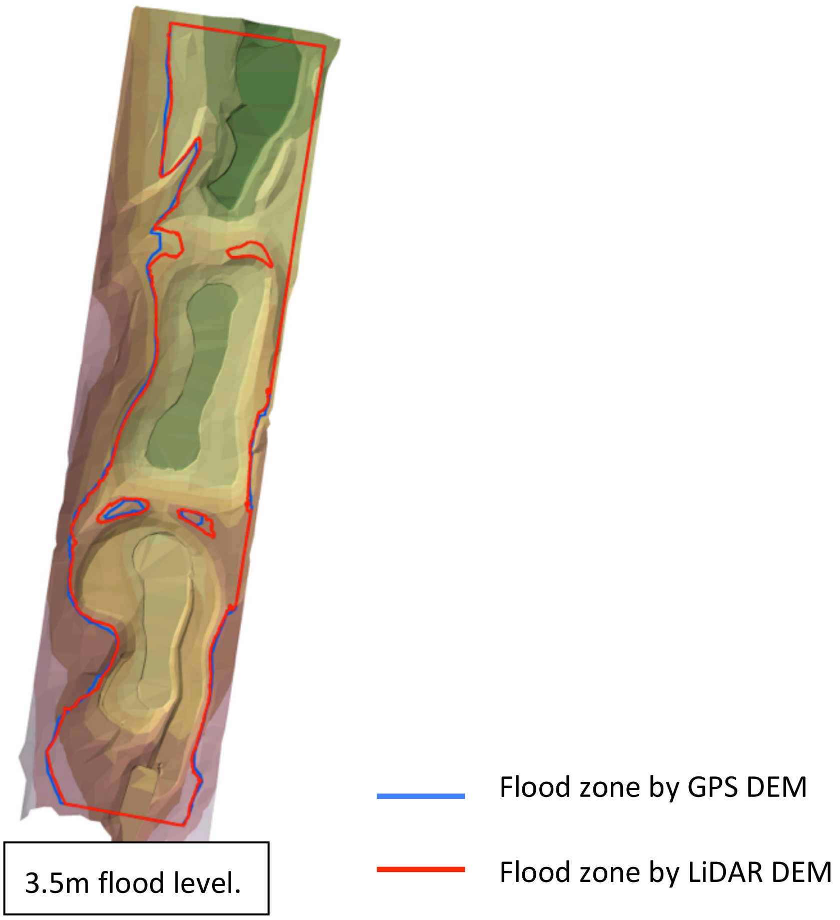

Figure 17 Flood zone delineation produced from GPS DEM and LiDAR DEM for each flood level.

4.5 Flood Inundation Depth and Volume

Flood inundation depth and volume analysis was successfully completed by generating raster surfaces of flood inundation depths across flood zones for flood surface levels of 4.5 m and 3.5 m for GPS generated DEM and LiDAR generated DEM.

Table 10 summarises differences of inundation depth for each DEM. As is shown the maximum inundation depth calculated against the LiDAR generated DEM is 0.477 m shallower than the maximum inundation depth calculated against the GPS generated DEM. All inundation differences have been used to calculate the RMSE value for inundation depth. Table 10 shows that this expected inundation depth error value to be 0.264 m. In regards to estimation of flood damages previous studies (Moel and Aerts, 2010) have shown that this level of uncertainty can equate to lowest damage estimates up to 5-6 times lower than the highest estimates.

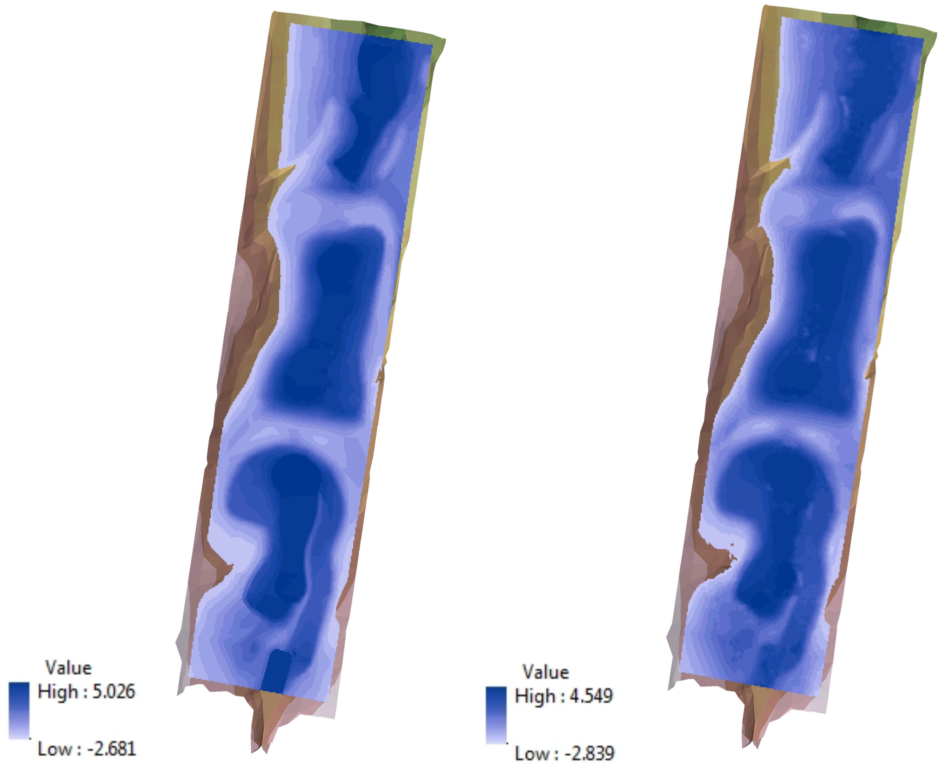

Figure 18 Raster images of flood inundation depths for 4.5m water level. GPS is shown on left and LiDAR on right.

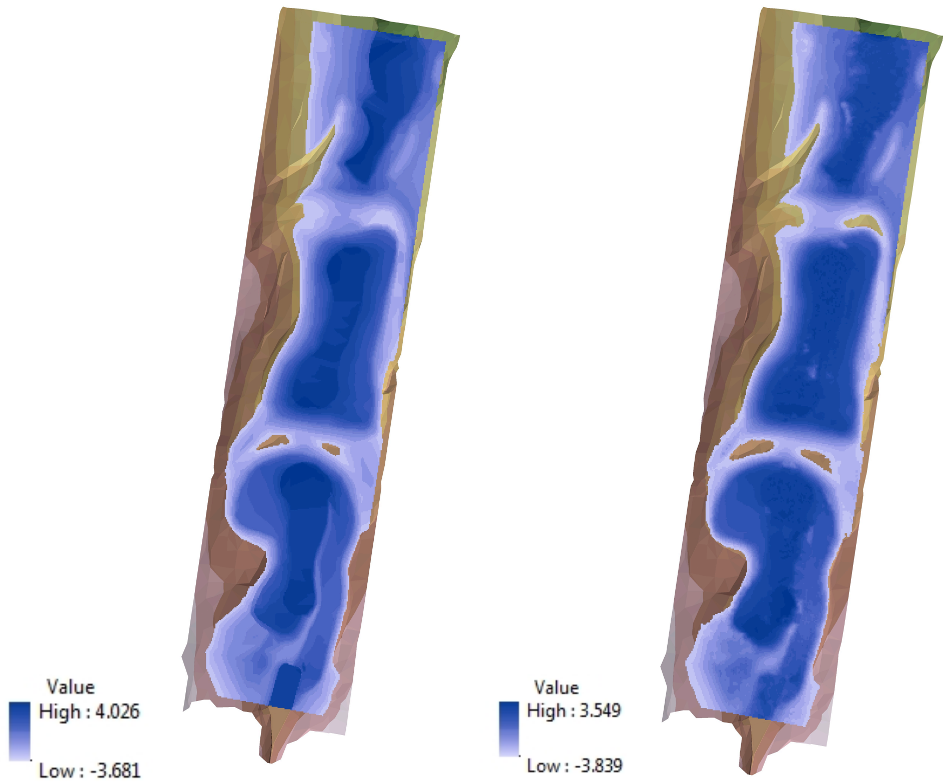

Figure 19 Raster images of flood depths for 3.5 metre water level. GPS is shown on left and LiDAR on right.

DEM source	Flood Level (m)	Flood volume (m^3)	Maximum flood depth (m)	RMSE - Water depth (m)
GPS	4.5	176776.8	5.03	
LiDAR	4.5	165595.7	4.55	0.264
GPS	3.5	112473.1	4.03	
LiDAR	3.5	102430.5	3.55	0.264

Table 10 Flood inundation depth and volume for each flood water surface across GPS generated DEM and LiDAR generated DEM.

These raster layers were used to calculate flood water volumes for each flood level. Table 10 these volume calculations for each DEM source. For a flood level of 4.5 m the LiDAR generated DEM produced a flood water volume 11,181.1 m^3 less than what would be the expected flood water volume for this flood water level, as determined by water volume produced from GPS generated DEM. The LiDAR generated DEM has underestimated the water volume by 6.3% of expected volume. Similarly for a flood level of 3.5 m the LiDAR generated DEM produced a flood water volume 10,042.6 m^3 less than that computed against the GPS generated DEM. In this flood event, the LiDAR generated DEM has underestimated the flood water volume by 8.9%.

These volume differences are substantial and would have great impact on flood modelling downstream. It is clear that a DEM that is higher than the ground surface, as is the case for the LiDAR generated DEM, has substantial impact on flood volume due to the variables used to calculate the volume, namely surface area and inundation depth. A higher than actual LiDAR generated DEM produces a flood zone of lesser area than the actual ground surface, and inundation depths shallower than the ground surface would estimate. The water volume is a factor of these two variables and has therefore exhibited these smaller differences in water volume to actual.

4.6 Conclusion

This chapter has presented the results of this research. Validation of GPS data acquisition has been presented and discussed. Vertical accuracy of LiDAR derived DEM has been presented across different grade and land cover classes. These vertical accuracies have been statistically analysed and discussed in regards to results in other studies. Flood zone delineation has been calculated for two different flood surface levels and errors in flood zone surface areas over LiDAR derived DEM have been discussed. Flood inundation depth and water volume analysis has been undertaken and relationship to errors in LiDAR derived DEM has been discussed.

Chapter 5 – Conclusions

5.1 Introduction

Overall the majority of the project aims have been achieved. Vertical accuracy of airborne LiDAR derived DEM has been analysed across the study area of West Creek, Toowoomba, Queensland. Undesirable results were produced in validating GPS data acquisition. However, results from vertical accuracy analysis are consistent with previous research showing that airborne LiDAR data has expected RMSE values between 0.113 m and 0.309 m. The largest RMSE values were produced over areas of grades greater than 20% and areas of long grass/shrubs according to defined land cover classes. Lowest RMSE values were produced over grades 0-5% and areas of cut grass/pavement.

The airborne LiDAR derived DEM has been used for flood zone delineation for indicative flood surface levels estimated from nearby stream gauge station. This was compared to flood zone delineation over GPS derived DEM for the same flood surface levels. The results showed that the LiDAR derived DEM was generally higher in elevation than the GPS derived DEM causing the flood zone delineation to be underestimated by the LiDAR DEM between 1.64-3.7% of the correct flood zone. Flood inundation depths and water volumes were calculated for the LiDAR DEM and compared to depths and volumes calculated using GPS DEM. The RMSE value of depth error for LiDAR derived DEM was calculated as 0.264 m. Differences were significant in volume calculations with the LiDAR DEM underestimating the total water volume by values between 6.3-8.9%.

5.2 Further Research and Recommendations

The results obtained are based off a single survey. Validation of the GPS survey showed mixed results. No gross systematic errors were encountered, although errors were encountered as noted in section 4.1. Further validation of these results would be beneficial in the form of another independent survey over the same study area. This survey would be beneficial as it would be occur at a different time to the original survey and would vary in actual ground points located. Further weight to the study could be gained by using total stations to capture ground data around areas of heavy tree cover, as it was in these areas that the accuracy of the GPS fell and only limited useful data could be obtained. It can be noted that further hydrological survey would need to be completed through water bodies. The data was not accurately gathered at the time of the survey due to safety and property damage concerns. An independent survey of the study area that captured accurate data through areas of heavy tree cover and through water bodies would be most beneficial in confirming these results.

The same logic would also be applied in recommending undertaking the same studies over different areas of the LiDAR data provided by Schlencker Mapping Pty Ltd and over areas of LiDAR data by other sources. This would add weight to validating the accuracy of LiDAR generated DEMs by not limiting the study to 2010 Schlencker Mapping LiDAR Data Capture Project.

It would be recommended to undertake further research in the use of the data sets for flood modelling. Software such as MUSIC (Model for Urban Stormwater Improvement Conceptualisation) or HEC-RAS (Hydrologic Engineering Centre River Analysis System) could be used to model flood events using the GPS and LiDAR generated DEMs with more accurate site-specific data. These software packages have the ability to calculate flow directions, flow velocities, and water quality with input of rainfall quantity, rainfall duration and ground geological properties. This would be beneficial in understanding the relationship between errors in the LiDAR generated DEM and predictions of flash flood behaviour and flood mitigation measures.

5.3 Conclusion

This research has used airborne LiDAR data for DEM generation and for key applications in flood plain mapping. Results have generally agreed with previous studies although LiDAR data has been shown to introduce larger than desirable inaccuracies in some flood plain mapping outputs. Limitations and extent of the research has left much scope for future research into this study area.

Appendices

Appendix A - Project Specification

University of Southern Queensland
FACULTY OF ENGINEERING AND SURVEYING

ENG4111/ENG4112 Research Project
PROJECT SPECIFICATION

FOR: **Maxwell James BURKE, U1002661**

TOPIC: LiDAR Data for digital elevation model generation and flood plain mapping

SUPERVISOR: Dr Xiaoye Liu

PROJECT AIM: This project aims to use airborne LiDAR data to generate a high-resolution DEM for characteristic analysis of West Creek catchment, Toowoomba, QLD. Effective flash flood forecasting for specific locations is a big challenge and calls for accurate spatial information on catchment characteristics. Drainage networks and sub-catchment boundaries will be extracted from LiDAR-derived DEM. The accuracy of DEM and drainage networks will be verified using GPS.

PROGRAMME: (Issue A, 14 July 2013)

- Research studies relating to flood plain mapping, LiDAR technology, DEM generation.
- Obtain LiDAR data of West Creek Catchment in Toowoomba. To be provided by supervisor during on site attendance of University of Southern Queensland.
- Perform GPS topographic survey of West Creek Catchment in Toowoomba.
- Reduce LiDAR data and generate DEM from LiDAR data. Inclusive of applying appropriate filters to remove no-ground points. Extract drainage networks and catchment boundaries from LiDAR generated DEM.
- Generate DEM and extract drainage networks and catchment boundaries from GPS survey.
- Compare DEMs of GPS and LiDAR data over correlating areas. Calculations for flash flooding predictions from GPS and LiDAR data.
- Analysis and evaluation of airborne LiDAR generated DEM for catchment management and flash flood prediction.

AGREED:

_______________(Student) _______________(Supervisor)

14/07/2013 14/07/2013

Appendix B – Risk Assessment Matrix

University of Southern Queensland
Risk Management Plan

Date: 24/7/13	**Faculty/Department:** Surveying	**Assessment completed by:** Max Burke	**Contact number:** 0435154967
What is the task? GPS Topographic Survey		**Location where task is being conducted:** West Creek Reserve from Stennar St south to Kearneys Spring Park.	
Why is the task being conducted? ENG4112 Research Project			
What are the nominal conditions?			
Personnel	**Equipment**	**Environment**	**Other**
Max Burke	Trimble TSC3 Controller Trimble R8 GPS receiver	Outdoors, day time	
Briefly explain the procedure for this task (including reference to other procedures) 1. Site identification 2. GPS topographic survey 3. Download and processing field data			

Risk register and Analysis

[ALARP = As Low As Reasonably Practicable]

Element or Sub Element/ Process Step	**The Risk: What can happen and what will be the result**	**EXISTING CONTROLS**	**Risk Rating with existing controls? See next page**			**Is it ALARP? Yes/No**	**ADDITIONAL CONTROLS REQUIRED**	**Risk Rating with additional controls?**			**Is it ALARP? Yes/No**	**Risk Decision: Accept Transfer Treat**
List major steps or tasks in process	– Electric shock – Eye infection – Fire / explosion – Physical injury – Cut / graze Chemical burn	List all current controls that are already in place or that will be used to undertake the task eg – List of Personal Protective Equipment (PPE) – Identify types facility, location – Existing safety measurers Existing emergency procedures	**Consequences**	**Likelihood**	**Rating**		Additional controls may be required to reduce risk rating eg – Greater containment (PC2) – Additional PPE – gloves safety glasses Specific induction / training	**Consequences**	**Likelihood**	**Rating**		
1. Site Identification	- Sun/weather Exposure	- None	3	C	**M**	No	- Hat, sunglasses, long arm/leg clothing, sunscreen, water bottle	1	E	**L**	Yes	Transfer/treat
	- Cut/graze	- None	2	C	**M**	No	- Carry first aid kit, wear long pants/long sleeve clothing, wear safety boots	1	D	**L**	Yes	Transfer/treat
	- Insect/snake bite	- None	3	D	**M**	No	- Work boots, long leg pants, keep clear of areas of apparent insect or snake habitation	2	D	**L**	Yes	Transfer/treat
	- Crossing roads	- None	4	D	**M**	No	- High visibility vest, use of pedestrian crossings and traffic signals	3	E	**L**	Yes	Transfer/accept
	- Water Features	- None	3	D	**M**	No	- Keep clear of deep water features, keep clear of unstable ground near water features	3	E	**L**	Yes	Transfer/accept

Element or Sub Element/ Process Step	The Risk: What can happen and what will be the result	EXISTING CONTROLS	Risk Rating with existing controls? See next page			Is it ALARP? Yes/No	ADDITIONAL CONTROLS REQUIRED	Risk Rating with additional controls?			Is it ALARP? Yes/No	Risk Decision: Accept Transfer Treat
List major steps or tasks in process	– Electric shock – Eye infection – Fire / explosion – Physical injury – Cut / graze Chemical burn	List all current controls that are already in place or that will be used to undertake the task eg – List of Personal Protective Equipment (PPE) – Identify types facility, location – Existing safety measures Existing emergency procedures	**Consequences**	**Likelihood**	**Rating**		Additional controls may be required to reduce risk rating eg – Greater containment (PC2) – Additional PPE – gloves safety glasses Specific induction / training	**Consequences**	**Likelihood**	**Rating**		
2. GPS topographic survey	- Sun/weather Exposure	- None	3	C	**M**	No	- Hat, sunglasses, long arm/leg clothing, sunscreen, water bottle	1	E	**L**	Yes	Transfer/treat
	- Cut/graze	- None	2	C	**M**	No	- Carry first aid kit, wear long pants/long sleeve clothing, wear safety boots	1	D	**L**	Yes	Transfer/treat
	- Insect/snake bite	- None	3	D	**M**	No	- Work boots, long leg pants, keep clear of areas of apparent insect or snake habitation	2	D	**L**	Yes	Transfer/treat
	- Crossing roads	- None	4	D	**M**	No	- High visibility vest, use of pedestrian crossings and traffic signals	3	E	**L**	Yes	Transfer/accept
	- Water Features	- None	3	D	**M**	No	- Keep clear of deep water features, keep clear of unstable ground near water features	3	E	**L**	Yes	Transfer/accept
3. Download and processing field data	- Electric Shock	- None	3	D	**M**	No	- Keep clear of power points	3	E		Yes	Transfer

Risk Treatment Schedule

Risk No:	Risk (from Risk Register)	Treatment	Person Responsible for Implementation	Timetable for Implementation	Date treatment Completed	Review Effectiveness Effective/Not Effective

Notes:

USQ RISK RATING ADAPTED FROM AS4360:2004

Note: In estimating the level of risk, initially estimate the risk with existing controls and then review risk controls if risk level arising from the risks is not minimal

TABLE 1 - CONSEQUENCE

Level	Descriptor	Examples of Description
1	Insignificant	No injuries. Minor delays. Little financial loss. $0 - $4,999*
2	Minor	First aid required. Small spill/gas release easily contained within work area. Nil environmental impact. Financial loss $5,000 - $49,999*
3	Moderate	Medical treatment required. Large spill/gas release contained on campus with help of emergency services. Nil environmental impact. Financial loss $50,000 - $99,999*
4	Major	Extensive or multiple injuries. Hospitalisation required. Permanent severe health effects. Spill/gas release spreads outside campus area. Minimal environmental impact. Financial loss $100,000 - $250,000*
5	Catastrophic	Death of one or more people. Toxic substance or toxic gas release spreads outside campus area. Release of genetically modified organism (s) (GMO). Major environmental impact. Financial loss greater than $250,000*

* Financial loss includes direct costs eg workers compensation and property damage and indirect costs, eg impact of loss of research data and accident investigation time.

TABLE 2 - PROBABILITY

Level	Descriptor	Examples of Description
A	Almost certain	The event is expected to occur in most circumstances. Common or repetitive occurrence at USQ. Constant exposure to hazard. Very high probability of damage.
B	Likely	The event will probably occur in most circumstances. Known history of occurrence at USQ. Frequent exposure to hazard. High probability of damage.
C	Possible	The event could occur at some time. History of single occurrence at USQ. Regular or occasional exposure to hazard. Moderate probability of damage.
D	Unlikely	The event is not likely to occur. Known occurrence in industry. Infrequent exposure to hazard. Low probability of damage.
E	Rare	The event may occur only in exceptional circumstances. No reported occurrence globally. Rare exposure to hazard. Very low probability of damage. Requires multiple system failures.

USQ RISK RATING ADAPTED FROM AS4360:2004

TABLE 3 – RISK RATING

Probability	Consequence				
	Insignificant 1	Minor 2	Moderate 3	Major 4	Catastrophic 5
A (Almost certain)	M	H	E	E	E
B (Likely)	M	H	H	E	E
C (Possible)	L	M	H	H	H
D (Unlikely)	L	L	M	M	M
E (Rare)	L	L	L	L	L

TABLE 4 - RECOMMENDED ACTION GUIDE

Abbrev	Action Level	Descriptor
E	Extreme	The proposed task or process activity MUST NOT proceed until the supervisor has reviewed the task or process design and risk controls. They must take steps to firstly eliminate the risk and if this is not possible to introduce measures to control the risk by reducing the level of risk to the lowest level achievable. In the case of an existing hazard that is identified, controls must be put in place immediately.
H	High	Urgent action is required to eliminate or reduce the foreseeable risk arising from the task or process. The supervisor must be made aware of the hazard. However, the supervisor may give special permission for staff to undertake some high risk activities provided that system of work is clearly documented, specific training has been given in the required procedure and an adequate review of the task and risk controls has been undertaken. This includes providing risk controls identified in Legislation, Australian Standards, Codes of Practice etc.* A detailed Standard Operating Procedure is required. * and monitoring of its implementation must occur to check the risk level
M	Moderate	Action to eliminate or reduce the risk is required within a specified period. The supervisor should approve all moderate risk task or process activities. A Standard Operating Procedure or Safe Work Method statement is required
L	Low	Manage by routine procedures.

*Note: These regulatory documents identify specific requirements/controls that must be implemented to reduce the risk of an individual undertaking the task to a level that the regulatory body identifies as being acceptable.

The task should not proceed if the risk rating after the controls are implemented is still either HIGH or EXTREME or if any risk is not As Low As Reasonably Practicable (ALARP).

This Risk Assessment score of Low (L) is only on the condition that all existing and additional controls are in place at the time of the task being conducted.

Assessment completed by:	
Name: **Max Burke**	Signature:
Position: **Student**	Contact No: **0435154967**
Date: **24/7/13**	
Supervisor	
Name:	Signature:
Position:	Contact No:
Date: **24/7/13**	
Supervisor	
Name:	Signature:
Position:	Contact No:
Date: **24/7/13**	

7 Day Review of Controls:

This Risk Management Plan is to be reviewed not later than seven (7) days after the commencement of the project.

Reviewing Officer	
Name:	Signature:
Position:	Contact No:
Date:	
Supervisor	
Name:	Signature:
Position:	Contact No:
Date:	

12 Monthly Review of this Risk Management Plan:

This Risk Management Plan is to be reviewed every twelve (12) months and whenever a change has been made to the project or workplace.

Reviewing Officer	
Name:	Signature:
Position:	Contact No:
Date:	
Supervisor	
Name:	Signature:
Position:	Contact No:
Date:	

<u>Guidance Notes for review of Controls and Risk Management Plan.</u>

When monitoring the effectiveness of **control measures**, it may be helpful to ask the following questions:

• **Have the chosen control measures been implemented as planned?**
  - Are the chosen control measures in place?
  - Are the measures being used?
  - Are the measures being used correctly?

• **Are the chosen control measures working?**
  - Have any the changes made to manage exposure to the assessed risks resulted in what was intended?
  - Has exposure to the assessed risks been eliminated or adequately reduced?

• **Are there any new problems?**
  - Have the implemented control measures introduced any new problems?
  - Have the implemented control measures resulted in the worsening of any existing problems?

To answer these questions:

• consult with workers, supervisors and health and safety representatives;
• measure people's exposure (e.g. taking noise measurements in the case of isolation of a noise source);
• consult and monitor incident reports; and
• review safety committee meeting minutes where possible.

Set a date for the review of the **risk management process**. When reviewing, check if:

• the process that is currently in place is still valid;
• things have changed that could make the operating processes or system outdated;
• technological or other changes have affected the current workplace; and
• a different system should be used altogether

Appendix C – LiDAR Report for: Toowoomba Regional Council 2010 LiDAR Capture Project.

SCHLENCKER MAPPING PTY LTD

LiDAR Report for:

TOOWOOMBA REGIONAL COUNCIL

Toowoomba Regional Council

2010 LiDAR Capture Project

BRIEF:

Schlencker Mapping undertook data acquisition using Airborne Laser Scanning (ALS) techniques over a large portion of the Toowoomba Regional Council LGA area. In total more than 2760 square kilometers of data was collected.

ACQUISITION:

Data collection was undertaken using a fixed wing aircraft using the Optech “ALTM Gemini” ALS scanner. On board GPS and IMU systems were supplemented with ground GPS base stations running at all times during flight.

BASE STATIONS:

The airborne survey position was computed from the onboard Applanix dual frequency GPS receiver along with ground base stations and supplemented by corrections from the Applanix IMU. Base stations used were the D.E.R.M. Toowoomba Permanent Base (PM753327) and Toowoomba Regional Council Permanent Base.

GROUND CONTROL:

Ground control points were used as check points against the remotely sensed data. These points were measured using Rapid Static GPS methodologies and consisted of 302 locations throughout the project areas. Control around the urban area of Toowoomba was provided by Toowoomba Regional Council.

The residuals measured on the ground control when compared against the LiDAR surface were as follows:

Toowoomba (179 points)
Average dz 0.021
Average magnitude 0.073
Root mean square 0.101
Std deviation 0.099

Toowoomba South (12 points)
Average dz +0.017
Average magnitude 0.027
Root mean square 0.034
Std deviation 0.032

Oakey (19 points)
Average dz +0.012
Average magnitude 0.035
Root mean square 0.043
Std deviation 0.042

Dam Break Area (14 points)
Average dz 0.034
Average magnitude 0.052
Root mean square 0.065
Std deviation 0.058

Pipeline (6 points)
Average dz 0.031
Average magnitude 0.078
Root mean square 0.091
Std deviation 0.093

Haden (5 points)
Average dz +0.032
Average magnitude 0.041
Root mean square 0.051
Std deviation 0.043

Clifton (7 points)
Average dz -0.005
Average magnitude 0.051
Root mean square 0.060
Std deviation 0.065

Yarraman (6 points)
Average dz +0.028
Average magnitude 0.050
Root mean square 0.053
Std deviation 0.049

Cooyar (5 points)
Average dz +0.000
Average magnitude 0.034
Root mean square 0.039
Std deviation 0.044

Quinlow & Peranga (12 points)
Average dz -0.001
Average magnitude 0.073
Root mean square 0.081
Std deviation 0.084

Pittsworth (15 points)
Average dz +0.004
Average magnitude 0.056
Root mean square 0.068
Std deviation 0.070

Cecil Plains (8 points)
Average dz +0.004
Average magnitude 0.054
Root mean square 0.067
Std deviation 0.072

Tummaville (5 points)
Average dz +0.007
Average magnitude 0.021
Root mean square 0.033
Std deviation 0.036

Millmerran (8 points)
Average dz +0.009
Average magnitude 0.052
Root mean square 0.062
Std deviation 0.066

DATA SUPPLIED:

The following datasets have been supplied as part of the project:

- Ground Points in XYZ(Flight Line) format
- Non-Ground Points in XYZ(Flight Line) format
- 1m DTM in XYZ format
- 1m DTM in ASCII Grid format
- 0.25m Contours in SHP format
- All returns in LAS format

Data has been provided on a square 1km x 1km tile grid.

File naming conventions are based on the South-West corner of the tile and this is shown at the start of each file name. An example of naming for a tile of the 1m DTM is below:

394000_6955000_1k_1m_DEM.xyz - where 394000,6955000 is the South-West corner coordinate of the tile.

REFERENCE DATUM:

The horizontal datum for the project is Geodetic Datum Australia (GDA) and the projection Map Grid Australia (MGA) 1994, Zone 56. The vertical datum is the Australian Height Datum (AHD) based on the ground base stations.

LIDAR METADATA:

Acquisition Start Date	29th June 2010
Acquisition End Date	16th July 3010
Device Name	Optech 'ALTM Gemini'
IMU	Applanix 'Litton 510'
Flying Height (AGL)	1200m
No. of Runs	242
Swath Width	1000m
Side Overlap	30 %
Horizontal Datum	GDA94
Vertical Datum	AHD
Map Projection	MGA Zone56
Control	302 surveyed GPS control points
Vertical Accuracy	±0.15m @ 1σ
Horizontal Accuracy	±0.22m @ 1σ
Surface Type	Ground and DTM
Average Point Separation	1.0m
Laser Return Types	1^{st} through to 4^{th}

DATA VALIDATION:

As LiDAR scanning is a predominately a remote process, data validation is required to confirm the captured data. This is accomplished by comparing field survey data to the remotely sensed data.

Field survey for data validation was undertaken using Trimble R8 GNSS GPS receivers, using continuous topo recording mode with measurements at 50 meter intervals, along gravel and bitumen roads, using a car mounted receiver. During measurement some difficulties were experienced, including loss of lock due to terrain or vegetation, and this may cause some erroneous measurements in the RTK operation, and not necessarily in the laser scanned ground data.

Measurement was made from separate PSM's in each area that had been used to establish the ground control:

At each PSM, the set up was confirmed by check measurements to other existing PSM's as well as ground control targets established for the project and additional points measured by RTK methods that would be suitable for checking using the mobile RTK system.

At each of the check areas the following kilometers of road were measured:

Cecil Plains	8.7 kilometers	261 points
Clifton	20.1 kilometers	568 points
Crows Nest	10.8 kilometers	321 points
Esk	13.5 kilometers	361 points
Goombungee	16.0 kilometers	540 points
Gowrie	14.4 kilometers	458 points
Highfields	10.7 kilometers	300 points
MacLagen	14.3 kilometers	383 points
Millmerran	12.2 kilometers	355 points
Oakey	20.6 kilometers	730 points
Pittsworth	14.8 kilometers	466 points
Toogoolawah	26.3 kilometers	813 points
Toowoomba	21.2 kilometers	457 points
Yarraman	13.7 kilometers	319 points

By measuring along roads, a variety of areas can be verified as well as obtaining validation across different scanning swaths. This is a more effective validation than the traditional method of measuring a lot of points in a restricted area such as a sports field.

A total of 218 kilometers of roads were measured recording 6332 points to an accuracy of +/- .05 meters.

The areas and PSM's used as bases for the validation measurement and the results obtained were as follows:

Cecil Plains From PSM 70770
8 kilometers of roads
261 points
Average magnitude: .052
RMS: .070
Standard Deviation: .058
Points falling outside .15 meters: 13
Percentage within .15 meters: 95.0%

Clifton From PSM 46598
8 kilometers of roads
568 points
Average magnitude: .036
RMS: .046
Standard Deviation: .045
Points falling outside .15 meters: 1
Percentage within .15 meters: 99.8%

Crows Nest From PSM 42419
8 kilometers of roads
321 points
Average magnitude: .067
RMS: .091
Standard Deviation: .089
Points falling outside .15 meters: 32
Percentage within .15 meters: 90.0%

Esk From PSM 32719
35 kilometers of roads
361 points
Average magnitude: .096
RMS: .110
Standard Deviation: .100
Points falling outside .15 meters: 61
Percentage within .15 meters: 83.1%

Goombungee From PSM 70731
22 kilometers of roads
540 points
Average magnitude: .071
RMS: .085
Standard Deviation: .059
Points falling outside .15 meters: 34
Percentage within .15 meters: 93.7%

Gowrie From PSM 4059
20 kilometers of roads
458 points
Average magnitude: .064
RMS: .081
Standard Deviation: .069
Points falling outside .15 meters: 32
Percentage within .15 meters: 93.0%

Highfields From PSM 44129
36 kilometers of roads
300 points
Average magnitude: .082
RMS: .094
Standard Deviation: .050
Points falling outside .15 meters: 16
Percentage within .15 meters: 94.7%

MacLagen From PSM 44037
7 kilometers of roads
383 points
Average magnitude: .046
RMS: .063
Standard Deviation: .063
Points falling outside .15 meters: 15
Percentage within .15 meters: 96.0%

Millmerran From PSM 111709
13 kilometers of roads
355 points
Average magnitude: .036
RMS: .048
Standard Deviation: .048
Points falling outside .15 meters: 2
Percentage within .15 meters: 99.4%

Oakey From PSM 114608
13 kilometers of roads
730 points
Average magnitude: .078
RMS: .091
Standard Deviation: .080
Points falling outside .15 meters: 50
Percentage within .15 meters: 93.2%

Pittsworth From PSM 71157
13 kilometers of roads
466 points
Average magnitude: .049
RMS: .062
Standard Deviation: .052
Points falling outside .15 meters: 4
Percentage within .15 meters: 99.1%

Toogoolawah From PSM 1808
13 kilometers of roads
813 points
Average magnitude: .071
RMS: .087
Standard Deviation: .069
Points falling outside .15 meters: 50
Percentage within .15 meters: 93.8%

Toowoomba From PSM 5337
13 kilometers of roads
457 points
Average magnitude: .076
RMS: .100
Standard Deviation: .083
Points falling outside .15 meters: 55
Percentage within .15 meters: 87.9%

Yarraman From PSM 80996
13 kilometers of roads
319 points
Average magnitude: .057
RMS: .073
Standard Deviation: .058
Points falling outside .15 meters: 7
Percentage within .15 meters: 97.8%

Overall, on the total area verified, the accuracy achieved was over 94% of points within .15 meters, well within the accuracy specifications for the project.

Appendix D – Project Timeline

A timeline for completion of this research project is as follows:

- Continue literature review and background information (early July – mid July)
- Attend University of Southern Queensland for approximately one week (mid July – early August) and complete the following:
  - 2-3 days of GPS topographic survey of Gowrie creek catchment
  - 1 day of reduction of GPS data
  - 1-2 day of reduction of provided LiDAR data of Gowrie Creek catchment
- Calculation of drainage networks, catchment boundaries and flash flood levels from both GPS and LiDAR generated DEMs (early August)
- Comparison and analysis of GPS and LiDAR generated DEMs and calculations (early August – mid August)
- Prepare draft dissertation based on above findings – complete chapters 4 and 5 of dissertation, fill out chapter 3 (mid August – early September)
- Submit draft dissertation early September (latest 11 September)
- Receive feedback from supervisor and amend dissertation accordingly (mid September – mid October)
- Final revision, printing and collation of research project (mid October)
- Submit final dissertation 4:00pm, Thursday 24th October

References

Adams, J.C., and Chandler, J.H. (2002). Evaluation of lidar and medium scale photogrammetry for detecting soft-cliff coastal change, *Photogrammetric Record*, 17(99), pp 405–418.

Bowen, Z.H., and Waltermire, R.G. (2002). Evaluation of light detection and ranging (lidar) for measuring river corridor topography, *Journal of the American Water Resources Association*, 38(1), pp 33–41.

Cobby, D.M., Mason, D.C. and Davenport, I.J. (2001). Image processing of airborne laser altimetry data for improved river modeling, *ISPRS Journal of Photogrammetry and Remote Sensing*, 56(2), pp 121–138.

de Moel H., van Alphen J., Aerts J. C. J. H. (2009) Flood maps in Europe—methods, availability and use. *Nat Hazards Earth System Sciences,* 9(2), pp 289–301. DOI 10.5194/nhess-9-289-2009

de Moel, H., Aerts, J. C. J. H. (2010). Effect of uncertainty in land use, damage models and inundation depth on flood damage estimates. *Nat Hazards (2011),* 58, pp 407-425. DOI 10.1007/s11069-010-9675-6

Dowman, I., and Fischer, P. (2001). A comparison of airborne IfSAR and LIDAR data over the Vaihingen test site, *Proceedings of the OEEPE Workshop on Airborne Laserscanning and Interferometric SAR for Detailed Digital Elevation Models* (K. Torlegard and J. Nelson, editors), 01–03 March, Stockholm, Sweden (OEEPE Pub- lication No. 40, available from the Bundesamt für Kartographie und Geodaesie, Frankfurt am Main, Germany, or at http://www. oeepe.org/publications/pdf/no_40.pdf, last accessed 23 October 2003), pp. 160–169.

Flood, M. (2001). Laser altimetry – from science to commercial LiDAR mapping. *Photogrammetric Engineering and Remote Sensing* 67(11)

Hodgson, M. E. and Bresnahan, P. (2004). Accuracy of Airborne LiDAR-Derived Elevation: Empirical Assessment and Error Budget. *Photogrammetric Engineering and Remote Sensing, 70*(3), pp 331-339.

Hodgson, M.E., Jensen, J.R. Schmidt, L. Schill, S. and Davis, B. (2003). An evaluation of lidar- and IFSAR-derived digital elevation models in leaf-on conditions with USGS Level 1 and Level 2 DEMs, *Remote Sensing of Environment*, 84, pp 295–308.

Hollaus, M., Wagner, W., and Kraus, K. (2005). Airborne laser scanning and usefulness for hydrological models. *Advances in Geosciences* 5(1).

Insurance Council of Australia. (2011). The Nature and Causes of Flooding in Toowoomba 10 January 2011. *ICA Hydrology Panel 14 February 2011*

Liu, X. (2008). Airborne LiDAR for DEM generation: some critical issues. *Progress in Physical Geography, 32*(1), pp 31-49. doi:10.1177/0309133308089496

Liu, X. and Zhang, Z. (2010). Extracting drainage network from high resolution DEM in Toowoomba, Queensland. In: Queensland Surveying and Spatial Conference 2010 (QSSC 2010), 1-3 Sept 2010, Brisbane, Australia.

McDougall, K., Liu, X., Basnet, B. and Apan, A. (2008, July). Digital Elevation Model Accuracy Requirements For Catchment Management. *Global Warming: What's Happening In Paradise?* Queensland Spatial Conference 2008, Gold Coast, QLD.

Merz B., Thieken A. H., Gocht M. (2007). Flood risk mapping at the local scale: concepts and challenges. *Advances in natural and technological hazards research*, 13, pp 231–251.

Queensland Government Department of Natural Resources and Mines (QLD DNRM). (2012). Streamflow Data, 422326A Gowrie Creek at Cranley. [Last accessed: 2nd September 2013. http://watermonitoring.dnrm.qld.gov.au/host.htm]

Raber, G. T., Jensen, J. R., Hodgson, M. E., Tullis, J. A., Davis, B. A. and Berglend, J. (2007). Impact of LiDAR Nominal Post-spacing on DEM Accuracy and Flood Zone Delineation. *Photogrammetric Engineering and Remote Sensing,* 73(7).

Schlencker Mapping Pty Ltd. (2010). LiDAR Report for: Toowoomba Regional Council 2010 LiDAR Capture Project.

Wind H. G., Nierop T. M., de Blois C. J., de Kok J. L. (1999). Analysis of flood damages from the 1993 and 1995 Meuse floods. *Water Resource Res,* 35(11), pp 3459–3465. doi:10.1029/1999WR900192

Zhang, K. , Chen, S., Whitman, D., Shyu, M. L., Yan, J. and Zhang, C. (2003). A Progressive Morphological Filter for Removing Nonground Measurements From Airborne LiDAR Data. *IEEE Transactions on Geoscience and Remote Sensing,* 41(4), pp 872-882. doi:10.1109/TGRS.2003.810682