Quantifying sediment transport from eroding gullies using LiDAR

Sarah Benn

Follow this and additional works at: http://ro.uow.edu.au/thsci

Recommended Citation
Abstract
Gully erosion contributes greatly to sedimentation rates and soil loss in a number of environments globally. Gullies incise drainage lines, increase connectivity within the landscape and facilitate the transportation of sediment and nutrients from upland areas—contributing to excessive sedimentation and nutrient loading in drinking water reservoirs. The extent and increase in gully erosion has traditionally been measured through methods such as aerial photography and cross-sectional surveys. New methods such as high resolution topographic surveys provide the opportunity to measure geomorphic change at levels of detail not previously seen. This study sought to use LiDAR to quantify the response of two gully networks within the Southern Tablelands of New South Wales to a large rainfall event.

High resolution Digital Elevation Models (DEMs) were constructed from LiDAR datasets and differenced to find areas of change using Geomorphic Change Detection software. This enabled the volume of sediment lost from the study sites due to the rainfall event to be determined, which was then used to estimate potential volumes of nitrogen and phosphorus exported. Average gully slope, drainage area, aspect and stream order were all assessed as potential morphological controls on the location and intensity of gully erosion at the study sites.

Both study sites were net erosional during the study period, estimated to have exported thousands of m$^3$ of sediment (13,835 ± 3,945 m$^3$ at Arthursleigh and 2,855 ± 1,587 m$^3$ at Dixons Ck) and associated concentrations of nitrogen and phosphorus (between 3 – 12 t N and 0.47 – 1.7 t P at Arthursleigh and 1 – 4 t N and 0.28 – 0.63 t P at Dixons Ck). The areal change at both sites was small and spatially variable but erosion occurred primarily on gully walls and floors. Morphological controls were deemed to have no influence on erosion at either study site.

This study suggests that LiDAR is a useful tool for quantifying change in gully extent while also providing insight into potential nutrient outputs. It is also suggested that morphological controls such as average slope and drainage area are not the sole determinants for the location and intensity of erosion, with other potential influences such as the rainfall event being considered.

Degree Type
Thesis

Degree Name
BEnviSci Adv Hon

Department
School of Earth & Environmental Sciences

Advisor(s)
Tim Cohen

This thesis is available at Research Online: http://ro.uow.edu.au/thsci/107
Keywords
GIS, Gully erosion, change detection, water, DEM

This thesis is available at Research Online: http://ro.uow.edu.au/thsci/107
Quantifying sediment transport from eroding gullies using LiDAR

Sarah Benn

A research report submitted in partial fulfilment of the requirements for the award of the degree of Bachelor of Environmental Science Advanced (Honours)

October 2015
The information in this thesis is entirely the result of investigations conducted by the author, unless otherwise acknowledged, and has not been submitted in part, or otherwise, for any other degree or qualification.

Sarah Benn
27th October 2015
Cover image: Gully at Arthursleigh in the Southern Tablelands of New South Wales, photographed on 20th October 2015 by Charissa Harris
Acknowledgements

There’s no doubt about it—honours is hard. Never in my life have I dedicated so much time, energy and brainpower to one single thing. However I can also confidently say that I have never before learnt so much or grown as substantially as a person in such a short period of time. The completion of this project would not have been possible without the assistance and general presence of a number of people.

Firstly, to my university supervisor Dr. Tim Cohen; thank you for your encouragement, feedback, direction and suggestions. I appreciate that your office door was always open and this thesis would not have been anywhere near as comprehensive without your gentle nudging, which I am thankful for.

Alex and Heidi in SAL, thank you for your support with everything GIS related. Alex you were always available and always helpful and I thank you sincerely for that. I’d also like to extend my thanks to Marina McGlinn for ensuring the smooth running of the BEnvSci program and for being helpful at all times, no matter what the issue.

Thank you also to John Bickmore at WaterNSW for providing everything I needed to start this project and to Bernie Millynn for taking over in John’s absence and providing helpful advice and critical review. I would also like to thank Lizanne Wilmot for providing generous access to her thesis and resources.

Finally, special mention goes to my honours cohort and friends for helping maintain my sanity throughout the year. To my girls, thanks for the coffees, chats, long lunches and girls nights away from thesis writing. To my boys, thank you for the endless banter, positive life encouragement and mathematical assistance when required. To my flatmates, thank you for taking care of me during the year. To Sherry in particular, thank you for the chats, offers of tea and your editorial expertise. And last of all, to my parents, thank you for tolerating my moods and taking care of me from afar and for your support throughout the year. Mum, thank you for your emotional support and advice and dad, thank you for texting me pictures of frogs, gardens, food and whatever else you happened to be up to while I was working on my thesis, they always brightened my day.
Abstract

Gully erosion contributes greatly to sedimentation rates and soil loss in a number of environments globally. Gullies incise drainage lines, increase connectivity within the landscape and facilitate the transportation of sediment and nutrients from upland areas—contributing to excessive sedimentation and nutrient loading in drinking water reservoirs. The extent and increase in gully erosion has traditionally been measured through methods such as aerial photography and cross-sectional surveys. New methods such as high resolution topographic surveys provide the opportunity to measure geomorphic change at levels of detail not previously seen. This study sought to use LiDAR to quantify the response of two gully networks within the Southern Tablelands of New South Wales to a large rainfall event.

High resolution Digital Elevation Models (DEMs) were constructed from LiDAR datasets and differenced to find areas of change using Geomorphic Change Detection software. This enabled the volume of sediment lost from the study sites due to the rainfall event to be determined, which was then used to estimate potential volumes of nitrogen and phosphorus exported. Average gully slope, drainage area, aspect and stream order were all assessed as potential morphological controls on the location and intensity of gully erosion at the study sites.

Both study sites were net erosional during the study period, estimated to have exported thousands of m$^3$ of sediment (13,835 ± 3,945 m$^3$ at Arthursleigh and 2,855 ± 1,587 m$^3$ at Dixons Ck) and associated concentrations of nitrogen and phosphorus (between 3 – 12 t N and 0.47 – 1.7 t P at Arthursleigh and 1 – 4 t N and 0.28 – 0.63 t P at Dixons Ck). The areal change at both sites was small and spatially variable but erosion occurred primarily on gully walls and floors. Morphological controls were deemed to have no influence on erosion at either study site.

This study suggests that LiDAR is a useful tool for quantifying change in gully extent while also providing insight into potential nutrient outputs. It is also suggested that morphological controls such as average slope and drainage area are not the sole determinants for the location and intensity of erosion, with other potential influences such as the rainfall event being considered.
# Table of Contents

Acknowledgements ........................................................................................................... i  
Abstract .......................................................................................................................... ii  
Table of Contents ............................................................................................................. iii  
Table of Figures .............................................................................................................. vi  
Table of Tables ............................................................................................................... ix  
List of Abbreviations ....................................................................................................... x  

Chapter One: Introduction ............................................................................................. 1  
  1.1 Study context ........................................................................................................... 1  
  1.2 Aims and objectives ............................................................................................... 2  
  1.3 Thesis structure .................................................................................................... 3  

Chapter Two: Literature Review ................................................................................... 4  
  2.1 An introduction to gully erosion ........................................................................... 4  
  2.1.1 Controls on gully erosion .................................................................................. 5  
  2.1.2 Gully erosion in Australia ............................................................................... 7  
  2.1.3 The consequences of gully erosion ................................................................. 8  
  2.2 History of gully erosion in NSW ......................................................................... 10  
  2.3 Techniques for measuring and managing gully erosion and change .................. 13  
  2.3.1 Measuring gully erosion .................................................................................. 13  
  2.3.2 Managing gully erosion .................................................................................. 13  
  2.4 The use of high resolution topographic data for modelling sediment transport and nutrient export loads ......................................................................................... 15  
  2.4.1 Quantifying error in DEMs of Difference (DoDs) ........................................... 16  
  2.5 Concluding remarks ............................................................................................. 17  

Chapter Three: Regional Setting ................................................................................. 18  
  3.1 Location ................................................................................................................ 18  
  3.2 Geological setting ................................................................................................. 20  
  3.3 Soils ....................................................................................................................... 21  
  3.4 Climate .................................................................................................................. 22  
  3.4.1 Rainfall record ................................................................................................. 22  
  3.4.2 March 2012 rainfall event .............................................................................. 24  
  3.5 Land use and gully characteristics ....................................................................... 28  
  3.5.1 Catchment wide ............................................................................................. 28
### Chapter Four: Methods

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1 Quantifying gully erosion</td>
<td>36</td>
</tr>
<tr>
<td>4.1.1 LiDAR survey</td>
<td>36</td>
</tr>
<tr>
<td>4.1.2 Development of Digital Elevation Models (DEM)</td>
<td>37</td>
</tr>
<tr>
<td>4.1.3 Change detection</td>
<td>38</td>
</tr>
<tr>
<td>4.1.4 Change detection uncertainty</td>
<td>38</td>
</tr>
<tr>
<td>4.1.5 Assessment of morphological controls on gully erosion</td>
<td>42</td>
</tr>
<tr>
<td>4.2 Determination of nitrogen and phosphorus</td>
<td>46</td>
</tr>
<tr>
<td>4.3 Comparison of change in 2011-2012 with historical rates of change</td>
<td>49</td>
</tr>
</tbody>
</table>

### Chapter Five: Results

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.1 Uncertainty analysis</td>
<td>51</td>
</tr>
<tr>
<td>5.1.1 Selected uncertainty analysis method</td>
<td>56</td>
</tr>
<tr>
<td>5.2 Reach scale results</td>
<td>57</td>
</tr>
<tr>
<td>5.2.1 Erosional and depositional changes</td>
<td>57</td>
</tr>
<tr>
<td>5.2.2 Rates of sediment export</td>
<td>61</td>
</tr>
<tr>
<td>5.3 Morphological controls on gully erosion</td>
<td>63</td>
</tr>
<tr>
<td>5.3.1 Drainage area</td>
<td>63</td>
</tr>
<tr>
<td>5.3.2 Average slope</td>
<td>64</td>
</tr>
<tr>
<td>5.3.3 Stream order</td>
<td>65</td>
</tr>
<tr>
<td>5.3.4 Aspect</td>
<td>67</td>
</tr>
<tr>
<td>5.4 Nitrogen and phosphorus</td>
<td>68</td>
</tr>
<tr>
<td>5.4.1 Nitrogen and phosphorus characteristics</td>
<td>68</td>
</tr>
<tr>
<td>5.4.2 Estimation of nitrogen and phosphorus eroded between 2011-2012</td>
<td>70</td>
</tr>
<tr>
<td>5.5 Change in 2011-2012 Compared with Historical Rates of Change</td>
<td>72</td>
</tr>
<tr>
<td>5.6 Summary of results</td>
<td>75</td>
</tr>
</tbody>
</table>

### Chapter Six: Discussion

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.1 Uncertainty analysis in DEMs of Difference</td>
<td>76</td>
</tr>
<tr>
<td>6.2 Reach scale changes</td>
<td>77</td>
</tr>
<tr>
<td>6.2.1 Morphological response of gullies to the March 2012 rainfall event</td>
<td>77</td>
</tr>
<tr>
<td>6.3 Morphological controls on gully erosion</td>
<td>78</td>
</tr>
<tr>
<td>6.4 Estimated nitrogen and phosphorus export</td>
<td>79</td>
</tr>
<tr>
<td>6.5 Rates of change compared with historical rates of change</td>
<td>81</td>
</tr>
<tr>
<td>6.5.1 Sediment export rates</td>
<td>82</td>
</tr>
</tbody>
</table>
6.5.2 Nutrient export rates.........................................................83

Chapter Seven: Conclusions and Recommendations........................................85
  7.1 Recommendations................................................................................86

References.....................................................................................................87

Appendix A – Soil test results ........................................................................93
Appendix B – BOM IFD Charts for Arthursleigh and Dixons Ck......................94
Appendix C – LiDAR metadata report............................................................96
Appendix D – N and P export calculations.....................................................97
Appendix E – Nutrient and sediment export rate calculations........................102
Appendix F – Uncertainty analysis results....................................................104
Appendix G – Raw change detection maps ..................................................105
Appendix H – GIS data................................................................................107
# Table of Figures

**Figure 2.1**: Example of gully erosion at Arthursleigh in the Southern Tablelands of NSW .................. 4  
**Figure 2.2**: Gully density map of areas with gully density data within Australia........................................ 7  
**Figure 2.3**: Locality map showing the greater Southern Tablelands region of NSW ............................ 11  
**Figure 2.4**: Comparison of overland flow routes between swampy meadows (chain-of-ponds) and incised channels............................................................................................................................................. 12

**Figure 3.1**: The location of the study areas within the greater Warragamba catchment and within their respective drainage units........................................................................................................ 19  
**Figure 3.2**: Geology of the Warragamba Catchment ....................................................................................... 20  
**Figure 3.3**: The location of daily rainfall stations used in the study............................................................. 23  
**Figure 3.4**: Rainfall intensity maps representing the individual days comprising the event and the total rainfall over the three days........................................................................................................ 25  
**Figure 3.5**: Total rainfall spanning the period of the study from 1/08/2011-20/06/2012. ......................... 27  
**Figure 3.6**: Gully erosion within the Warragamba catchment, showing the increased density within the western portion........................................................................................................................................ 29  
**Figure 3.7**: Headcut erosion at Arthursleigh................................................................................................ 30  
**Figure 3.8**: Long profile of the primary gully at Arthursleigh................................................................. 31  
**Figure 3.9**: The location of both the long profile and five transects taken at Arthursleigh...................... 32  
**Figure 3.10**: Sheer gully walls in the northern portion of Dixons Ck (left) and a small headcut in the cropped southern portion of Dixons Ck (right)...................................................................................................................... 33  
**Figure 3.11**: Long profile of the primary gully at Dixons Ck........................................................................ 34  
**Figure 3.12**: The location of both the long profile and six transects taken at Dixons Ck..................... 35

**Figure 4.1**: Clipped DEMs used for change detection analysis ............................................................... 37  
**Figure 4.2**: a) Spatially uniform error surface with a value of 0.20 m used for MinLoD analysis. b) spatially variable error surface derived via a fuzzy inference system used for probabilistic analysis. 39  
**Figure 4.3**: An example from the 2011 Dixons Ck LiDAR showing the inputs used to create a spatially variable FIS error surface.......................................................................................................................... 41  
**Figure 4.4**: An example of contour banks directing the delineated drainage lines around the gullies at Arthursleigh .................................................................................................................................................... 42  
**Figure 4.5**: An example from Arthursleigh showing how the gully area (in pink) was clipped according to the catchment areas (orange) produced by ArcHydro .................................................................................................................. 43  
**Figure 4.6**: An example from Arthursleigh showing how a polygon representing the study area has been sectioned according to gully segment, with each segment representing a separate average slope value........................................................................................................................................ 44
Figure 4.7: An example of stream order classified gullies at Dixons Ck ............................................ 45
Figure 4.8: The location of soil test sites used to determine average nitrogen and phosphorus
centrations for both study sites............................................................................................................. 46
Figure 4.9: Diagrammatic explanation of the four scenarios considered when estimating N + P
export. ..................................................................................................................................................... 48
Figure 4.10: Gullies at Dixons Ck under dense vegetation, making it difficult to discern the location
of headcuts. .......................................................................................................................................... 49

Figure 5.1: Comparison of uncertainty analysis methods used to determine net volumetric change
with calculated RMS error ..................................................................................................................... 52
Figure 5.2: DoD outputs for a small subsection of Dixons Ck. .................................................................54
Figure 5.3: Elevation change distributions for the DoDs produced for a small subsection of Dixons
Ck.......................................................................................................................................................... 55
Figure 5.4: Reach scale map of the gullies at Arthursleigh showing the DoD using 0.20m MinLoD +
95% CI. ........................................................................................................................................ 58
Figure 5.5: Elevation change distributions for Arthursleigh expressed as surface area (a) and volume
(b). ...................................................................................................................................................... 59
Figure 5.6: Reach scale map of the gullies at Dixons Ck overlain with the DoD created with 0.20m
MinLoD + 95% CI. ............................................................................................................................... 60
Figure 5.7: Elevation change distributions for Dixons Ck expressed as surface area (a) and volume
(b). ...................................................................................................................................................... 61
Figure 5.8: Linear regression plots of total change (m^3) vs drainage area (m^2) at a) Arthursleigh and
b) Dixons Ck ........................................................................................................................................ 63
Figure 5.9: Linear regression plots of total change (m3) vs average slope (%) at a) Arthursleigh and
b) Dixons Ck ....................................................................................................................................... 64
Figure 5.10: Total erosion for each stream order class (a) and mean change per metre for each stream
order class (b) at Arthursleigh................................................................................................................ 65
Figure 5.11: Total erosion for each stream order class (a) and mean change per metre for each stream
order class (b) at Dixons Ck.................................................................................................................. 66
Figure 5.12: Total erosion in north and south flowing tributaries at Arthursleigh (a) and east and west
flowing tributaries at Dixons Ck (b) ..................................................................................................... 67
Figure 5.13: Linear regression plots showing a) nitrogen vs Clay %, b) phosphorus vs clay %, c)
nitrogen vs silt %, d) phosphorus vs silt % ......................................................................................... 69
Figure 5.14: The extension of gullies at Arthursleigh through time from 1949-2011 ......................... 73
Figure 5.15: A section of gullies at Arthursleigh showing both gully extension and recession through
time from 1949-2011.. ........................................................................................................................... 74
Figure 6.1: Estimated total sediment yields for the catchment of Jerrabomberra Creek within the Southern Tablelands from before European settlement showing the peak and subsequent decline in sediment yield.
Table of Tables

Table 3.1: Mean monthly rainfall data from stations closest to study sites. ......................................................... 23
Table 3.2: Annual summary statistics and daily totals for rainfall stations close to the study sites. .................. 24
Table 3.3: Intensity-Frequency-Duration analysis for 24hr and 72hr periods for all weather stations. ......................... ......................................................................................................................................................... 26

Table 4.1: Attributes for the four surveys used in this study to develop DEMs. .................................................. 36
Table 4.2: Summary of the different uncertainty analysis methods used and their associated error surfaces ......................................................................................................................................................... 39
Table 4.3: The number tributaries classified according to their aspect at both study sites .......................... 44
Table 4.4: Different treatments applied to nitrogen and phosphorus export estimations ............................ 47
Table 4.5: Available imagery for Arthursleigh used to estimate historical rates of change .......................... 50

Table 5.1: Volumetric change for Arthursleigh calculated from the DoD ......................................................... 57
Table 5.2: Volumetric change for Dixons Ck calculated from the DoD ............................................................. 59
Table 5.3: Total mass of sediment exported at both sites under four scenarios examined. ....................... 62
Table 5.4: Average nitrogen and phosphorus content per 1 m$^3$ of soil at the study sites ....................... 68
Table 5.5: Tonnages of nitrogen and phosphorus exported from Arthursleigh between 2011 and 2012. .... 70

Table 5.6: Tonnages of nitrogen and phosphorus exported from Dixons Ck between 2011 and 2012. .... 71
Table 5.7: The extension of gully heads and the average rate of extension at Arthursleigh since 1949 measured from aerial photographs of the site. ................................................................................................................................................................................................. 72

Table 6.1: Modelled nitrogen and phosphorus exports from gully erosion for the Upper Wollondilly (within which Dixons Ck is located) and Wollondilly (within which Arthursleigh is located) sub-catchments ........................................................................................................................................................................................................................................ 80
Table 6.2: Sediment export rates in the Southern Tablelands from different time periods ..................... 83
Table 6.3: Comparison of rates of nitrogen and phosphorus export at Arthursleigh and Dixons Ck against an estimated rate for the Southern Tablelands during peak erosion during European Settlement .................................................................................................................................................................................................................................................................................. 83
List of Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AHD</td>
<td>Australian height datum</td>
</tr>
<tr>
<td>ARI</td>
<td>Average recurrence interval</td>
</tr>
<tr>
<td>BOM</td>
<td>Bureau of Meteorology</td>
</tr>
<tr>
<td>DEM</td>
<td>Digital Elevation Model</td>
</tr>
<tr>
<td>DoD</td>
<td>DEM of difference</td>
</tr>
<tr>
<td>DSM</td>
<td>Digital surface model</td>
</tr>
<tr>
<td>FIS</td>
<td>Fuzzy inference system</td>
</tr>
<tr>
<td>GCD</td>
<td>Geomorphic change detection</td>
</tr>
<tr>
<td>IFD</td>
<td>Intensity frequency duration</td>
</tr>
<tr>
<td>MinLoD</td>
<td>Minimum level of detection</td>
</tr>
<tr>
<td>N</td>
<td>Nitrogen</td>
</tr>
<tr>
<td>P</td>
<td>Phosphorus</td>
</tr>
<tr>
<td>RTK-GPS</td>
<td>Real time kinematic- global positioning system</td>
</tr>
<tr>
<td>TIN</td>
<td>Triangular irregular network</td>
</tr>
<tr>
<td>TLS</td>
<td>Terrestrial laser scanner</td>
</tr>
</tbody>
</table>
Chapter One: Introduction

1.1 Study context
Gully erosion represents a large contribution to soil loss and sedimentation rates in a number of environments (Poesen et al., 2003). Gullies generally manifest as steep sided erosional channels, bare of vegetation on both the walls and floor, with a head that cuts upstream (Ford et al., 1993). Environments that are particularly prone to the development of gullies include those with topography that focuses overland flow into a concentrated stream, areas where land management practices have involved a reduction of vegetative cover and environments where the soil profile offers little resistance to erosive flow (Bocco, 1991; Rose et al., 2014). Gully erosion can be initiated by extreme events such as floods or fire, intrinsic thresholds such as slope steepening and flow confinement or basin wide and site specific changes such as land use practices and ploughing (Prosser, 1991).

The development of gullies increases connectivity within the landscape and effectively enables the transportation of runoff and sediments from upland areas into watercourses, affecting water quality (Poesen et al., 2003). The use and exploitation of lands in upper catchment areas is increasingly being found to have a detrimental effect on water quality due to increased sedimentation and nutrient loads in runoff, which is then concentrated downstream (Valentin et al., 2005). Gully erosion in upper catchment areas has been found to be a large contributor to excessive sedimentation and nutrient loading in reservoirs (Armstrong & Mackenzie, 2002; Wasson et al., 2002). Research in the Southern Tablelands of New South Wales (NSW) indicates that gullied catchments produce a sediment yield at least an order of magnitude higher than ungullied catchments in the same region (Armstrong & Mackenzie, 2002). In addition to this, the erosion of topsoil from catchments represents a significant loss in terms of arable land available for agricultural use. In NSW, soil forms at a rate of 0.04 – 0.4 tonnes/ha per year, however losses from pastures can exceed 1 tonne/ha per year, making soil an essentially non-renewable resource (Alt et al., 2009). As well as resulting in a loss of soil, gullies developing on agricultural land can also impede the passage of farm equipment and reduce the agricultural output of a property (Shruthi et al., 2015).

For this reason, gullies in water catchments represent a significant concern to land managers, particularly those concerned with water quality. While the amount of sediment eroding from gullied areas in NSW has slowed dramatically since large volumes yielded during the 1800s coinciding with European settlement (Wasson et al., 1998), turbidity and nutrient issues
continue to affect potable water storages in NSW (Olley et al., 2004). Monitoring gully erosion in catchment areas remains a key issue for land managers, allowing for preventative and remedial works to be applied. Repeat topographic surveys are an accepted and widely used method for examining temporal change in erosional environments (James et al., 2007; Rose et al., 2014; Thoma et al., 2005; Wheaton et al., 2010). Repeat surveys with methods such as LiDAR (Light Detection and Ranging) can provide an indication of the rate of headcut progression as well as the volume of sediment being lost from gullied reaches over the survey period, providing high resolution data to land managers (Rengers & Tucker, 2015; Wheaton et al., 2010).

This study examines the response of gullies at two study sites within the Warragamba catchment in NSW to a large rainfall event in March 2012. The drainage units within which both sites are located have been classified as at risk of pollution from suspended solids, nitrogen and phosphorus associated with gully erosion (Sydney Catchment Authority’s Pollution Source Assessment Tool (PSAT)) (Sydney Catchment Authority, 2011a). While repeat topographic surveys are an increasingly popular method of assessing morphological change by land managers, this method has not yet been used to assess sediment and nutrient export from eroding gullies within the Southern Tablelands.

1.2 Aims and objectives
This project aims to use high resolution repeat LiDAR surveys to determine the response of gullies at two study sites to a large rainfall event in March 2012. This study aims to quantify movement of sediment within the gullies and provide an estimation of the amount of nitrogen and phosphorus eroded from the gullies due to the rainfall event. Specifically, this project will:

- Use repeat LiDAR at two field sites to quantify rates and location of change
- Use change detection as a pilot study for the development of a model for quantifying sediment transport and nutrient export loads from eroding gullies
- Assess the impact of a large rainfall event (March 2012) on gully erosion at the two study sites and place the LiDAR derived rates of change in context of historical changes in gully extent
The importance of this study is twofold:

- This study will explore the impacts of gully erosion on Sydney’s drinking water catchment on a small scale. Both study sites drain into the Wollondilly River which forms an integral part of the Warragamba catchment—Sydney’s primary drinking water supply.
- This study seeks to quantify the landscape response of gullies to an event of a given magnitude—information that may assist in informing best practice for negating the effects of future large magnitude storm events.

1.3 Thesis structure
This thesis presents a review of the current literature on gully erosion, covering gully erosion in the Southern Tablelands of NSW and methods for managing and monitoring gully erosion before covering the use of high resolution topographic surveys for measuring geomorphic change and determining sediment and nutrient exports (Chapter 2). Chapter 3 covers the regional setting of the Warragamba catchment and the study sites, including a characterisation of the March 2012 rainfall event and gully morphology at both study sites. The methods of data collection, analysis and use of Geomorphic Change Detection software are detailed in Chapter 4. In Chapter 5, the results of the analysis of LiDAR and aerial photography are presented, along with estimations of nitrogen and phosphorus export from eroding gullies. The following chapter (Chapter 6) discusses the implications of the results of this study, in particular their relation to the broader literature on gully erosion in the Southern Tablelands, including the limitations of this study. Finally, in Chapter 7 a number of recommendations for future avenues of investigation into gullies in the Southern Tablelands using LiDAR are provided, along with the broader conclusions identified from this study.
Chapter Two: Literature Review

2.1 An introduction to gully erosion
Gully erosion represents a major contribution to sediment generation in many environments (Poesen et al., 2003; Rustomji, 2006a). Permanent erosion gullies can best be described as incised channels on alluvial or colluvial deposits, created by overland or subsurface flow (Fig. 2.1) (Rustomji, 2006a). Gullies are often considered permanent features when they cannot easily be removed by ordinary farm tillage, as opposed to ephemeral agricultural gullies which develop along natural drainage lines and are filled each year (Meyer, 1986). After developing, gullies can persist at scales of decades to centuries—eroding and expanding until some threshold is reached and aggradation commences (Rustomji, 2006a; Valentin et al., 2005).

![Figure 2.1: Example of gully erosion at Arthursleigh in the Southern Tablelands of New South Wales (Credit: Charissa Harris)](image)

Gully erosion occurs in many different parts of the world including Australia (Rustomji, 2006a; Wasson et al., 1998), South Africa (Boardman et al., 2003), China (Fang & Guo, 2015), the United States (Gellis et al., 2001; James et al., 2007) and Europe (Martinez-Casasnovas, 2003; Poesen & Govers, 1990). In these regions, gully erosion has also been found to contribute significant amounts of sediment to waterways, affecting water quality and
aquatic habitat (Valentin et al., 2005). For this reason, much consideration has been given to the prevention and control of gully erosion in order to prevent future soil losses and associated effects (Poesen et al., 2003; Valentin et al., 2005).

2.2.1 Controls on gully erosion
The rate and volume of sediment yielded from an eroding gully system is highly dependent on a number of factors including land use, lithology and temporal factors such as seasonality. Land use has a dramatic effect on the amount of sediment yielded. The rate of erosion from intensive land use may dramatically exceed the rate of natural erosion occurring in a region beforehand, leading to extensive landscape changes (Meyer, 1986). If not managed correctly, agricultural land can be prone to developing large gully networks and in turn, exporting large volumes of sediment due to the reduction of protective ground cover and incision of drainage lines (Scott, 2001). Findings from south-eastern Australia indicate that the sediment transport capacity for cropland is 2 times higher than that of degraded pasture, and 20 times higher than that of good pasture and native forest (Verstraeten et al., 2007). Furthermore, agricultural land is predisposed to the formation of ephemeral gullies—gullies that develop along drainage lines year-to-year but are filled in by tillage (Meyer, 1986). Ephemeral gullies can represent a large contribution to erosion from agricultural lands, up to 30 to 100 per cent being reported in some regions (Casalí et al., 1999). Although ephemeral gullies are filled by tillage at the end of the season, the soil with which they are filled is often of inferior quality, leading to a net loss of valuable topsoil from the system (Daggupati et al., 2014).

The distribution of lithology in an area strongly influences soil type and landforms which in turn can increase predisposition to gully erosion (Olley et al., 2004). Bedrock structures such as joints can influence the development of gullies in mountainous areas by structurally controlling the gravitational and hydrological processes occurring (Loye et al., 2012). Furthermore, by controlling the shape of the landscape, lithology determines factors such as contributing drainage area, local slope gradients and aspect—which are all morphological factors that have been found to influence gully erosion (Fang & Guo, 2015; Montgomery & Dietrich, 1989; Sheridan et al., 2000; Torri & Poesen, 2014; Valentin et al., 2005). Slope aspect is believed to influence erosion due to the degree of sunlight opposing slopes receive, with more sun exposed slopes often experiencing greater erosion (Fang & Guo, 2015). Hill slope gradient also influences erosion, with increased slopes expected to facilitate more extreme overland flow, removing sediment more effectively (Torri & Poesen, 2014). Drainage area controls the amount of overland flow likely to pass through a drainage line. It
is expected that larger drainage areas result in higher flows which would result in increased erosion (Montgomery & Dietrich, 1989; Torri & Poesen, 2014).

Perhaps the greatest influence of lithology on sediment yield is the type of soil found in a region, including the rate of soil production and the thickness of the soil profile (Edwards & Zierholz, 1991), with some soil types being more prone to erosion than others. Dispersive soils are a particularly problematic soil associated with gully erosion. Dispersive soils contain a high proportion of sodium ions, which results in larger repulsive than attractive forces between clay particles when submerged (Umesh et al., 2011). When these soils are exposed, saturation from overland flows causes the clay particles to segregate which in turn causes the soils to disperse (Ford et al., 1993).

Seasons and the magnitude and frequency of events such as storms and droughts can impact the amount of sediment yielded from a gully system. The formation of ephemeral gullies in some regions has a strong connection with rainfall events, erosion being particularly likely in months where the ground is wetter and there is less vegetative cover (Capra et al., 2009). In alluvial gully environments, frequent cycles of wetting and drying are believed to contribute to the basal sapping of subsoils, leading to gully growth (Brooks et al., 2007). Storm events may cause sediments to be derived from other sources such as sheet and rill erosion in addition to erosion from gullies (Olley et al., 1993). Flooding can result in overland flow rushing over the sidewalls of gullies, undercutting the sidewalls and eroding gully floors (Saynor & Erskine, 2006). Flooding after sustained periods of drought in particular can lead to severe erosion (Caitecheon et al., 2012), primarily due to the removal of protective groundcover vegetation during drought making the bare earth more susceptible to incision by overland flow (Waters & Haynes, 2001).
2.2.2 Gully erosion in Australia
Rainfall in Australia is both spatially and temporally variable. Stream hydrological regimes in Australia are dominated by storm and flood events, represented by low annual runoff and high variability (Olive & Rieger, 1986). This high variability contributes to erosion in many Australian catchments and many Australian rivers are typically turbid with high loads of colloidal material due to the effects of gully erosion and bank slumping (Davis & Koop, 2006), some of which may be a function of landscape disturbance since initial settlement. Sediment in Australian catchments is supplied by a combination of hillslope, channel and gully erosion (Olley & Wasson, 2003). Australia has had a particularly damaging history of gully erosion, some of which will be detailed in Chapter 2.2. Significant gullying has occurred within south-eastern NSW (Armstrong & Mackenzie, 2002; Prosser, 1991; Prosser et al., 1994) the Murray Darling Basin, spanning parts of Queensland, New South Wales and Victoria (Scott, 2001) and areas in tropical and sub-tropical Queensland (Brooks et al., 2007; Saxton et al., 2012). Figure 2.2 shows the extent and density of gullies across Australia as produced for the National Land and Water Resource Audit (Hughes et al., 2001).

![Figure 2.2: Gully density map of areas with gully density data within Australia. Green areas represent kilometres of gully length per square kilometre, white represents no data. Red square shows the location of the Southern Tablelands, the primary focus of this thesis. From Hughes et al. (2001).](image-url)
The most intense areas of erosion can be seen in the eastern highlands of NSW, however these gullies developed and underwent most of their expansion the late 19\textsuperscript{th} century (Prosser \textit{et al.}, 2001a). This is largely contrasted with the developing situation in north Queensland where gullies have been recently developing and expanding on grazing lands, delivering significant amounts of sediment and nutrients into large rivers such as the Burdekin (Prosser \textit{et al.}, 2001a). Tasmania and far north Queensland have very little gully erosion, which can be attributed to good vegetative cover, naturally well-developed stream networks and broad valleys (Prosser \textit{et al.}, 2001a).

\subsection*{2.2.3 The consequences of gully erosion}

The effects of gully erosion can be felt at both a local and at a catchment wide scale. On a local scale there are issues with loss of soil and available arable land for agriculture (Alt \textit{et al.}, 2009). At a catchment-wide scale, water quality issues related to nutrient loading and turbidity from upper catchment areas can be amplified into water storages. It can be difficult to quantify just how much sediment eroded from the top of a gully system will be transported through a catchment area, as the most dense sediments are deposited first and very fine material may remain in suspension for a long period of time (Meyer, 1986). Generally speaking, sediment from gully erosion is released in discrete pulses, as headcut erosion drives upstream incision (Rengers & Tucker, 2015). These discrete pulses, often associated with extreme weather events, can create cycles of eutrophication and turbidity problems in lower catchment areas (Davis & Koop, 2006).

Nitrogen (N) and phosphorus (P), liberated from the soil by gully erosion and overland flow, are delivered to stream channels via runoff (Agudelo \textit{et al.}, 2011). These nutrients contribute greatly to the eutrophication of water sources which presents issues for fisheries, aquaculture, tourism and can threaten drinking water supplies with some species of cyanobacterium shown to pose a serious threat to human health (Hawkins \textit{et al.}, 1985). Agricultural catchments have long contributed to increased nutrient loading and erosion-induced turbidity in water supplies they contribute to (Armstrong & Mackenzie, 2002). The addition of N and P from fertilisers and animal waste as well as that from gully erosion can make the nutrient loads from these lands particularly high (Davis & Koop, 2006). While N and P are not the only factors that contribute to eutrophication, better management of gully erosion can limit the amount of N and P available in waterways for assimilation by algae, thus limiting the growth of algal blooms (Davis & Koop, 2006).
Turbid flows originating from gully erosion and bank slumping in upper catchment areas represent a common problem associated with gully erosion (Davis & Koop, 2006). Suspended sediments in waterways can affect the temperature, taste, abrasiveness, odour and clarity of water (Oschwald, 1972). Turbidity can also cause a reduction in light penetration which has negative consequences for photosynthetic organisms within aquatic ecosystems (Oschwald, 1972). Additionally, an influx of large amounts of coarse sediment can alter river bed morphology, covering aquatic vegetation, large woody debris and removing valuable habitat (Prosser et al., 2001b).
2.2 History of gully erosion in NSW

It is generally accepted that European settlement and land use practices in Australia resulted in a dramatic change to the landscape, particularly in south-eastern NSW (Eyles, 1977; Saxton et al., 2012; Wasson et al., 1998). Prior to European settlement, it is believed that much of the landscape was dominated by alluvial flats covered with grasses and sedge. These ‘swampy meadows’ facilitated aggradation within the landscape, with the moist swampy basins accumulating sediment (Prosser et al., 1994). Within these basins, drainage lines were characterised by chains of ponds; small reedy streams flowing between deep ponds, on the swampy floodplains (Eyles, 1977). Despite the general trend toward aggradation within the landscape, episodes of gully erosion still occurred before settlement, largely thought to be due to the effects of climate and fire (McKenzie et al., 2004).

Major gully erosion started throughout south-eastern NSW in the late 1800s, coinciding with rapid agricultural development in the area (McKenzie et al., 2004). The Southern Tablelands and the Goulburn region of NSW (Fig. 2.3) in particular experienced a large degree of alteration due to the establishment of the area as prime sheep country. It is estimated that the rate of sediment export from drainage lines increased by a factor of more than 150 between 1842 and 1944 from pre-European settlement levels (Olley & Wasson, 2003). This period saw nearly every valley in south eastern Australia experiencing some degree of incision (Prosser, 1991; Wasson et al., 1998). The large increase in sediment eroded into waterways since European settlement has had a profound effect on river systems, with much of the sediment being stored (Prosser et al., 2001b)—sediment is still working its way through river systems such as the Murrumbidgee (McKenzie et al., 2004; Prosser et al., 2001b) and is expected to continue to influence the ecology of these waterways for many years to come (Prosser et al., 2001b).
The reasons for the sudden massive advent of gully erosion in south-eastern NSW are numerous. Large volumes of livestock grazed the perennial grasses in the region, reducing groundcover, and the hooves of stock often further disturbed the soil around waterholes and drainage lines (Scott, 2001). Continual close grazing, ring barking of trees as well as the ploughing of valley floors, with the intention of draining swampy areas all contributed to increases rates of surface runoff in the region (Eyles, 1977; Wasson et al., 1998). Increased surface runoff resulted in an increased capacity to erode slopes and the concentration of drainage lines. This in turn resulted in dramatic channel network incision and extension which transformed the small chains of ponds systems into continuous channels and gullies (Eyles, 1977; Prosser, 1991; Wasson et al., 1998) (Fig. 2.4). The clearing of vegetation, planting of crops and grazing by hooved animals is believed to have contributed to the extensive network of gullies and incised channels seen in this region today (Wasson et al., 1998).
As well as modification to vegetation and drainage lines by European settlers, the soils within the Southern Tablelands have also contributed to the susceptibility of the region to gully erosion. A large degree of the soil within this region is sodic in nature (Hird, 1991). Sodic soils are those in which the proportion of sodium on the clay fraction within the soil exceeds 6% (Ford et al., 1993). A high proportion of sodium within the soil causes clay particles to swell excessively when they become wet. The clay particles separate and the aggregates within the soil lose their integrity and the soil is said to be dispersive (Ford et al., 1993). This characteristic heightens the probability of gully erosion occurring in a landscape as the soils are prone to losing their structural stability, and surface and subsurface soils are easily removed by water in the landscape, particularly once the protective topsoil is removed (Ford et al., 1993).

The increased sediment yield resulting from European settlement is believed to have come to a peak, and is currently at a level between pre-settlement and peak values (Wasson et al., 1998). Many of the gullies in this region had virtually reached their current extent by the time
aerial photography was used in the 1940s (Prosser & Winchester, 1996). Despite the reduction in sediment yield from gullies, gully erosion still remains an issue in catchment areas.

2.3 Techniques for measuring and managing gully erosion and change

2.3.1 Measuring gully erosion
Measuring gully erosion rates and extent has long been a topic of interest to land managers. A number of different techniques exist for measuring and monitoring gully erosion, depending on the scale of assessment required. Traditional ground level surveys often incorporate the use of tools such as tapes, poles, total stations, rulers and microtopographic profilers to determine cross-sectional area and reach length (Castillo et al., 2012). The application of remote sensing techniques for gully measurement are broad and can involve the use of photogrammetry (Martínez-Casasnovas et al., 2004), laser scanning such as LiDAR or TLS (Terrestrial Laser Scanning) (James et al., 2007; Rengers & Tucker, 2015; Rose et al., 2014) and large scale imagery captured by satellite (Gilad et al., 2012; Knight et al., 2007). Multi-temporal surveys of gullied areas provide the greatest amount of insight into change in gully extent and morphology, indicating whether an area is actively eroding. Repeat surveys equip land managers with the information required to develop sustainable land use practices, including the stabilisation of existing gullies and the identification of sensitive areas at risk of becoming gullied (Shruthi et al., 2015).

2.3.2 Managing gully erosion
There are a number of techniques which can be applied to both prevent and manage gully erosion and landscape change. The ideal scenario is one in which gullies do not have the opportunity to develop in the first place, and a number of methods are being applied to both ensure this and prevent further incision and extension of existing gully networks.

Susceptibility modelling
Susceptibility modelling can provide the means to identify areas at high risk of gully erosion, which can allow land managers to ensure that appropriate preventative measures are taken. Dewitte et al. (2015) determined that there was a relationship between soil surface slope gradient and drainage area at the point of gully head initiation in a number of catchments, which led to the development of a predictive model for at risk areas for gully initiation. Similarly, Conoscenti et al. (2014) apply a predictive model for gully initiation which takes into account environmental attributes likely to contribute to gully erosion. The Sydney Catchment Authority employs a similar concept in its Pollution Source Assessment Tool.
(PSAT), assessing 14 key catchment activities including gully erosion against risk of four priority pollutants – pathogens, nitrogen, phosphorus and suspended solids (Sydney Catchment Authority, 2011a). This tool allows for the identification of high risk drainage units so that resources allocated to managing these risks can be prioritised.

**Sustainable agriculture**

Managing agricultural land in such a way that opportunities for erosion are minimised and areas that are eroding are treated immediately is one of the most effective ways for preventing gully erosion. Maintaining groundcover is important to minimise the effects of overland flow and prevent the development of channels that may evolve into gullies (Alt et al., 2009; Valentin et al., 2005). Breaks in pasture cover can be caused by overgrazing of lands and overwearing of stock tracks, which can also develop into gullies (Alt et al., 2009). The best management practices involve rotating stock through pastures and preventing the development of tracks by fencing off damaged areas and rotating food and water sources so that stock have no reason to continuously walk on a single track (Alt et al., 2009). Constructed banks such as contour banks and diversion banks are structures designed to control and intercept overland flow on slopes, reducing the velocity of the water and thus its erosional potential (Alt et al., 2009).

**Gully rehabilitation and soil conservation**

After gullies have already established, control structures or earthworks may have to be implemented to prevent further extension and erosion of the gully network and to remediate the landscape. Earthworks can be performed to either fill in small gullies, or smooth the sides of larger gullies to encourage revegetation (Soil Conservation Service, 2014; Valentin et al., 2005). Drop structures can be constructed at gully heads to prevent the continued migration of the head upslope. Drop structures should utilise guide banks, a cut off trench to prevent the structure from being undercut and a flume or chute which carries the water away from the structure (Alt et al., 2009). Dams are a tool that can be used to drown existing gully heads, divert active flows away from gullies and as a tool to trap sediment eroding from gullies upstream, preventing it from further travelling down the catchment (Alt et al., 2009; Soil Conservation Service, 2014).

Revegetated gully walls and sides provide indication that the system is no longer actively eroding. Forested gullies, particularly those with vegetated floors have been found to be far less active than those lacking in vegetation (Rey, 2003). Plant roots increase the stability and
infiltration ability of soils (Valentin et al., 2005), and for this reason revegetation is often a key strategy used to remediate gullied areas. Vegetation in gully bottoms has been found to reduce the likelihood of further incision, due to the increased hydraulic resistance provided by the vegetation (Poesen et al., 2003).

2.4 The use of high resolution topographic data for modelling sediment transport and nutrient export loads
High resolution topographic data has been widely used to model sediment transport, and in turn, calculate nutrient export loads. Modelling sediment transport from remotely sensed data is not a new concept, and has been performed using multi-temporal orthophotos and DEMs (Digital Elevation Models) (Martinez-Casasnovas, 2003). However, DEMs generated from satellite remotely sensed data can lack the spatial and temporal resolution required to detect change at the scale required to model sediment transport (James et al., 2007). High resolution topographic surveys such as LiDAR can assist greatly in the assessment of upland soil erosion, providing a significant increase in resolution (≤1m cf. ~25m for satellite or contour derived DEMs) allowing for more accurate analysis (Huising & Gomes Pereira, 1998; James et al., 2007; Martinez-Casasnovas, 2003).

High resolution topographic methods provide the capability to assess sediment budgets physically, rather than empirically, by calculating the difference and rate of loss of sediment in an area (Thoma et al., 2005). This morphological method has long been used in fluvial geomorphology through the application of repeat surveys of river/gully planform, however there is a tendency for cross-sectional surveys to underestimate the magnitude of volumetric change as a few cross-sectional surveys are often extrapolated and used as a representation of an entire erosional reach (Fuller et al., 2003). Fine-scale DEMs generated from high resolution topographic techniques are providing both a more accurate and less time consuming alternative to these existing methods (Wheaton et al., 2010). The nature of LiDAR makes it very suited to this application. Laser scanning methods provide a measurement of the distance between the instrument and a point, generating point clouds of different densities depending on the resolution of the instrument used (Huising & Gomes Pereira, 1998). Erosional change is determined through the differencing of point clouds or generated DSMs (Digital Surface Models) and DEMs (Rengers & Tucker, 2015). Very high resolution laser methods such as terrestrial laser scanning surveys (TLS) can provide centimetre-scale detail, allowing for minute changes in features such as gully heads to be
captured (Rengers & Tucker, 2015). Alternative methods such as the use of RTK-GPS (Brasington et al., 2000) and total stations (Milne & Sear, 1997) work off the same principle; collecting data at a number of points which can then be interpolated to produce a surface. However these methods often require the deployment of benchmarks and base stations to ensure that the x,y,z data collected is correctly ground-truthed (Brasington et al., 2000; Milne & Sear, 1997). While incredibly precise, these surveys can be very time intensive, depending on the area covered (Ouédraogo et al., 2014).

The generation of DEMs or TINs (Triangular Irregular Networks) through interpolation of the points generated by high resolution topographic surveys provides the basis for quantifying sediment transport in the systems studied (Brasington et al., 2000; James et al., 2007; Thoma et al., 2005; Wheaton et al., 2010). Producing a DEM of Difference (DoD) by subtracting surfaces from one another allows for the investigation of sediment transport, including both areas of erosion and deposition (Wheaton et al., 2010). The difference in volume between DoDs can be converted into a measure of sediment load and in turn an estimation of nutrient export, which is dependent on the specific soil type found in an area of study (Thoma et al., 2005).

2.4.1 Quantifying error in DEMs of Difference (DoDs)

While DEM differencing may appear to be a straight forward method of elevation change detection, a large number of uncertainties are related to its application. These uncertainties are primarily associated with the topographic survey process itself (eg. Instrumental accuracy, point quality, point density and distribution), the temporal interval between surveys and the interpolation methods used to construct the DEMs from surveyed points (Lane, 1998). The addition of these uncertainties into the DoD can make it difficult to discern morphological change from noise, particularly if the changes are of a smaller magnitude than calculated error estimates (Wheaton et al., 2010). Wheaton et al. (2010) provide a relationship between vertical uncertainty ($\delta(z)$) and DEM surfaces:

$$Z_{Actual} = Z_{DEM} \pm \delta(z)$$

Equation 1 (Wheaton et al. 2010)

where $Z_{Actual}$ represents the true elevation value and $Z_{DEM}$ represents the spatially paired DEM elevation. Uncertainties for a single DEM are additive and altogether result in $\delta(z)$ (Taylor, 1997). A complete estimation of $\delta(z)$ is often not realistically achievable through regular survey practice, which has resulted in the use of uncertainty estimation methods such
as repeat observation of control points (Brasington et al., 2000), the designation of uniform error surfaces and fuzzy inference systems (FIS) (Wheaton et al., 2010).

The uncertainties present in separate DEM inputs can be propagated into the DoD as shown by Brasington et al. (2003):

\[ \delta u_{DoD} = \sqrt{ (\delta z_{New})^2 + (\delta z_{Old})^2 } \]

**Equation 2 (Brasington et al.2003)**

Where \( \delta u_{DoD} \) represents propagated error in the DoD and \( \delta z_{New} \) and \( \delta z_{Old} \) represent the individual error in the new and old DEMs. This method represents the use of a simple threshold or minimal level of detection (MinLoD) whereby a spatially uniform estimate of error is constructed and all values below this threshold are discarded as noise. This becomes problematic when an average MinLoD is applied over areas with variable point density ie. steep slopes vs flat areas—leading to more information being discarded over steep areas and less over flat areas than is necessary (Wheaton et al., 2010). Spatially variable error models attempt to remedy this problem by assigning variable estimates of error to the individual DEMs by taking into account factors such as survey point quality, slope, GPS point quality and vegetation density (Wheaton et al., 2010). Together these individual errors are propagated into the DoD and in theory, a variable error surface better representing variable ground surfaces is produced (Wheaton et al., 2010).

### 2.5 Concluding remarks

Gully erosion remains a problematic issue in catchment areas due to the sediment and nutrients liberated by the erosional process (Olley et al., 2004). The rates and extent of gully erosion within the Southern Tablelands have not yet been investigated using high resolution topographic survey methods, which presents an opportunity to provide more detailed information regarding gully erosion to land managers. The following chapters outline the regional setting of two key sites used in this study, the methods chosen for this investigation and the results of the investigation into gully erosion at two sites within the Southern Tablelands.
Chapter Three: Regional Setting

3.1 Location

The Southern Tablelands of NSW are located on the Great Dividing Range, comprising a ~180 km wide belt of mountainous areas and tablelands that separate the coastal plain to the east from the interior lowlands of the Murray Basin (Eyles, 1977; Kemp & Hope, 2014). The region generally decreases in elevation from east to west; from ~750 m near Goulburn decreasing to ~400 m past Yass, moving away from the Great Diving Range (Hird, 1991).

The Wollondilly River forms the major drainage system within the north-eastern portion of the Southern Tablelands, with the Shoalhaven and Yass rivers also draining the region (Hird, 1991). The Wollondilly River forms a large part of the Warragamba catchment, flowing from near Crookwell in the western part of the catchment until it reaches Lake Burragorang; Sydney’s primary drinking water supply, created by the construction of Warragamba dam (Fig. 3.1).

Arthursleigh is located in the Southern Highlands, approximately 34km north east of Goulburn (34°34’38.5”S, 150°01’42.14”E; Fig. 3.1). The study site is located within the Eden Forest drainage unit which drains an area of 141.2 km$^2$ and is part of the Wollondilly River sub-catchment. The gully network being examined drains an area of 8.16 km$^2$ and is 5 km long.

The Dixons Ck study site extends over two properties and is located in the Southern Tablelands, near the town of Mummel and 15 km north-west of Goulburn (34°41’07.06”S, 149°34’22.32”E; Fig. 3.1). The study site is located within the Dixons Ck drainage unit which drains an area of 64.8 km$^2$ and is part of the Upper Wollondilly River sub-catchment. The network being examined in this study drains an area of 55.5 km$^2$ and is approximately 5 km long.
Figure 3.1: The location of the study areas within the greater Warragamba catchment and within their respective drainage units. Dixons Ck gullies can be seen on the left and Arthursleigh gullies on the right. All spatial data and basemaps provided by Water NSW.
3.2 Geological setting
Lithology strongly influences land forms and soil type. The eastern portion of the Warragamba catchment is dominated by the sandstone of the Sydney Basin, which has been deeply dissected into gorges, plateaus and escarpments (Olley et al., 2004) (Fig.3.2) The western portion of the catchment is comprised of the rocks of the Lachlan Fold Belt, which includes granites, sedimentary rocks and volcanic complexes (Olley et al., 2004). The granitic outcrops of the Lachlan Fold Belt contribute to the rolling topography of the region which makes it so suitable for grazing (Olley et al., 2004).

Figure 3.2: Geology of the Warragamba Catchment. Stars denote the locations of the study sites. (Olley et al., 2004)
The Arthursleigh study site sits upon two different lithologies; Mt Pleasant Granite to the east and the Bindook Porphyry to the west (NSW DPI, 2003). The Mt Pleasant Granite is felsic intrusive granite, Devonian in age whereas the Bindook Porphyry is largely composed ofporphyritic rocks with quartz and feldspar crystals, along with some dacite and tuff, and is also Devonian in age (Hird, 1991; NSW DPI, 2003). Undulating rises with gentle slopes are common in the area and elevation ranges between 570-720 m AHD.

The Dixons Ck drainage unit is part of the Shoalhaven Plateau physiographic region (Offenburg, 1974) and the surface topography is undulating to hilly with the drainage network deeply incising into the dissected country (Armstrong & Mackenzie, 2002). The bedrock is Wologorong granite which is late Silurian in age (Offenburg, 1974) and is composed primarily of plutonic rocks which range from granite to granodiorite in composition (Hird, 1991). An area of undifferentiated Cainozoic alluvium is also present in the southern quarter of the Dixons Ck study site (NSW DPI, 2003). Elevation in the study area ranges between 657-803 m AHD.

### 3.3 Soils

Soils that have developed on the sandstones of the eastern portion of the Warragamba catchment are generally of a low fertility and sandy (Fredericks, 1994), particularly compared with rich fertile soils developed on the Cainozoic basalts in the west of the catchment (Fig. 3.2). The granite and volcanic derived soils of the Wollondilly sub-catchment are infertile and susceptible to gully erosion, however they have been used extensively for grazing (Olley et al., 2004).

The soils at the Arthursleigh study site can best generally be described as acidic red and yellow duplex soils with bleached A₂ horizons, characteristic of podzols (Hird, 1991). The A horizons at Arthursleigh have sandy to sandy loam textures (Wilmot, 2007) with a typical composition of 9% clay, 18% silt, 28% fine sand and 40% coarse sand. The B horizon is approximately 40% clay (Appendix A, soil test results) and is highly sodic and prone to erosion when exposed (Wilmot, 2007). Gullying is common along drainage lines in the area due to the unstable nature of the B horizon when exposed and the history of vegetation clearance and landscape disturbance (Hird, 1991).

Yellow podzolic soils are the most common soils found in the Dixons Ck study area (Hird, 1991). These soils generally present with coarse-medium yellow brown A horizons, distinct pale A₂ horizons and friable clayey B horizons (Hird, 1991). Specifically, the A horizon of
the study area is composed of loamy sand (characteristically 8% clay, 20% silt, 47% fine sand, 25% coarse sand) and the B horizon is generally 60% clay (Armstrong & Mackenzie, 2002). Siliceous sands may also be found along drainage lines. Gully erosion commonly occurs along drainage lines and sheet erosion is likely during drought or following bushfire (Hird, 1991).

### 3.4 Climate
Both study sites are located within the South Eastern Highlands Bioregion (NSW NPWS, 2003) which is characterised by a temperate climate with warm summers and no dry season. Catchment wide rainfall is often influenced by the southern extension of tropical low pressure systems, however localised convective storms are not uncommon (Fredericks, 1994). Rainfall is typically delivered from the west, with the highest rainfall falling in the highest parts of the catchment—the southern highlands near Moss Vale and the high plateaus of the Cox River catchment (Olley et al., 2004). The Goulburn region has a mean annual temperature range between 6-19.6°C (BOM, 2015). Information on rainfall and climate specific to the study areas is limited due to the distribution and availability of BOM stations and data. Rainfall data has been sourced from a number of BOM stations closest to the study sites.

#### 3.4.1 Rainfall record
A number of BOM daily rainfall stations exist within the Southern Tablelands region. Rainfall stations were chosen in this study according to their proximity to the study sites and the presence of daily rainfall totals during the March 2012 rainfall event. The Arthursleigh site has two rainfall stations within a 10 km radius, Big Hill and Brayton. Dixons Ck has three stations within a 10 km radius; Goulburn (Cherryton), Goulburn TAFE and Goulburn (Pomeroy) with Goulburn (Cherryton) being located within the Dixons Ck drainage unit (Fig.3.3).
Figure 3.3: The location of daily rainfall stations used in the study. BH: Big Hill, B: Brayton, GT: Goulburn TAFE, GC: Goulburn (Cherryton), GP: Goulburn (Pomeroy).

Table 3.1: Mean monthly rainfall data from stations closest to study sites. All data sourced from BOM.

<table>
<thead>
<tr>
<th>Station</th>
<th>ARTHURSLEIGH</th>
<th>DIXONS CK</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Big Hill (Glen Dusk)</td>
<td>Brayton (Longreach)</td>
</tr>
<tr>
<td>Record</td>
<td>1944-2014</td>
<td>1959-present</td>
</tr>
<tr>
<td>JAN</td>
<td>71.3</td>
<td>64.5</td>
</tr>
<tr>
<td>FEB</td>
<td>81.0</td>
<td>70.9</td>
</tr>
<tr>
<td>MAR</td>
<td>68.1</td>
<td>63.5</td>
</tr>
<tr>
<td>APR</td>
<td>54.4</td>
<td>52.0</td>
</tr>
<tr>
<td>MAY</td>
<td>46.6</td>
<td>43.5</td>
</tr>
<tr>
<td>JUN</td>
<td>61.7</td>
<td>54.8</td>
</tr>
<tr>
<td>JUL</td>
<td>39.1</td>
<td>37.8</td>
</tr>
<tr>
<td>AUG</td>
<td>45.6</td>
<td>49.4</td>
</tr>
<tr>
<td>SEP</td>
<td>44.0</td>
<td>47.8</td>
</tr>
<tr>
<td>OCT</td>
<td>61.1</td>
<td>60.9</td>
</tr>
<tr>
<td>NOV</td>
<td>63.8</td>
<td>62.6</td>
</tr>
<tr>
<td>DEC</td>
<td>60.1</td>
<td>61.5</td>
</tr>
<tr>
<td>Mean Annual</td>
<td>706.2</td>
<td>700.9</td>
</tr>
</tbody>
</table>
Mean annual rainfall is generally consistent across all sites, ranging between 614-706.2 mm with more rainfall occurring in the summer months (Table 3.1). The wettest month at Arthursleigh is February whereas December-January experiences the greatest amount of rainfall at Dixons Ck.

### 3.4.2 March 2012 rainfall event

This study examines the impact of a large rainfall event on gully erosion within the study areas. In southern NSW, a significant rainfall event developed toward the end of February 2012 which led to substantial flooding in some areas with as many as 25 local government areas declaring national disasters (BOM, 2012). Between the 29th February and the 2nd March 2012 cumulative rainfall at stations near the study sites far exceeded February and March averages for those stations (Table 3.2). Total rainfall for February 2012 was the highest on record at Brayton (232.2 mm) and Goulburn (Cherryton) (206.4 mm) and within the 95th percentile for all other stations (BOM, 2015) (Table 3.2). Rainfall at all stations over the three day period was nearly three times the calculated March mean and median (Table 3.2).

<table>
<thead>
<tr>
<th>Station</th>
<th>29/02/2012 Rainfall (mm)</th>
<th>1/03/2012 Rainfall (mm)</th>
<th>2/03/2012 Rainfall (mm)</th>
<th>3 day total</th>
<th>Feb 2012 total (mm)</th>
<th>Mar 2012 total (mm)</th>
<th>All years March mean (mm)</th>
<th>All years March median (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARTHURSLEIGH</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Big Hill</td>
<td>79</td>
<td>61.4</td>
<td>29.6</td>
<td>170</td>
<td>202</td>
<td>203.6</td>
<td>68.1</td>
<td>45.4</td>
</tr>
<tr>
<td>Brayton</td>
<td>70</td>
<td>69.5</td>
<td>10.5</td>
<td>150</td>
<td>232.2</td>
<td>199</td>
<td>63.5</td>
<td>51</td>
</tr>
<tr>
<td>DIXONS CK</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Goulburn (Cherryton)</td>
<td>55</td>
<td>79</td>
<td>13</td>
<td>147</td>
<td>206.4</td>
<td>192.1</td>
<td>51.5</td>
<td>44.4</td>
</tr>
<tr>
<td>Goulburn TAFE</td>
<td>57.6</td>
<td>67.6</td>
<td>15.6</td>
<td>140.8</td>
<td>164.8</td>
<td>179</td>
<td>57</td>
<td>49.6</td>
</tr>
<tr>
<td>Goulburn (Pomeroy)</td>
<td>55.8</td>
<td>92.2</td>
<td>19.4</td>
<td>167.4</td>
<td>179.4</td>
<td>209.4</td>
<td>54.1</td>
<td>37.7</td>
</tr>
</tbody>
</table>

The intensity and distribution of rainfall varied during the three day event (Fig. 3.4). On the 29/02/2012, the heaviest rainfall was experienced in the centre of the southern portion of the Warragamba catchment (Fig. 3.4a). The most intense rainfall was experienced on the 1/03/2012 in the western portion of the catchment (Fig. 3.4b) while on the 2/03/2012 the rainfall was most heavily focused to a smaller area of the western portion of the catchment (Fig. 3.4c). The total rainfall over the three day period was most intense just to the north of the two study sites (Fig. 3.4d).
Figure 3.4: Rainfall intensity maps representing the individual days comprising the event and the total rainfall over the three days. (a) 29/02/2012, (b) 1/03/2012, (c) 2/03/2012, (d) total rainfall. Map presents the southern half of Warragamba catchment only.
Assessment of the intensity-frequency-duration of the event indicates that the rainfall at both sites over a 24hr period has a return interval of 2-5 years (Table 3.3). Over a 72hr period, the Average Recurrence Interval (ARI) calculated at each weather station varies dramatically with the ARI for Arthursleigh likely being around 10 years and Dixons Ck being closer to 20-50 years. The station at Goulburn (Pomeroy) returned the highest 72hr ARI, defining the rainfall event as having a 50-100 year recurrence interval.

Table 3.3: Intensity-Frequency-Duration analysis for 24hr and 72hr periods for all weather stations. See Appendix B for BOM IFD charts and tables used for this analysis.

<table>
<thead>
<tr>
<th>Station</th>
<th>24hr (mm)</th>
<th>ARI</th>
<th>72hr (mm)</th>
<th>ARI</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ARTHURSLEIGH</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Big Hill</td>
<td>79</td>
<td>2-5</td>
<td>170</td>
<td>10-20</td>
</tr>
<tr>
<td>Brayton</td>
<td>70</td>
<td>1-2</td>
<td>150</td>
<td>5-10</td>
</tr>
<tr>
<td><strong>DIXONS CK</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Goulburn (Cherryton)</td>
<td>79</td>
<td>2-5</td>
<td>147</td>
<td>20-50</td>
</tr>
<tr>
<td>Goulburn TAFE</td>
<td>67.6</td>
<td>2-5</td>
<td>140.8</td>
<td>10-20</td>
</tr>
<tr>
<td>Goulburn</td>
<td>92.2</td>
<td>5-10</td>
<td>167.4</td>
<td>50-100</td>
</tr>
</tbody>
</table>
An examination of the daily rainfall for the duration of the study (01/08/2011-20/06/2012) at both sites shows that the rainfall experienced in March 2012 was the most significant rainfall event experienced during the study period (Fig. 3.5).

Figure 3.5: Total rainfall spanning the period of the study from 1/08/2011-20/06/2012 recorded at a) Goulburn (Cherryton), representing rainfall at Dixons Ck and b) Big Hill, representing rainfall at Arthursleigh. Red arrow indicates the March 2012 rainfall event.

The March 2012 rainfall event was the largest event experienced during the period of this study, with intense rainfall over the three day period and an average ARI of approximately 10-20 years. It is hypothesised that this rainfall event contributed to erosion within the gully networks being examined within this study.
3.5 Land use and gully characteristics

3.5.1 Catchment wide
The predominant land cover within the Warragamba catchment is pasture and woody vegetation. The rugged sandstone plateaus that cover much of the lower catchment are generally infertile and unsuitable for agricultural use. These areas remain heavily vegetated with dry sclerophyll forest (Fredericks, 1994). Low gradient parts of sub-catchments such as the Wollondilly have been cleared and are primarily composed of grassland, along with some areas of open eucalyptus woodland (Olley et al., 2004). The natural vegetation of the region surrounding Goulburn has been dramatically altered and cleared since European settlement. Existing vegetation forms a mix of intermediate-dry sclerophyll forest in hilly regions, savannah woodlands on lower slopes and dry-wet tussock grassland on the plains (Hird, 1991).

The widespread gully erosion within the western portion of the Warragamba catchment Fig 3.6) is recognised to have been initiated by the clearing practices associated with European settlement (Armstrong & Mackenzie, 2002) (see Ch. 2.2). It is indicated that the total length of gullies within the Warragamba catchment is approximately 1600 km with the Wollondilly sub-catchment contains around 90% of these gullies alone. (Olley et al., 2004). Many of these gullies have already reached their fullest extent and have started to revegetate and stabilise (Olley et al., 2004).
Figure 3.6: Gully erosion within the Warragamba catchment, showing the increased density within the western portion. Adapted from Rustomji (2006a).
3.5.2 Study sites
The area of land now known as Arthursleigh has had a long history of agricultural land use. Initially the land was covered in open forest, dominated by eucalypts however the land was slowly cleared to make way firstly for wheat crops and then livestock pasture (Fletcher, 2002). The property is now owned by the University of Sydney, however prior to this the property was run over a 99 year lease which did not require reinvestment back into the property. This period saw the clearing of all remaining native forest and the development of an extensive and intensive network of gullies. (Fletcher, 2002). Under current management, the farm operates as a commercial grazing property, running sheep and cattle (Fletcher, 2002).

The gullies at Arthursleigh are dendritic in form, with a number of individual headcut tributaries (Fig. 3.7) branching off of a primary gully which is approximately 5.7 km in length (Fig. 3.8). Figure 3.8 shows the long profile of the primary gully at Arthursleigh, revealing a number of steps in the gully floor during its decent from approximately 660 m AHD to 580 m AHD. The most notable step at Arthursleigh is located near transect d., just below the sediment dam (Fig. 3.8). This is due to the presence of a flume to control flow and prevent headcuts from migrating into the dam.

A number of transects of the primary gully at Arthursleigh are shown in Figure 3.9. The gully both widens and deepens down its length; with the steepest walls being found at transect e. Even at its shallowest, the gullies at Arthursleigh are significantly incised. The primary gully ranges in depth of 3 m at transect a, compared with 8 m at transect e (Fig.3.9).

Figure 3.7: Headcut erosion at Arthursleigh (Credit: Charissa Harris)
Figure 3.8: Long profile of the primary gully at Arthursleigh, showing the location of five transects taken along its length. Stars denote the location of headcuts and secondary knickpoints.
Figure 3.9: The location of both the long profile and five transects taken at Arthursleigh. Transects a-e also shown.
The Dixons Ck study area was once vegetated with dry sclerophyll forest; however most of this has now been cleared. Areas of remnant open forest still remain and the pasture in the area is primarily composed of native species. Historically the land has principally been used for sheep grazing (Armstrong & Mackenzie, 2002). The Dixons Ck study area currently spans two properties, which utilise the land in vastly different ways. The northern portion of the study area is both a farm and a recreational summer camp. Stock has been excluded from the gullied areas and gully treatments such as dams, earthworks and replanting have been utilised. The southern portion of the study area operates as a farm growing crops. The gullies in this portion wind through tilled areas and crops are planted within a few metres of gully walls. The gully floors and some wall sections are vegetated with grasses (Fig. 3.10).

The gullies at Dixons Ck form a dendritic drainage pattern with a number of individual headcut tributaries attached to a primary gully which is approximately 7.2 km long. Figure 3.11 shows the long profiles of the primary gully at Dixons Ck, revealing the location of two major steps along its length; between transect a and b and downstream from transect e. The profile has been split into the gully above the dam (north) and the gully below the dam (south) to maintain detail during display. There is a change in elevation of ~80 m along the profile from its highest point to its lowest.

The Dixons Ck gullies are most deeply incised in the northern half of the study area (~10 m) with areas of bedrock exposed in some locations (Fig. 3.12); particularly near transect b (Fig. 3.12). The gully floors in this area are sparsely vegetated and the walls range between being bare of vegetation and heavily covered with blackberry. The gully loses its degree of incision at transect d, just before it flows into the dam. Transects at e and f reveal a much narrower and shallow gully than what is present at the top of the profile at b and c (Fig. 3.12).

![Figure 3.10: Sheer gully walls in the northern portion of Dixons Ck (left) and a small headcut in the cropped southern portion of Dixons Ck (right)](image)
Figure 3.11: Long profile of the primary gully at Dixons Ck with the location of six transects shown. The Northern profile represents the gully above the sediment dam while the Southern profile represents the gully below the dam. Stars denote the location of knickpoints and secondary headcuts.
Figure 3.12: The location of both the long profile and six transects taken at Dixons Ck. Transects a-f also shown.
Chapter Four: Methods

4.1 Quantifying gully erosion

4.1.1 LiDAR survey
To quantify change in gully extent at the study sites, LiDAR surveys were captured both before and after the rainfall event in March 2012. As covered in Chapter 2, high resolution topographic survey methods provide both a higher resolution and more spatially distributed and complete analysis of any change occurring in an area than traditional methods such as cross-sectional channel surveys (Brasington et al., 2000; Huising & Gomes Pereira, 1998; James et al., 2007; Martinez-Casasnovas et al., 2004).

LiDAR was first captured on the 1/08/2011 for both Dixons Ck and Arthursleigh by NSW Land and Property Information (LPI). This dataset was captured using a Leica ALS50-II Airborne Laser Scanner with a Honeywell URIS IMU for the purposes of georeferencing. Further information regarding the 2011 dataset has been assumed from both the 2012 dataset and other surveys performed by the LPI around the time of this capture as the metadata report for the 2011 captures at the study sites was unavailable. The second collection of LiDAR was performed on 20/06/2012 by Fugro Spatial Solutions Pty Ltd using a Leica ALS50-II Airborne Laser Scanner with an IPAS10 IMU (see Appendix C for metadata report). The areas captured by the LiDAR defined the extent of the study sites for the purposes of this study. Both the 2011 and 2012 surveys were completed in GDA94 MGA Zone 55 (Dixons Ck) or GDA94 MGA Zone 56 (Arthursleigh) with vertical datum AHD. It is not known whether the 2011 LPI datasets were collected using ground control points, however the 2012 Fugro datasets used the 2011 LPI datasets as a control dataset. All datasets were provided as classified ALS point clouds in LAS format (see Table 4.1 for dataset attributes).

Table 4.1: Attributes for the four surveys used in this study to develop DEMs. Point count represents the number of ground return points only.

<table>
<thead>
<tr>
<th>Survey</th>
<th>Point Count</th>
<th>Point Density (pt/m²)</th>
<th>Vertical Precision</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dixons Ck 2011</td>
<td>8,554,781</td>
<td>1.19</td>
<td>Unknown</td>
</tr>
<tr>
<td>Dixons Ck 2012</td>
<td>5,964,390</td>
<td>0.96</td>
<td>0.10m @ 67% CI</td>
</tr>
<tr>
<td>Arthursleigh 2011</td>
<td>15,607,936</td>
<td>1.23</td>
<td>Unknown</td>
</tr>
<tr>
<td>Arthursleigh 2012</td>
<td>10,500,982</td>
<td>0.96</td>
<td>0.10m @67% CI</td>
</tr>
</tbody>
</table>
4.1.2 Development of Digital Elevation Models (DEM)

The LiDAR surveys were imported into ArcMap 10.2.0 where only ground return points were imported into a terrain dataset. Terrain datasets are useful for the storage of large volumes of data as they organise the data for fast retrieval and generate a Triangular Irregular Network (TIN) surface on the fly for visualisation purposes. The terrain was converted to raster format using TIN based methods and a cell-size of 1m with natural neighbour interpolation. TIN based interpolation methods are commonly used to turn high resolution topographic surveys into surfaces as they preserve the precision of the input data while also being able to model values between known points (Wheaton et al., 2013; Wheaton et al., 2010).

It was important that the raster DEMs created were both orthogonal and concurrent—that is that they are correctly aligned with each other, in order to complete geomorphic change detection analysis (Wheaton et al., 2010). All DEMs were created with the same (1m) grid resolution to ensure orthogonality and the same extents to ensure concurrency (on a per site basis). The entire area covered by the LiDAR was transformed into a raster and the rasters were later clipped using a polygon which outlined only the gullied areas of interest (Fig 4.1). Sediment dams (marked in Fig 4.1) were excluded from the clipped area so that the difference in dam water levels between the two surveys did not interfere with the accuracy of change detection results. For example, if the difference in dam water level were identified by the software as deposition, the overall results would be skewed to show more deposition than what actually occurred on the ground.

![Figure 4.1: Clipped DEMs used for change detection analysis outlining only the gullied areas at the study sites. a) Arthursleigh b) Dixons Ck. Star denotes omitted sediment dam](image-url)
4.1.3 Change detection
To quantify any morphological change at the study sites, the Geomorphic Change Detection 6.1.8 (GCD) add-in for ArcGIS 10 (Wheaton et al., 2010) was used to perform DEM of Difference (DoD) analysis. In its simplest terms, DoD analysis subtracts the ‘youngest’ DEM from the ‘oldest’ DEM in order to quantify elevation change that has occurred between the two surveys. This analysis can be performed using the raster calculator capabilities of ArcMap, however the GCD add-in allows for an overall faster processing time as well as the ability to further segregate and investigate the DoD results.

Negative elevation changes within the DoD represent areas of erosion whereas positive elevation changes represent areas of deposition. DoD analysis was performed for both study sites, using the 2011 survey as the baseline. DoD analysis allows for an examination of both the spatial distribution of change as well as a quantification of volumetric changes associated with gully erosion, and its use has become increasingly common in studies attempting to quantify sediment transport and net landscape change (Brasington et al., 2000; Lane et al., 2003; Rumsby et al., 2008; Wheaton et al., 2013; Wheaton et al., 2010).

4.1.4 Change detection uncertainty
The overall accuracy of DoD analysis is dependent on input DEM quality, that is how well the DEM represents the survey data (Brasington et al., 2000). As discussed in Chapter 2.4.1, error associated with topographic survey practices are often propagated into DEMs, and from there into any DoD created (Lane, 1998; Wise, 1998). The addition of these uncertainties can make it difficult to distinguish morphological change from noise (Wheaton et al., 2010), and for this reason it is important to attempt to provide a prediction of the error within a dataset. Wheaton et al. (2010) provide a relationship between vertical uncertainty \( \delta(z) \) and DEM surfaces:

\[
Z_{\text{Actual}} = Z_{\text{DEM}} \pm \delta(z)
\]

Equation 3 (Wheaton et al. 2010)

where \( Z_{\text{Actual}} \) represents the true elevation value and \( Z_{\text{DEM}} \) represents the elevation represented in the DEM. The value of \( \delta(z) \) is a result of the propagated error from all the inputs (instrument precision, measurement error), interpolation error and sampling error (Wheaton et al., 2010). Finding the value of \( \delta(z) \) can be as simple as assuming that the manufacturers reported error is a good representation of the error, through to more complex measures such as attempting to quantify a complete error budget (Lichti et al., 2005). It is
important to note that due to the multitude of contributing variables, no approach can fully account for $\delta(z)$ within a dataset.

The GCD add-in provides methods of uncertainty analysis to both quantify the error within a dataset and ensure that potential error is given due consideration and propagated throughout the DoD. Five methods of uncertainty analysis were examined during this study to determine what level of detection was most appropriate for the study (Table 4.2). The methods examined include the use of spatially uniform error surfaces and spatially variable error surfaces. Spatially uniform surfaces prescribe the same level of error to the entire area under examination, whereas spatially variable surfaces seek to quantify sources of error more thoroughly and provide a variable estimation of error (Fig. 4.2).

Table 4.2: Summary of the different uncertainty analysis methods used and their associated error surfaces

<table>
<thead>
<tr>
<th>Uncertainty Analysis Method</th>
<th>Error Surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.20 m MinLoD</td>
<td>Uniform</td>
</tr>
<tr>
<td>0.30 m MinLoD</td>
<td>Uniform</td>
</tr>
<tr>
<td>0.20 m MinLoD with 95% CI</td>
<td>Uniform</td>
</tr>
<tr>
<td>0.30 m MinLoD with 95% CI</td>
<td>Uniform</td>
</tr>
<tr>
<td>FIS error surface with 95% CI</td>
<td>Spatially variable</td>
</tr>
</tbody>
</table>

Figure 4.2: a) Spatially uniform error surface with a value of 0.20 m used for MinLoD analysis. b) spatially variable error surface derived via a fuzzy inference system used for probabilistic analysis. Note the variation in error assigned to some areas in this method. Units are in metres
The ‘minimum level of detection’ (MinLoD) (Brasington et al., 2000) approach is the most simplistic method used, applying a user defined threshold below which all change is considered to be noise and is discarded from the result. The MinLoD thresholds tested in this study were 0.20m and 0.30m, which discarded values of ±0.2m and ±0.3m respectively. While 0.20m most closely represented the survey error reported within the 2012 LiDAR metadata, 0.30m was also assessed due to the unknown error present in the 2011 survey.

Another method trialled was a MinLoD with a 0.95 confidence interval. This method applies a similar thresholding principle to the MinLoD alone, however the probability of results being real are also adjusted with a declining weighting function (Lane et al., 2003). This allows the user to probabilistically define a confidence interval based on at what probability level the user is willing to accept change is real. In this study, 0.20 m and 0.30 m uniform surfaces were used with a conservative 0.95 confidence interval.

The final method used involved the creation of spatially variable error surfaces for each DEM using LiDAR point density and raster slope via the use of a fuzzy inference system (FIS)(see Wheaton et al. (2010) for a full explanation of FIS methodology) (Fig. 4.3). These spatially variable errors were then propagated into the DoD and thresholded using a 0.95 confidence interval (Lane et al., 2003).
Figure 4.3: An example from the 2011 Dixons Ck LiDAR showing the inputs used to create a spatially variable FIS error surface. a) Slope degrees, b) point density, c) FIS surface. Units are in metres.
4.1.5 Assessment of morphological controls on gully erosion

It has been found that factors such as drainage area, slope (Montgomery & Dietrich, 1989; Torri & Poesen, 2014) and aspect (Fang & Guo, 2015) can impact the likelihood of gully erosion, particularly the development of gully heads occurring. This study used the DoD outputs to determine the effect of drainage area, slope, aspect and stream order on gully erosion within the study sites.

Drainage area

The effect of drainage area was determined by first using ArcHydro Tools for ArcGIS to delineate the catchment areas of the gullies within the study areas. The Terrain Processing Workflow included within ArcHydro Tools was used as a standardised process for both study sites. The drainage lines defined by ArcHydro did not entirely represent the gullies present at the study sites due to the influence of gully control structures such as contour banks influencing the flow direction of water on the surface of the DEM, however they were deemed to be close enough for the purposes of this study (Fig 4.4).

Figure 4.4: An example of contour banks directing the delineated drainage lines (in yellow) around the gullies at Arthursleigh
The derived catchments were used to manually segregate sections of the study areas, and these sections were then applied within GCD using the budget segregation tool (Fig 4.5). This tool separates the DoD output according to input areas, in this case catchment area. Linear regression analysis was performed using the erosion volumes output by GCD compared against the catchment areas produced from the ArcHydro output to determine whether drainage area influenced gully erosion.

![Figure 4.5: An example from Arthursleigh showing how the gully area (in pink) was clipped according to the catchment areas (orange) produced by ArcHydro](image)

**Average gully slope**

Average slope (%) for each gully segment was calculated using the Add Surface Information tool within the 3D Analyst Toolbox in ArcMap 10.2. The gullied areas were then manually segmented according to slope and then these sections were applied within GCD using the budget segregation tool (Fig 4.6). Linear regression analysis was performed to compare the erosion volumes provided by GCD with the average slope (%) values provided by ArcMap to determine whether slope had an influence upon gully erosion at the study sites.
Figure 4.6: An example from Arthursleigh showing how a polygon representing the study area has been sectioned according to gully segment, with each segment representing a separate average slope value

**Aspect**

The dominant aspect of tributaries at both study sites was determined by visual examination with the assistance of an aspect raster created from the DEMs. Tributaries at Arthursleigh were deemed either north or south flowing while tributaries at Dixons Ck were classified as either east or west flowing (Table 4.3).

**Table 4.3: The number tributaries classified according to their aspect at both study sites**

<table>
<thead>
<tr>
<th>Arthursleigh</th>
<th></th>
<th>Dixons Ck</th>
</tr>
</thead>
<tbody>
<tr>
<td>North</td>
<td>South</td>
<td>East</td>
</tr>
<tr>
<td>8</td>
<td>5</td>
<td>9</td>
</tr>
</tbody>
</table>

The gullied areas were manually segmented according to visual classification while viewing an aspect raster of the study areas and the budget segregation tool within GCD was used to produce volumes eroded in each aspect classified tributary. A t-test was used to compare whether the mean erosion at each site was significantly different due to aspect.
Stream order

The ‘Assign River Order’ tool within ArcHydro was used to designate a stream order to the drainage lines derived at each study site using the Strahler methodology (Strahler, 1957). The study areas were segmented according to stream order (Fig 4.7) and the budget segregation tool within GCD was used to determine the erosion volumes for each ordered stream. Although theoretically similar concepts, both drainage area and stream order have been examined in this study to account for the fact that the drainage lines derived when calculating drainage area were not entirely representative of the gullies present on site. An assessment of stream order provided the opportunity to assess just the gullies present on the LiDAR imagery without making assumptions about catchment areas.

![Figure 4.7: An example of stream order classified gullies at Dixons Ck](image)

The cumulative erosion values for each stream order classification were examined as well as the mean change (m$^3$ m$^{-1}$). Mean change was derived by dividing the cumulative erosion volume by the cumulative distance of each stream order classified segment. The calculation was performed in this manner because a comparison of means through a method such as a t-test was not possible because as stream order increased, the number of streams classified as such diminished (eg. 32 first order streams cf. 1 fourth order stream at Dixons Ck).
4.2 Determination of nitrogen and phosphorus

LiDAR has previously been used to find erosion volumes and in turn estimate mass wasting of sediment and nutrients from fluvial systems (Thoma et al., 2005). This study used volumes derived from the GCD add-in multiplied by soil bulk density values derived from soil testing performed by the Soil Conservation Service to estimate mass wasting at both study sites. Soil testing at 15 sites spanning both study areas was completed on the 8/5/2012 (Fig 4.8) (See Appendix A for full report). As well as providing bulk density values, values representing total nitrogen and phosphorus concentration (ppm) were also provided. Nitrogen and phosphorus loads were estimated by multiplying the concentration of total nitrogen or phosphorus by the calculated mass of eroded sediment.

Figure 4.8: The location of soil test sites used to determine average nitrogen and phosphorus concentrations for both study sites. Test site locations provided by Water NSW.
Four different scenarios were considered for the estimation of nitrogen, phosphorus and sediment exported from the study sites (Table 4.4). This was due to the presence of sediment dams located within the gully networks at both sites, and the assumption that the dams would capture some sediment and prevent it from being exported. Scenario A assumes that all sediment is exported from the system and does not consider the effect of differing composition between soil horizons. Scenarios B, C and D all took into consideration the difference in composition of the A and B horizon at the sample sites (see Appendix D for detailed calculations). Scenario C and D both assume that the dams have trapped sediment and prevented it from being exported. Figure 4.9 provides a diagrammatic explanation of the scenarios considered when estimating nitrogen and phosphorus export amounts.

Table 4.4: Different treatments applied to nitrogen and phosphorus export estimations. B, C and D consider the difference in composition of the A and B horizon

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>All sediment exported from gully network</td>
</tr>
<tr>
<td>B</td>
<td>All sediment exported, difference in A and B horizon factored into calculations</td>
</tr>
<tr>
<td>C</td>
<td>All sediment exported below sediment dams, only clay and silt exported above dams</td>
</tr>
<tr>
<td>D</td>
<td>All sediment exported below dams, only 50% of clay and silt exported above dams</td>
</tr>
</tbody>
</table>
Figure 4.9: Diagrammatic explanation of the four scenarios considered when estimating N + P export. Scenario B, C and D all factor the difference in composition of the A and B horizon in the calculations.
4.3 Comparison of change in 2011-2012 with historical rates of change

To place this study within the historical context of gully erosion within the Southern Tablelands, an attempt was made to quantify the historical rate of gully erosion at both study sites. This was performed through an examination of available historical aerial photography available for both sites. Due to the nature of both the landscape and the LiDAR captured at Dixons Ck, it was not possible to determine a rate for this study site. The LiDAR captured at Dixons Ck covered only the centre portion of a gully network, clipping out many heads and making them unable to be measured. Additional to this, some gully heads that were present on the LiDAR are located in a heavily wooden region of Dixons Ck and cannot be seen on aerial photography under the dense vegetation (Fig 4.10).

Figure 4.10: Gullies at Dixons Ck under dense vegetation, making it difficult to discern the location of headcuts.
Arthursleigh had a comprehensive record of past aerial photography, with imagery covering from 1949 to 2011 (Table 4.5). To assess the rate of gully extension at Arthursleigh, gully heads present on the 1949 imagery were digitised and their location compared against all subsequent imagery. Qualitative visual assessments as well as measurements between the 1949 heads and subsequent heads were noted to determine an average rate of gully erosion. It should be noted that some imagery, in particular the 1991 imagery, were not provided georeferenced entirely accurately. This imagery has still been included in order to contribute to the overall picture of change over time at Arthursleigh.

Table 4.5: Available imagery for Arthursleigh used to estimate historical rates of change. All imagery provided by Water NSW

<table>
<thead>
<tr>
<th>Study Site</th>
<th>Imagery Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arthursleigh</td>
<td>1949</td>
</tr>
<tr>
<td></td>
<td>1969</td>
</tr>
<tr>
<td></td>
<td>1991</td>
</tr>
<tr>
<td></td>
<td>2008</td>
</tr>
<tr>
<td></td>
<td>2011</td>
</tr>
</tbody>
</table>
Chapter Five: Results

5.1 Uncertainty analysis

Two DEMs were created via TIN interpolation for both the Arthursleigh and Dixons Ck sites, representing the study areas in 2011 and 2012. The Geomorphic Change Detection (GCD 6.1.8) add-in for ArcGIS (Wheaton et al., 2010) was used to produce a DEM of difference (DoD) for each site, with negative elevation change values representing erosion and positive elevation change values representing deposition. GCD was also used to apply five different methods of uncertainty analysis to account for error within the DEMs and provide a more realistic interpretation of morphological change within the gully networks. Analysis using LiDAR derived DEMs indicates that the gullies at both study sites were net erosional during 2011-2012. Fig. 5.1 shows a comparison of the net change calculated for each uncertainty analysis method used at both study sites. The raw result for Arthursleigh and Dixons Ck indicates a net loss of 87,026 m$^3$ and 29,954 m$^3$ of sediment respectively. This estimate is more than halved by the 0.20m MinLoD with an estimated loss of 30,474 m$^3$ at Arthursleigh and 6,107 m$^3$ at Dixons Ck (Fig 5.1 i). The addition of a 95% confidence interval (CI) further reduces these results to 13,834 m$^3$ and 2855 m$^3$ (Fig.5.1 ii). The 0.30m MinLoD provides a more conservative initial estimate with a net loss of 21,144 m$^3$ at Arthursleigh and 4,074 m$^3$ at Dixons Ck (Fig 5.1 iii), reducing to 9,294 m$^3$ and 2023 m$^3$ respectively with the addition of a 95% CI (Fig 5.1 iv). The FIS approach provides a more liberal estimate of erosion at both sites than other methods used (with the exception of 0.20m MinLoD at Arthursleigh) with 26,449 m$^3$ at Arthursleigh and 6,730 m$^3$ at Dixons Ck (Fig 5.1 v). Despite this, it is still 70-78% less than the raw DoD estimate. This indicates that a large proportion of the fine scale change detected between the two DEMs is noise (see Chapter 2.4.1).
Figure 5.1: Comparison of uncertainty analysis methods used to determine net volumetric change with calculated RMS error at a) Arthursleigh b) Dixons Ck. Raw result with no uncertainty analysis applied, i) 0.20 m MinLoD, ii) 0.20 m MinLoD with 95% CI, iii) 0.30 m MinLoD, iv) 0.30 m MinLoD with 95% CI, v) FIS error with 95% CI

The MinLoD approach (both 0.20 m and 0.30 m) produces the largest estimates of error at both study sites (Fig 5.1). Both the 0.20m and 0.30m MinLoD applied at the Dixons Ck study site produces error estimates greater than the calculated result. The smallest estimates of error were those produced by the use of a MinLoD with a 95% CI (Fig 5.1).
Fig 5.2 shows the spatial distribution of change under each uncertainty analysis method using a small subsection of the Dixons Ck study site as an example. The raw output presented in Fig 5.2 (a) shows an area which is predicted to be largely erosional with the exception of a depositional channel in the centre. It should be noted that this area of deposition is likely due to a change in water level in the channel between sampling; however this subsection shows a clear example where both ‘erosional’ and ‘depositional’ changes are present. Fig 5.2 (b) shows the output of the FIS propagated error approach. This method retained a greater degree of fine scale change than the other methods; however it also detected a large amount of fine scale change around the very edges of the clip area used to designate the areas of the study. Fig 5.2 (c) and (e) show the 0.20m and 0.30m MinLoD approaches respectively. Both these methods have largely removed all instances of fine scale change. The addition of the probabilistic threshold alters the spatial distribution of change identified in the DoD (Fig 5.2 (d), (f)) compared with the MinLoD alone, largely removing the depositional channel area and identifying only a few small areas of erosion.

Another method of investigating change between two DEMs is to plot a histogram of volumetric change. Fig 5.3 shows the elevation change distribution histograms for each method used, providing an indication of how the uncertainty analysis reduces the result from the raw output (Fig. 5.3 a). The FIS approach (Fig 5.3 b) elevation change distribution shows how fine-scale changes in the centre of the histogram have been retained, compared with the other methods used. Additionally, the histogram has been further thinned with the application of the 95% CI. The histograms for the two MinLoD approaches (Fig. 5.3 c, e) show how a MinLoD simply removes the parts of the elevation change distribution below the desired threshold, reflecting the potential accuracy of the original dataset. The addition of the 0.95 probabilistic threshold to the MinLoD alters the elevation change distribution as seen in Fig. 5.3 (d), (f) by further thinning the results based on their probabilistic likelihood.
Figure 5.2: DoD outputs for a small subsection of Dixons Ck. Red indicates erosion and blue indicates deposition. a) raw output, b) FIS propagated error with 95% CI, c) 0.20m MinLoD, d) 0.20m MinLoD with 95% CI, e) 0.30m MinLoD, f) 0.30m MinLoD with 95% CI. Flow direction is from left to right.
Figure 5.3: Elevation change distributions for the DoDs produced for a small subsection of Dixons Ck. Red represents change associated with erosion while blue represents deposition. Grey represents values removed by the uncertainty analysis method. a) Raw b) FIS propagated error with 95% CI, c) 0.20m MinLoD, d) 0.20m MinLoD with 95% CI, e) 0.30m MinLoD, f) 0.30m MinLoD with 95% CI
5.1.1 Selected uncertainty analysis method

For the purposes of this study, only one uncertainty analysis method is used to derive the results for section 5.2 to 5.4. The methodology chosen for this purpose is the 0.20m MinLoD with a 0.95 probabilistic threshold. The errors associated with the MinLoD approach alone (particularly at Dixons Ck) make this method less robust than other methods trialled (Fig. 5.1). While the FIS propagated error with a 0.95 probabilistic threshold is the most complex method used and provides a reasonable estimate of error in the DEM, it also appears to have over-predicted areas of fine scale change within the DoDs, particularly along the edges of the clip polygon used (Fig. 5.2 b). These areas are primarily just outside the gully walls and change in these regions is more likely to be noise rather than actual change. Wheaton (2008) provides a comparison between different change detection pathways in terms of the percentage of information lost/information recovered compared with a basic 0.10m MinLoD. His study showed that the FIS methodology and MinLoD with a 0.95 probabilistic threshold returned similar results, with the uniform surface method losing slightly less information that the FIS propagated error (Wheaton, 2008). The 0.20m MinLoD with 95% CI has been selected in this study over the 0.30m MinLoD with 95% CI as this most closely represents the reported error of 0.10m provided with the LiDAR metadata (Chapter 4). The implications of this choice are discussed in Chapter 6.
5.2 Reach scale results
Changes at the reach scale between 2011-2012 were calculated from the DoD, which was used to volumetrically quantify erosion and deposition which occurred at both study sites. The results in this section were derived through the application of a 0.20m MinLoD with a 0.95 probabilistic threshold to the DoD.

5.2.1 Erosional and depositional changes

**Arthursleigh**

Most of the gullies at Arthursleigh have not experienced a particularly large amount of erosion or deposition with only 2.1% of the entire study area experiencing any detectable change (Table 5.1). Despite this small area, Arthursleigh is net erosional between 2011-2012 having experienced 14,236 m$^3$ of erosion and 402 m$^3$ of deposition resulting in a net loss of -13,835 m$^3$ of sediment (Table 5.1). Spatially, the most notable areas of erosion appear to occur on existing gully walls, with a smaller amount occurring on the floors (Fig. 5.4). The most intense areas of erosion occur on ‘meander bends’ toward the lower section of the gully network. There is no obvious spatial pattern to areas of deposition.

<table>
<thead>
<tr>
<th>Erosion (m$^3$)</th>
<th>14,236 ± 3,943</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deposition (m$^3$)</td>
<td>402 ± 104</td>
</tr>
<tr>
<td>Net change (m$^3$)</td>
<td>-13,835 ± 3,945</td>
</tr>
<tr>
<td>% Area of change</td>
<td>2.1</td>
</tr>
</tbody>
</table>
Figure 5.4: Reach scale map of the gullies at Arthursleigh showing the DoD using 0.20m MinLoD + 95% CI. Red indicates erosion, blue indicates deposition. Crosses denote erosion on gully floors, star denotes gully wall erosion.
The average depth of erosion at Arthursleigh was estimated at 1.02 m, with an average depth of deposition of 1.09 m. As seen in Fig. 5.5 (a), the discernible area of change at Arthursleigh is nearly negligible. Fig. 5.5 (b) shows that the volumetric change at Arthursleigh was dominated by erosion. Both Fig. 5.5 (a) and (b) show that both the area and volume of change at Arthursleigh are dominated by erosional processes, with very few positive values on the histograms indicating deposition.

Dixons Ck

Compared to the overall area under examination at the Dixons Ck study site, 1.3% of the gullied regions have experienced any change between 2011 and 2012 (Table 5.2). The gully networks at Dixons Ck are erosional, having experienced 4,773 m$^3$ of erosion and 1,917 m$^3$ of deposition resulting in a net loss of -2,855 m$^3$ of sediment (Table 5.2). Spatially, there does not appear to be a pattern to the erosion and deposition in the upper half of the study area. In the lower half, erosion appears to occur primarily on gully walls, with some areas of deposition on gully floors (Fig. 5.6).

Table 5.2: Volumetric change for Dixons Ck calculated from the DoD

<table>
<thead>
<tr>
<th>Erosion (m$^3$)</th>
<th>4,773 ± 1,444</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deposition (m$^3$)</td>
<td>1,917 ± 658</td>
</tr>
<tr>
<td>Net change (m$^3$)</td>
<td>-2,855 ± 1,587</td>
</tr>
<tr>
<td>% Area of change</td>
<td>1.3</td>
</tr>
</tbody>
</table>
Figure 5.6: Reach scale map of the gullies at Dixons Ck overlain with the DoD created with 0.20m MinLoD + 95% CI. Crosses denote erosion on gully floors, star denotes gully wall erosion.
The average depth of erosion at Dixons Ck was estimated at 0.93m, with an average depth of deposition estimated at 0.82m. Fig. 5.7 (a) shows the areal distribution of erosion at Dixons Ck, which is negligible under the 0.20m MinLoD with 95% CI method used. Volumetric change at Dixons Ck was proportionately more erosional however some areas of detectable deposition also exist (Fig. 5.7 b).

Figure 5.7: Elevation change distributions for Dixons Ck expressed as surface area (a) and volume (b). Red represents change associated with erosion while blue represents deposition. Grey represents values removed by the uncertainty analysis method

5.2.2 Rates of sediment export
Using the erosion volumes calculated from the DoD and soil bulk density from soil sample analysis (Appendix A), the mass of sediment exported under four different scenarios was calculated (Chapter 4.2, Table 5.3). Scenario A assumes that all sediment was exported from the gully networks. Scenario B also assumes that all sediment was exported however the calculations take into account the different properties of the A and B soil horizons. Scenario C assumes all sediment was exported below the dams on both properties, and only clay and silt were exported above the dams while also accounting for the differences between the A and B soil horizons. Scenario D assumes that everything below the sediment dams was exported and only 50% of the silt and clay above the dams was exported while also taking into consideration the differences between the A and B horizons (Appendix D). The rates of sediment export were also calculated for each scenario by normalising the result of each scenario to year and drainage area (Table 5.3) (Appendix E).
Table 5.3: Total mass of sediment exported at both sites under four scenarios examined. Also included are the normalised rates of export under each scenario.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Arthursleigh</th>
<th>Dixons Ck</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total mass export (t)</td>
<td>Rate (t km(^2) yr(^{-1}))</td>
</tr>
<tr>
<td>A</td>
<td>21,859 ± 6,233</td>
<td>3,008 ± 857</td>
</tr>
<tr>
<td>B</td>
<td>23,045 ± 6,571</td>
<td>3,172 ± 904</td>
</tr>
<tr>
<td>C</td>
<td>12,918 ± 4,011</td>
<td>1,777 ± 551</td>
</tr>
<tr>
<td>D</td>
<td>9,587 ± 3,089</td>
<td>1,319 ± 425</td>
</tr>
</tbody>
</table>
5.3 Morphological controls on gully erosion

Four morphological parameters that may influence gully erosion were assessed using the volumetric output calculated from the DoD. Drainage area, average gully slope, stream order and aspect were all evaluated to determine whether they had any significant influence on gully erosion in the study areas during the time period observed.

5.3.1 Drainage area

Drainage area was found to have no significant influence on gully erosion at either study site. Linear regression analysis of drainage area against total change found that drainage area explained an insignificant amount of variation in total change at both Arthursleigh ($R^2 = 0.0109$, DF=39, $p =0.52$) (Fig 5.8 a) and Dixons Ck ($R^2 = 0.0077$, DF=42, $p =0.57$) (Fig. 5.9 b). Figure 5.8 shows that gullies with varying contributing areas had limited morphological responses between the two surveys. The gullies with the greatest net loss did not have the greatest drainage areas.

![Figure 5.8: Linear regression plots of total change (m^3) vs drainage area (m^2) at a) Arthursleigh and b) Dixons Ck](image-url)
5.3.2 Average slope

Average gully slope was found to have no significant influence on gully erosion at either study site. Linear regression analysis of average slope against total change found that average slope explained an insignificant amount of variation in total change at both Arthursleigh ($R^2 = 0.0048$, DF=90, $p=0.51$) (Fig 5.9 a) and Dixons Ck ($R^2 = 0.0055$, DF=82, $p =0.51$) (Fig. 5.10 b). At both sites, the steepest slopes did not produce the greatest areas of change.

![Linear regression plots of total change (m$^3$) vs average slope (%) at a) Arthursleigh and b) Dixons Ck](image)

Figure 5.9: Linear regression plots of total change (m$^3$) vs average slope (%) at a) Arthursleigh and b) Dixons Ck
5.3.3 Stream order

Cumulative erosion volume and mean erosion volume were both calculated from the DoD and partitioned according to stream order. Overall, first order streams at Arthursleigh were the most erosive, with a cumulative volume of 5751 ± 1443 m$^3$ (Fig 5.10 a). Second, third and fourth order streams had erosional volumes at 2704 ± 835 m$^3$, 2557 ± 689 m$^3$ and 2822 ± 981 m$^3$ respectively (Fig 5.10 a). First order streams at Arthursleigh also produced the highest mean rate of change at 1.02 m$^3$ m$^{-1}$ (Fig 5.10 b). Third order streams produced the second highest rate of change at 0.76 m$^3$ m$^{-1}$, with fourth order streams producing a slightly lower rate of 0.64 m$^3$ m$^{-1}$. Second order streams were found to have the lowest mean rate of change at 0.46 m$^3$ m$^{-1}$ (Fig 5.10 b).

![Graph of total erosion vs stream order](image1.png)

![Graph of mean change per metre vs stream order](image2.png)

*Figure 5.10: Total erosion for each stream order class (a) and mean change per metre for each stream order class (b) at Arthursleigh.*
Third order streams were the most erosive at Dixons Ck, having the highest total volume (1502 ± 713 m$^3$) and the highest rate of change (0.28 m$^3$ m$^{-1}$)(Fig 5.11 a, b). Second order streams experienced the second highest total amount of erosion (732 ± 402 m$^3$) however the mean change in these streams was less than that experienced by fourth order streams (0.08 m$^3$ m$^{-1}$ cf. 0.23 m$^3$ m$^{-1}$). First order streams at Dixons Ck experienced both the lowest net erosion (101 ± 280 m$^3$) and the lowest mean change (0.01 m$^3$ m$^{-1}$) (Fig 5.11 a, b).

![Figure 5.11: Total erosion for each stream order class (a) and mean change per metre for each stream order class (b) at Dixons Ck.](image)
5.3.4 Aspect

A comparison of erosion in tributary streams with different dominant aspects using a t-test was performed to assess whether aspect played a significant role in determining where erosion occurred. This examined the hypothesis that slopes facing certain directions would be more prone to erosion (i.e. northerly slopes are exposed to more sunlight which would result in drier soils and increased erosivity). At Arthursleigh, the tributaries were either dominantly north or south flowing whereas at Dixons Ck, the tributaries were either dominantly east or west flowing.

Overall, north flowing tributaries at Arthursleigh experienced 7,257 m$^3$ of erosion, with south flowing tributaries experiencing 6,577 m$^3$ (Fig 5.12 a). There was no significant difference between erosion in north flowing tributaries ($\mu=478.18$, SD=426.45) and south flowing tributaries ($\mu=577.57$, SD=1016.23) at Arthursleigh ($t=-0.25$, DF= 12, $p=0.80$). This indicates that aspect does not influence erosion in tributaries at Arthursleigh.

East flowing tributaries at Dixons Ck experienced 1,004 m$^3$ of erosion while west flowing tributaries experienced 1,056 m$^3$ of erosion (Fig 5.12 b). There was no significant difference between erosion in east flowing tributaries ($\mu=67.90$, SD=131.85) and west flowing tributaries ($\mu=47.91$, SD=119.66) at Dixons Ck ($t=0.34$, DF= 17, $p=0.74$). This indicates that aspect does not have an influence on erosion in tributaries at Dixons Ck.

![Figure 5.12: Total erosion in north and south flowing tributaries at Arthursleigh (a) and east and west flowing tributaries at Dixons Ck (b)](image-url)
5.4 Nitrogen and phosphorus

5.4.1 Nitrogen and phosphorus characteristics

A number of soil samples collected from the study sites and greater area in 2012 provide information about the total nitrogen and phosphorus concentrations for the soils within the study areas. It was determined that on average, 1 m$^3$ of soil at Arthursleigh contains 0.65 kg N and 0.082 kg P while 1 m$^3$ of soil at Dixons Ck contains 1.48 kg N and 0.224 kg P (Table 5.4, see Appendix D for detailed calculations).

Table 5.4: Average nitrogen and phosphorus content per 1 m$^3$ of soil at Arthursleigh and Dixons Ck

<table>
<thead>
<tr>
<th>Nutrient</th>
<th>Arthursleigh</th>
<th>Dixons Ck</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen (kg m$^{-3}$)</td>
<td>0.65</td>
<td>1.48</td>
</tr>
<tr>
<td>Phosphorus (kg m$^{-3}$)</td>
<td>0.082</td>
<td>0.224</td>
</tr>
</tbody>
</table>
Fig 5.13 shows the relationship between nitrogen and phosphorus concentrations and clay and silt percentages for the entire region covered by the soil samples collected. Silt content had a significant positive association with nitrogen concentration ($R^2 = 0.38$, DF= 25, $p = 0.0007$) and phosphorus concentration ($R^2=0.23$, DF=25, $p = 0.014$) (Fig.5.13 c, d). Clay content had a positive but insignificant relationship with both nitrogen ($R^2=0.018$, DF=25, $p = 0.51$) and phosphorus ($R^2=0.045$, DF=25, $p = 0.29$) concentration (Fig 5.13 a, b).

![Figure 5.13: Linear regression plots showing a) nitrogen vs Clay %, b) phosphorus vs clay %, c) nitrogen vs silt %, d) phosphorus vs silt %](image-url)
5.4.2 Estimation of nitrogen and phosphorus eroded between 2011-2012

The erosion volumes calculated by the GCD tool from the DoD were converted to tonnage amounts using the bulk density of soils within the study areas. Nitrogen and phosphorus concentrations from the study areas were then used to calculate the potential tonnage of these nutrients lost from the sites for the duration of the study. Rates of export for each site and nutrient were also calculated by normalising the exported tonnages to year and drainage area (See Appendix E for detailed calculations).

Table 5.5 shows the predicted tonnages of nitrogen and phosphorous eroded as well as an estimated rate of export from Arthursleigh under the four different scenarios applied. Scenario A produces the highest estimate with a result of $12 \pm 3$ t N and $1.7 \pm 0.49$ t P ($1.63 \pm 0.47$ t N km$^{-2}$ yr$^{-1}$ and $0.24 \pm 0.07$ t P km$^{-2}$ yr$^{-1}$). Taking into account the difference in soil composition between the A and B horizons further reduces the result under scenario B with an estimate of $9 \pm 3$ t N and $1.1 \pm 0.32$ t P ($1.22 \pm 0.35$ t N km$^{-2}$ yr$^{-1}$ and $0.16 \pm 0.07$ t P km$^{-2}$ yr$^{-1}$). Considering only clay and silt from above the dam nearly halves this result with scenario C estimating a loss of $5 \pm 1$ t N and $0.61 \pm 0.19$ t P ($0.67 \pm 0.20$ t N km$^{-2}$ yr$^{-1}$ and $0.085 \pm 0.026$ t P km$^{-2}$ yr$^{-1}$). Scenario D only marginally reduces the result found in scenario C with an estimate of $3 \pm 0.9$ t N and $0.47 \pm 0.15$ t P ($0.50 \pm 0.12$ t N km$^{-2}$ yr$^{-1}$ and $0.07 \pm 0.02$ t P km$^{-2}$ yr$^{-1}$).

Table 5.5: Tonnages of nitrogen and phosphorus exported from Arthursleigh between 2011 and 2012. Also listed are the estimated rates of export. A) All sediment exported, B) all sediment exported considering differences in A and B horizon composition, C) only clay and silt exported above sediment dams, D) 50% clay and silt exported above sediment dams

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Nitrogen (t)</th>
<th>Rate of N export (t N km$^{-2}$ yr$^{-1}$)</th>
<th>Phosphorus (t)</th>
<th>Rate of P export (t P km$^{-2}$ yr$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>12 ± 3</td>
<td>1.63 ± 0.47</td>
<td>1.7 ± 0.49</td>
<td>0.24 ± 0.07</td>
</tr>
<tr>
<td>B</td>
<td>9 ± 3</td>
<td>1.22 ± 0.35</td>
<td>1.1 ± 0.32</td>
<td>0.16 ± 0.07</td>
</tr>
<tr>
<td>C</td>
<td>5 ± 1</td>
<td>0.67 ± 0.20</td>
<td>0.61 ± 0.19</td>
<td>0.085 ± 0.026</td>
</tr>
<tr>
<td>D</td>
<td>3 ± 0.9</td>
<td>0.50 ± 0.12</td>
<td>0.47 ± 0.15</td>
<td>0.07 ± 0.02</td>
</tr>
</tbody>
</table>
Table 5.6 shows the predicted tonnages of nitrogen and phosphorous eroded as well as an estimated rate of export from Dixons Ck for the four scenarios applied. Scenario A produces the highest estimate for nitrogen and the second highest for phosphorus at $4 \pm 2 \text{ t N}$ and $0.49 \pm 0.27 \text{ t P}$ ($0.078 \pm 0.044 \text{ t N km}^{-2} \text{ yr}^{-1}$ and $0.0099 \pm 0.0055 \text{ t P km}^{-2} \text{ yr}^{-1}$). The difference in soil composition between the A and B horizons further reduces the estimate of N export under scenario B with a result of $2 \pm 1 \text{ t N}$, however P export increases at $0.63 \pm 0.29 \text{ t P}$ ($0.048 \pm 0.024 \text{ t N km}^{-2} \text{ yr}^{-1}$ and $0.012 \pm 0.005 \text{ t P km}^{-2} \text{ yr}^{-1}$). Considering only clay and silt from above the dam nearly halves this result with scenario C estimating a loss of $1 \pm 0.7 \text{ t N}$ and $0.38 \pm 0.19 \text{ t P}$ ($0.027 \pm 0.013 \text{ t N km}^{-2} \text{ yr}^{-1}$ and $0.0077 \pm 0.0039 \text{ t P km}^{-2} \text{ yr}^{-1}$). Scenario D only marginally reduces the result found in scenario C with an estimate of $1 \pm 0.5 \text{ t N}$ and $0.28 \pm 0.13 \text{ t P}$ ($0.021 \pm 0.009 \text{ t N km}^{-2} \text{ yr}^{-1}$ and $0.0057 \pm 0.0027 \text{ t P km}^{-2} \text{ yr}^{-1}$).

Table 5.6: Tonnages of nitrogen and phosphorus exported from Dixons Ck between 2011 and 2012. Also listed are estimated rates of export A) All sediment exported, B) all sediment exported considering differences in A and B horizon composition, C) only clay and silt exported above sediment dams, D) 50% clay and silt exported above sediment dams

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Nitrogen (t)</th>
<th>Rate of N export (t N km(^{-2}) yr(^{-1}))</th>
<th>Phosphorus (t)</th>
<th>Rate of P export (t P km(^{-2}) yr(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>$4 \pm 2$</td>
<td>$0.078 \pm 0.044$</td>
<td>$0.49 \pm 0.27$</td>
<td>$0.0099 \pm 0.0055$</td>
</tr>
<tr>
<td>B</td>
<td>$2 \pm 1$</td>
<td>$0.048 \pm 0.024$</td>
<td>$0.63 \pm 0.29$</td>
<td>$0.012 \pm 0.005$</td>
</tr>
<tr>
<td>C</td>
<td>$1 \pm 0.7$</td>
<td>$0.027 \pm 0.013$</td>
<td>$0.38 \pm 0.19$</td>
<td>$0.0077 \pm 0.0039$</td>
</tr>
<tr>
<td>D</td>
<td>$1 \pm 0.5$</td>
<td>$0.021 \pm 0.009$</td>
<td>$0.28 \pm 0.13$</td>
<td>$0.0057 \pm 0.0027$</td>
</tr>
</tbody>
</table>
5.5 Change in 2011-2012 Compared with Historical Rates of Change

Between 2011 and 2012, the DoD did not detect any change at gully heads, all areas of erosion identified were located either on gully walls or gully floors (see Fig. 5.4 and 5.6). This indicates that there was no extension of the gully networks at both Arthursleigh and Dixons Ck between 2011 and 2012.

Examination of the historical rate of change at Arthursleigh indicates that the gullies have extended in some areas since 1949, and receded in others. Figure 5.14 shows an area at Arthursleigh where gullies have extended over time. The positioning of small dams at the ends of these gullies makes further extension unlikely. Figure 5.15 provides an example from Arthursleigh where gullies have both extended and receded. The addition of a small dam appears to have facilitated the recovery of one arm of the gully network shown.

The difference in gully extent between 1949 and 2011 was used to estimate an average rate of gully erosion at Arthursleigh. Between 1949 and 1969 the gullies extended by approximately 17 m (Table 5.7). The period between 1969 and 1991 saw an additional 7 m of gully erosion. The period between 1991 and 2008 saw the gullies extend on average by 30 m. There was no measureable change in the extent of gullies between 2008 and 2011. The average rate of gully erosion at Arthursleigh is estimated to be 0.90 m yr\(^{-1}\) (Table 5.7).

Table 5.7: The extension of gully heads and the average rate of extension at Arthursleigh since 1949 measured from aerial photographs of the site.

<table>
<thead>
<tr>
<th>Year</th>
<th>Extension Since 1949 (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1949</td>
<td>0</td>
</tr>
<tr>
<td>1969</td>
<td>17</td>
</tr>
<tr>
<td>1991</td>
<td>25</td>
</tr>
<tr>
<td>2008</td>
<td>56</td>
</tr>
<tr>
<td>2011</td>
<td>56</td>
</tr>
<tr>
<td>Average Rate</td>
<td>0.90 m yr(^{-1})</td>
</tr>
</tbody>
</table>
Figure 5.14: The extension of gullies at Arthursleigh through time from 1949-2011. Yellow dots indicate 1949 gully heads.
Figure 5.15: A section of gully at Arthursleigh showing both gully extension and recession through time from 1949-2011. Gully heads in 1949 marked by yellow dots. Black arrow indicates recovering gully.
5.6 Summary of results

Geomorphic change detection analysis indicates that both study sites experienced change which resulted in net erosion from the gully networks. Despite the net erosion at both study sites, the areal distribution of change was small and erosion was primarily confined to gully walls and floors. The assessment of morphological controls on gully erosion found that drainage area, average gully slope and aspect did not significantly influence gully erosion during this study. It was found however that first order streams were the most erosive at Arthursleigh and third order streams were the most erosive at Dixons Ck.

An investigation of the nitrogen and phosphorus content of the soils at the study sites found that there was a significant relationship between soil silt content and nitrogen and phosphorus concentration. Positive but insignificant relationships were found between soil clay content and nitrogen and phosphorus concentration. Both study sites were found to have likely exported volumes of nitrogen and phosphorus between 2011 and 2012.

Compared to historical rates of erosion, the erosion experienced at the study sites between 2011 and 2012 was negligible with no extension due to gully headcuts experienced at either site. An examination of historical aerial photography at Arthursleigh found that while the gully networks have extended between 1949 and 2008, they appear to be relatively stable between 2008 and 2011 with some areas recovering and revegetating.
Chapter Six: Discussion

This study sought to use high resolution repeat LiDAR surveys to determine the response of gullies at two study sites to a large rainfall event in March 2012. These LiDAR surveys were used to quantify movement of sediment within the gullies and provide an estimation of the amount of nitrogen and phosphorus eroded from the gullies during the study period. Change detection analysis revealed that the gullies did experience change between 2011 and 2012, exporting sediment, nitrogen and phosphorus. This chapter will discuss in greater detail the trends identified within Chapter 5.

6.1 Uncertainty analysis in DEMs of Difference

This study has successfully used LiDAR data and Geomorphic Change Detection (GCD) analysis to assess change in gully volume and area within the Southern Tablelands. However the result derived in this study and indeed any study utilising a similar method is largely dependent on the method of uncertainty analysis used. As detailed in Chapter 5.1, the final uncertainty analysis method selected for use from the five assessed was a 0.20m MinLoD with a 95% confidence interval (CI). Deemed to be the least erroneous and most appropriate for this study, all sediment export tonnages have been derived through this methodology. This method is conservative as seen in Figure 5.3 (Chapter 5.1), thinning the GCD output fairly significantly. However, the question remains of how conservative one should be when approaching GCD analysis. Employing a more conservative 0.30m MinLoD would have rejected a further 0.10m of vertical change in the study, leading to reduced export volumes. Utilising the more liberal FIS methodology would have provided a greater estimate of erosion in the study areas. The problem is knowing which methodology best represents what occurred on the ground, which in order to estimate mathematically, would involve knowledge of the complete error budget which is not realistically possible (Wheaton et al., 2010).

In this study in particular, many assumptions were made about the possible error of the input datasets as the manufacturers’ error of the 2011 dataset was unknown. The most important thing to note is that the results produced in this study represent what is considered to be the best estimate of erosion within the study areas, given the procedures performed. Further quantification of the error within the datasets could have been performed with ground-truthed measurements to assess the accuracy of the LiDAR (Brasington et al., 2003), ground measurements of the thickness and extent of vegetation (particularly blackberry) present
around the gullies to provide additional error input (James et al., 2007) or direct measurements of sediment yield through stream monitoring to provide a comparison between LiDAR derived export volumes and actual export volumes (Armstrong & Mackenzie, 2002). The addition of these methods during the timeframe of this study was not practicable, but they have been highlighted to show how the uncertainty within GCD analysis may be further reduced. The addition of these methods would still not necessarily provide a true representation of what occurred on the ground, however they could increase the confidence in any result produced.

6.2 Reach scale changes

Both Arthursleigh and Dixons Ck were found to be net erosional between 2011 and 2012, with many small localised areas of change. The overall areal change experienced at both sites was very small (2.1% areal change at Arthursleigh, 1.3% at Dixons Ck). Despite the small area of change detected at both study sites, thousands of tonnes of sediment were still estimated to have been exported during the study period (Between 9,587 t to 21,859 t at Arthursleigh and 2,002 t to 4,297 t at Dixons Ck). The DoDs indicate that this sediment was derived from the walls and floors of the gullies which is consistent with the literature which indicates that gully walls can in some circumstances produce over half of the sediment exported from eroding gullies, particularly if the sidewalls are undercut (Blong et al., 1982; Crouch, 1987). Even though large volumes of sediment were calculated to have been exported (2,855 m$^3$ at Dixons Ck and 13,835 m$^3$ at Arthursleigh) this does not necessarily mean that this much sediment was actually transported through the drainage network and into the Warragamba catchment. Sediment yields from Australian rivers are quite low due to inefficient sediment delivery and transport capabilities resulting from low and variable rainfall and generally low elevations (Olive & Rieger, 1986). Assuming the DoDs estimated total net erosion correctly, it’s possible that this sediment may have been redistributed only a short distance outside the scope of the study areas.

6.2.1 Morphological response of gullies to the March 2012 rainfall event

One of the overarching hypothesis of this study was to assess the impact of a given rainfall event on gully erosion at the study sites. Intransitive extreme events such as flooding, fire and drought are often short term drivers of gully erosion (Chappell, 1983; Prosser, 1991). Where there is no temporal pattern to erosion and no outstanding geomorphic conditions, extreme events are likely to be the primary cause of erosion from gullies (Prosser, 1991). While the
storm event probably greatly contributed to gully erosion at the study sites, this study cannot say with absolute certainty whether the erosion detected by GCD analysis was chiefly due to the rainfall event or due to other underlying basin wide or site specific changes (Prosser, 1991). The primary reason for this is that the LiDAR data was not captured immediately before and after the rainfall event under examination, meaning that the combined influence of rainfall throughout the year may have contributed to the changes detected rather than just the single event. Figure 3.5 (Chapter 3.4.2) shows that although the event under examination was the largest experienced during the study period, rainfall was experienced at both sites both before and after the March 2012 rainfall event; however no other rainfall has an ARI any greater than one year, indicating that they were not particularly significant occurrences. There is also a lack of temporal data regarding the location of gully erosion at the study sites meaning that it is quite possible that the areas identified have been experiencing erosion for quite some time.

Despite this, it has been noted that the variability of rainfall in Australia often means that soil erosion is storm driven (Erskine & Saynor, 1996b). Studies in agricultural areas of NSW have indicated that major storms and floods account for the bulk of erosion experienced over long-term study periods (Adamson, 1974; Edwards, 1980; Erskine & Saynor, 1996a; Hairsine et al., 1993). The information presented in this study indicates that the March 2012 storm event was almost certainly responsible for the bulk of the erosion that occurred during the study; however the question of whether it was responsible for all of it remains unanswered.

6.3 Morphological controls on gully erosion

Analysis of the DoDs produced in this study indicated that drainage area, average gully slope and aspect did not have a significant control on where gully erosion occurred between 2011 and 2012. The gullies with the greatest drainage areas or slopes did not experience the greatest amount of erosion, and north facing tributaries were not the most erosive, contrary to what was hypothesised. The assessment of gully erosion by stream order also produced different results for both study sites, with first order gullies at Arthursleigh being the most erosive compared with third order gullies at Dixons Ck. This result implies that gully erosion at the study sites was driven by some other factor which has not been directly measured in this study. A possible cause of the largely localised areas of erosion identified in the DoDs is the rainfall event that occurred during March 2012. Storm events can be an effective driver of erosion in gullied areas, mobilising sediment initially through rainsplash (saltation) and rain-
flow until concentrated larger overland flows develop and transport sediment more effectively (Bull & Kirkby, 1997). Another possible control on erosion at the study sites not examined in this study is soil susceptibility to erosion. The surface roughness of the soil, due to the presence of vegetation (De Baets et al., 2006), rock fragments (Poesen et al., 1999) or other factors may have been higher than critical shear stress thresholds required for overland flow to mobilise sediment in some areas of the gullies—making patterns of erosion spatially variable (Torri et al., 2012). Additionally, soil composition also plays a role in susceptibility to erosion from concentrated flow, with sandier soils such as the podzols at Arthursleigh being more resistant to simple overland flow, becoming less resistant as infiltration of water into the soil profile occurs (Knapen et al., 2007).

Although not identified as controls on gully erosion in this study, drainage area, slope and aspect have all been identified as having some influence on gully erosion (Fang & Guo, 2015; Montgomery & Dietrich, 1989; Sheridan et al., 2000; Torri & Poesen, 2014). It is possible that these controls were not identified as influential in this study due to the short time frame of the study and the influence of the large rainfall event, soil type or surface roughness far outweighing any of the tested controls on erosion.

6.4 Estimated nitrogen and phosphorus export

Exported concentrations of nitrogen have been found to increase linearly with concentrations of suspended sediment and an increasing proportion of clay and silt (Garzon-Garcia et al., 2015). This finding is largely consistent with the examination of soil samples performed during this study whereby a positive relationship was found between silt and clay concentrations and nitrogen and phosphorus content at the study sites.

Despite the small areas of change experienced at both sites, it was still estimated that between 3 - 12 t N and 0.47 - 1.7 t P were exported at Arthursleigh and 1 - 4 t N and 0.28 - 0.49 t P from the gully networks at Dixons Ck. Normalised per year, these values are projected to be 3 - 13 t N yr⁻¹ and 0.52 - 1.9 t P yr⁻¹ at Arthursleigh and 1 - 4.5 t N yr⁻¹ and 0.31 - 0.55 t P yr⁻¹ at Dixons Ck. These rates fall within values modelled by Rustomji (2006b) for nitrogen and phosphorus export from gullies within the Warragamba catchment (Table 6.1). The Upper Wollondilly sub-catchment contains the Dixons Ck study area and the Wollondilly sub-catchment contains the Arthursleigh study area.
Table 6.1: Modelled nitrogen and phosphorus exports from gully erosion for the Upper Wollondilly (within which Dixons Ck is located) and Wollondilly (within which Arthursleigh is located) sub-catchments. (Rustomji 2006)

<table>
<thead>
<tr>
<th>Sub-Catchment/Study Site</th>
<th>Nitrogen (t yr⁻¹)</th>
<th>Phosphorus (t yr⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper Wollondilly</td>
<td>35</td>
<td>8.6</td>
</tr>
<tr>
<td>Dixons Ck</td>
<td>1 to 4.5</td>
<td>0.31 to 0.55</td>
</tr>
<tr>
<td>Wollondilly</td>
<td>64</td>
<td>16</td>
</tr>
<tr>
<td>Arthursleigh</td>
<td>3 to 13</td>
<td>0.52 to 1.9</td>
</tr>
</tbody>
</table>

As the values provided by Rustomji (2006b) represent sub-catchment wide values of nitrogen and phosphorus, without knowing the export of nutrients from other gully networks, no real comparison can be made however it is noteworthy that the results in this study do not exceed the values predicted by Rustomji (2006b).

One of the more important questions arising from the investigation into N and P export from eroding gullies in this study is whether or not the values estimated are a cause for concern when considering Sydney’s drinking water catchments. The Sydney Catchment Authority (2011b) reported that the long term average annual total nitrogen loading from the Warragamba catchment was between 100 to 1000 t yr⁻¹, with phosphorus loading ranging between 5 to 150 t yr⁻¹. When considered over the 2000 GL capacity of the Warragamba Reservoir, these values were not considered to be of any concern (Sydney Catchment Authority, 2011b). It is difficult to know the individual contribution of the study sites to N and P loading within the reservoir without specific measurement of the export of N and P from the gullies into the waterways, as opposed to potential estimates calculated from soil erosion presented in this study. However, the Sydney Catchment Authority (2011a) does flag the drainage unit within which Arthursleigh is located (Eden Forest) as high risk of phosphorus contamination associated with gully erosion, which indicates an existing problem with phosphorus export in this section of the catchment. It is also worth considering that the N and P exports calculated in this study were associated with a large storm event and storms and large flow conditions traditionally result in larger sediment, nutrient and phosphorus outputs.
6.5 Rates of change compared with historical rates of change

As detailed above, the overall areal change identified by GCD analysis at both sites in this study was very small, with changes confined to existing gully walls and floors. Furthermore, no new gully headcuts were identified from the GCD, leading to the conclusion that there was no extension of the gully networks at either site between August 2011 and June 2012. Additionally, little change was detected in the examination of aerial photography from 1949 to 2011 performed in this study, indicating that most of the gullying at the study sites occurred prior to 1949.

The small area of erosion and relatively low rate of gully head extension ($0.90$ $\text{m yr}^{-1}$) discovered at Arthursleigh is consistent with the literature on gully erosion in south eastern Australia which has found that sediment yields and gully erosion peaked after European settlement and are currently sitting at a stable level between peak yields and pre-European settlement yields (Wasson et al., 1998) (Fig 6.1). Many gully networks in south eastern Australia were already well developed by the time aerial photography started in the 1940s, and there has been little dramatic change since (Prosser & Winchester, 1996)—a finding largely consistent with the examination of the aerial photography captured at Arthursleigh. Additionally, the gullies at Arthursleigh have been shown previously to be recovering, revegetating and reducing in extent (Wilmot, 2007).

![Figure 6.1: Estimated total sediment yields for the catchment of Jerrabomberra Creek within the Southern Tablelands from before European settlement showing the peak and subsequent decline in sediment yield. Solid lines denote estimated average yields, dashed line denotes inferred sediment yield (From Wasson et al, 1998)](image-url)

Work in the New England tablelands of NSW attributes the decline in sedimentation rates and current stabilisation of rates of soil erosion to the depletion of erodible material within
catchments compared with what was available during the 1800s (Gale & Haworth, 2005). Another possible reason for the reduction in sediment yield is the recovery, revegetation and stabilisation of gully networks (Armstrong & Mackenzie, 2002). In some instances, the revegetation of gully networks occurs naturally however human intervention through gully control works and improved land management practices can also play a role in facilitating the recovery of eroding gullies (Armstrong & Mackenzie, 2002). It is important to note however that despite the reduced rate of sedimentation from gullies, research indicates that gully erosion still greatly contributes to the sediment budget and turbidity within riverine systems (Prosser et al., 2001b).

6.5.1 Sediment export rates

Olley and Wasson (2003) calculated the natural pre-European rate of sediment export in the Southern Tablelands to be approximately 3 to 4.5 t km\(^{-2}\) yr\(^{-1}\), believed to be primarily driven by sheet and rill erosion (Table 6.2). Between 1842 and 1944 it is estimated that the sediment export rate within different localities of the Southern Tablelands increased to between 100 t km\(^{-2}\) yr\(^{-1}\) and 980 t km\(^{-2}\) yr\(^{-1}\) due to the development of extensive and intensive gully networks (Table 6.2) (Olley & Wasson, 2003; Prosser et al., 1994; Wasson et al., 1998). Comparatively, the normalised rate of sediment export produced in this study estimated erosion to be occurring at Arthursleigh at a rate of 1,319 to 3,008 t km\(^{-2}\) yr\(^{-1}\) and at Dixons Ck at 41 to 87 t km\(^{-2}\) yr\(^{-1}\) (See chapter 5.2.2, Table 6.2). The Arthursleigh rate appears to indicate that sediment is being exported at this site at a rate that far exceeds what was encountered in the 1800s, however it is important to note that all rates in this study were derived from only one year of data—a year with potentially particularly bad erosion likely due to the rainfall event experienced in March 2012. Additionally, the values in this study were derived from high resolution LiDAR surveys which may have captured more detail than previous studies not employing high resolution topographic surveys.

A useful value for comparing current rates of change in the Southern Tablelands over time with those calculated in this study are those provided by Armstrong and Mackenzie (2002) in their study which covered a period of 11 years in an area close to the Dixons Ck study site. Armstrong and Mackenzie (2002) found that the rate of sediment export in gullied catchments in this region was approximately 150 to 180 t km\(^{-2}\) yr\(^{-1}\) (Table 6.2). Another useful rate for comparison is that calculated by Neil and Mazari (1993), derived from farm dam surveys in the Southern Tablelands. Their rate is a much more conservative 19.35 to
58.35 t km\(^{-2}\) yr\(^{-1}\). The rate derived for Dixons Ck is smaller than the rate derived by Armstrong and Mackenzie (2002) and within the range calculated by Neil and Mazari (1993), perhaps indicating that the gullies at Dixons Ck have become less active since the 1990s.

Table 6.2: Sediment export rates in the Southern Tablelands from different time periods.

<table>
<thead>
<tr>
<th>Period</th>
<th>Rate of Sediment Export (t km(^{-2})yr(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-European settlement (Pre 1842) (Olley &amp; Wasson, 2003)</td>
<td>3 to 4.5</td>
</tr>
<tr>
<td>European settlement (1842-1944) (Olley &amp; Wasson, 2003; Prosser et al., 1994)</td>
<td>100 to 980</td>
</tr>
<tr>
<td>Dam Surveys (~1960s-1990s) (Neil &amp; Mazari, 1993)</td>
<td>19.35 to 58.35*</td>
</tr>
<tr>
<td>This study (2011-2012)</td>
<td>1.319 to 3,008 (Arthursleigh) 41 to 87 (Dixons Ck)</td>
</tr>
</tbody>
</table>

* has been converted from volume (m\(^3\)) using assumed soil bulk density of 1.5 t/m\(^3\).

Elsewhere in Australia, Olive and Rieger (1986) in a review of existing work on soil erosion losses found ranges from 3-210 t km\(^{-2}\) yr\(^{-1}\) in Wagga Wagga ranging up to 4,200- 22,700 t km\(^{-2}\) yr\(^{-1}\) in Mackay in QLD where rainfall is much more significant than in the Southern Tablelands of NSW. The large range of sediment yield indicates that soil loss is highly variable depending on location, land use and soil composition.

6.5.2 Nutrient export rates

While peak nutrient export rates during European Settlement are unable to be measured, using the estimated peak erosion rate of 980 t km\(^{-2}\) yr\(^{-1}\) provided by Wasson et al. (1998), a rough estimation of nitrogen and phosphorus exported was calculated using the nitrogen and phosphorus concentration of soils at Arthursleigh and Dixons Ck. Nitrogen and phosphorus loss across the Southern Tablelands between 1842 and 1944 was estimated at 0.82 t N km\(^{-2}\) yr\(^{-1}\) and 0.13 t P km\(^{-2}\) yr\(^{-1}\) (Table 6.3).

Table 6.3: Comparison of rates of nitrogen and phosphorus export at Arthursleigh and Dixons Ck against an estimated rate for the Southern Tablelands during peak erosion during European Settlement

<table>
<thead>
<tr>
<th>Site</th>
<th>Nitrogen (t N km(^{-2})yr(^{-1}))</th>
<th>Phosphorus (t P km(^{-2})yr(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arthursleigh</td>
<td>0.50 to 1.63</td>
<td>0.065 to 0.24</td>
</tr>
<tr>
<td>Dixons Ck</td>
<td>0.021 to 0.078</td>
<td>0.0057 to 0.0099</td>
</tr>
<tr>
<td>Estimated Southern</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tablelands rate</td>
<td>0.82</td>
<td>0.13</td>
</tr>
</tbody>
</table>
The rates presented in Table 6.3 for Dixons Ck and Arthursleigh are within the range of the estimated values for the Southern Tablelands. The range of values presented for Dixons Ck (0.021 to 0.078 t N km\(^{-2}\) yr\(^{-1}\) and 0.0057 to 0.0099 t P km\(^{-2}\) yr\(^{-1}\)) is lower than the peak rate estimated for the Southern Tablelands which is consistent with the reported reduction in sediment yield since settlement (Wasson et al., 1998), and thus an assumed reduction in N and P export. The upper limit of values estimated for Arthursleigh (0.50 to 1.63 t N km\(^{-2}\) yr\(^{-1}\) and 0.065 to 0.24 t P km\(^{-2}\) yr\(^{-1}\)) exceeds the estimated values for peak European settlement. It should be noted that the rates calculated from this study incorporate only one year of data, and therefore may be slightly larger than if they were normalised over a period of 102 years like the Southern Tablelands rate. Additionally, the average recurrence interval (ARI) for the rainfall event covered in this study was about 20-50 years (Chapter 3.4.2 Table 3.3), meaning that the rainfall experienced at the study sites does not represent regular yearly rainfall values which further indicates that the erosion experienced and therefore nutrients exported in 2011 to 2012 may be greater than what would be expected in a typical year. For this reason, a direct comparison between the rates of nutrient export derived in this study and the estimated Southern Tablelands rate is not really feasible but is interesting to consider nonetheless.
Chapter Seven: Conclusions and Recommendations

Gully erosion contributes greatly to sedimentation rates and soil loss in a number of environments (Poesen et al., 2003). Gullies incise drainage lines, increase connectivity within the landscape and facilitate the transportation of sediment and nutrients from upland areas, affecting water quality (Poesen et al., 2003). Gully erosion in upper catchment areas represents a large contribution to excessive sedimentation and nutrient loading in drinking water reservoirs (Valentin et al., 2005; Wasson et al., 2002). Since European settlement in the 1800s, the Southern Tablelands of NSW has experienced severe gullying, with thousands of tonnes of sediment being liberated from the landscape and transported into the waterways (Olley & Wasson, 2003; Prosser et al., 2001b). Since the 1940s, gully erosion within the Southern Tablelands has somewhat stabilised (Olley & Wasson, 2003), however turbidity and nutrient loading related to gully erosion still remains an issue in drinking water catchments in NSW (Olley et al., 2004).

The areal change in extent of two gullied study sites due to the effect of a large storm in March 2012 was assessed using repeat LiDAR surveys taken before and after the event to quantify rates of erosion and estimate nutrient loss. Geomorphic Change Detection (GCD) analysis was used to difference the LiDAR datasets in order to find areas of change and quantify the volume of sediment lost from the study sites. The uncertainty within the DEMs of Difference (DoDs) produced was assessed through a number of different methodologies to derive the best possible result. Average gully slope, drainage area, aspect and stream order were all assessed as potential morphological controls on the location and intensity of gully erosion at the study sites. Estimates of potential nitrogen and phosphorus exported from the study sites between 2011 and 2012 were derived via the volumes of sediment eroded provided by the GCD. Finally, aerial photography at Arthursleigh was qualitatively assessed in order to determine an average rate of gully headcut progression at the study sites.

The results of this study have indicated that both study sites were net erosional within the study period, estimated to have exported thousands of tonnes of sediment and associated concentrations of nitrogen and phosphorus. The areal change at both sites was small and spatially variable but erosion occurred primarily on gully walls and floors. Estimated tonnages of nitrogen and phosphorus within the study period appear not to exceed what has been reported in the literature as acceptable.
The morphological controls on gully erosion assessed in this study were deemed to have no influence on the location or intensity of erosion at either study site. This indicates that other factors not assessed likely controlled erosion between 2011 and 2012, with the potential influences being the large rainfall event, soil type or gully roughness.

Finally, the assessment of aerial photography at Arthursleigh revealed that very little gully network extension has occurred at Arthursleigh during the 62 year record—a finding largely consistent with the literature on gully erosion within the Southern Tablelands.

### 7.1 Recommendations

**Further monitoring and surveys**

This study has successfully used high resolution LiDAR surveys to quantify change in gully extent, however the study is limited to a period of less than a year and primarily quantifies change associated with a storm event. Further monitoring of the study sites would provide the opportunity to quantify change over a longer period of time, assessing change both with and without the influence of erosive storms.

Further investigations could cover:

- An investigation of other erosive gullies within the catchment using LiDAR
- Examination downstream from gullies to assess where eroded sediment is being deposited
- Ground-truthing LiDAR surveys for increased accuracy
- An assessment of the effectiveness of farm dams at the study sites at capturing suspended sediment and bedload
- Examination of the effect of gully roughness in mitigating erosion/affecting DEM quality from LiDAR

Long-term analysis of gully change could lead to the development of a normalised baseline rate of gully areal increase which may prove useful when applied to the gullies elsewhere in the catchment.
References


Hairsine, P, Murphy, B, Packer, I & Rosewell, C 1993, ‘Profile of erosion from a major storm in the south-east cropping zone’, *Australian Journal of Soil and Water Conservation*, vol. 6, no. 4, pp. 50-5.


James, LA, Watson, DG & Hansen, WF 2007, ‘Using LiDAR data to map gullies and headwater streams under forest canopy: South Carolina, USA’, *Catena*, vol. 71, no. 1, pp. 32-44.


NSW DPI 2003, NSW 1:250,000 Statewide Geology, NSW Department of Primary Industries.


Sydney Catchment Authority 2011a, *Pollution Source Assessment Tools Results*, Sydney Catchment Authority, Penrith.


Torri, D, Poesen, J, Borselli, L, Bryan, R & Rossi, M 2012, ‘Spatial variation of bed roughness in eroding rills and gullies’, *Catena*, vol. 90, pp. 76-86.


<table>
<thead>
<tr>
<th>Lab No.</th>
<th>Method</th>
<th>700mm</th>
<th>1000mm</th>
<th>2000mm</th>
<th>3000mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Art 11</td>
<td>Dixons Creek 149.61303</td>
<td>-34.68331</td>
<td>0.0193</td>
<td>0.193</td>
</tr>
<tr>
<td>2</td>
<td>Art 15</td>
<td>Eden Forest</td>
<td>0.03</td>
<td>0.3</td>
<td>0.03</td>
</tr>
<tr>
<td>3</td>
<td>Art 21</td>
<td>Eden Forest</td>
<td>0.03</td>
<td>0.3</td>
<td>0.03</td>
</tr>
<tr>
<td>4</td>
<td>Art 41</td>
<td>Eden Forest</td>
<td>0.03</td>
<td>0.3</td>
<td>0.03</td>
</tr>
<tr>
<td>5</td>
<td>Art 42</td>
<td>Eden Forest</td>
<td>0.03</td>
<td>0.3</td>
<td>0.03</td>
</tr>
<tr>
<td>6</td>
<td>Art 43</td>
<td>Eden Forest</td>
<td>0.03</td>
<td>0.3</td>
<td>0.03</td>
</tr>
<tr>
<td>7</td>
<td>Art 44</td>
<td>Eden Forest</td>
<td>0.03</td>
<td>0.3</td>
<td>0.03</td>
</tr>
<tr>
<td>8</td>
<td>Art 51</td>
<td>Eden Forest</td>
<td>0.03</td>
<td>0.3</td>
<td>0.03</td>
</tr>
<tr>
<td>9</td>
<td>Art 52</td>
<td>Eden Forest</td>
<td>0.03</td>
<td>0.3</td>
<td>0.03</td>
</tr>
<tr>
<td>10</td>
<td>Art 53</td>
<td>Eden Forest</td>
<td>0.03</td>
<td>0.3</td>
<td>0.03</td>
</tr>
<tr>
<td>11</td>
<td>Art 54</td>
<td>Eden Forest</td>
<td>0.03</td>
<td>0.3</td>
<td>0.03</td>
</tr>
<tr>
<td>12</td>
<td>Art 55</td>
<td>Eden Forest</td>
<td>0.03</td>
<td>0.3</td>
<td>0.03</td>
</tr>
<tr>
<td>13</td>
<td>Art 56</td>
<td>Eden Forest</td>
<td>0.03</td>
<td>0.3</td>
<td>0.03</td>
</tr>
<tr>
<td>14</td>
<td>Art 57</td>
<td>Eden Forest</td>
<td>0.03</td>
<td>0.3</td>
<td>0.03</td>
</tr>
<tr>
<td>15</td>
<td>Art 58</td>
<td>Eden Forest</td>
<td>0.03</td>
<td>0.3</td>
<td>0.03</td>
</tr>
<tr>
<td>16</td>
<td>Art 59</td>
<td>Eden Forest</td>
<td>0.03</td>
<td>0.3</td>
<td>0.03</td>
</tr>
<tr>
<td>17</td>
<td>Art 60</td>
<td>Eden Forest</td>
<td>0.03</td>
<td>0.3</td>
<td>0.03</td>
</tr>
<tr>
<td>18</td>
<td>Art 61</td>
<td>Eden Forest</td>
<td>0.03</td>
<td>0.3</td>
<td>0.03</td>
</tr>
<tr>
<td>19</td>
<td>Art 62</td>
<td>Eden Forest</td>
<td>0.03</td>
<td>0.3</td>
<td>0.03</td>
</tr>
<tr>
<td>20</td>
<td>Art 63</td>
<td>Eden Forest</td>
<td>0.03</td>
<td>0.3</td>
<td>0.03</td>
</tr>
<tr>
<td>21</td>
<td>Art 64</td>
<td>Eden Forest</td>
<td>0.03</td>
<td>0.3</td>
<td>0.03</td>
</tr>
<tr>
<td>22</td>
<td>Art 65</td>
<td>Eden Forest</td>
<td>0.03</td>
<td>0.3</td>
<td>0.03</td>
</tr>
<tr>
<td>23</td>
<td>Art 66</td>
<td>Eden Forest</td>
<td>0.03</td>
<td>0.3</td>
<td>0.03</td>
</tr>
<tr>
<td>24</td>
<td>Art 67</td>
<td>Eden Forest</td>
<td>0.03</td>
<td>0.3</td>
<td>0.03</td>
</tr>
<tr>
<td>25</td>
<td>Art 68</td>
<td>Eden Forest</td>
<td>0.03</td>
<td>0.3</td>
<td>0.03</td>
</tr>
<tr>
<td>26</td>
<td>Art 69</td>
<td>Eden Forest</td>
<td>0.03</td>
<td>0.3</td>
<td>0.03</td>
</tr>
<tr>
<td>27</td>
<td>Art 70</td>
<td>Eden Forest</td>
<td>0.03</td>
<td>0.3</td>
<td>0.03</td>
</tr>
</tbody>
</table>

**Notes**

- Depositional - sandy
- Depositional sand - just behind water in dam
- Down to weathered granite
- 1000-2000 (weathered granite)
- 2000-2500 (weathered granite)
- River sediment
- River sediment
- River sediment
- No sample?
Appendix B – BOM IFD Charts for Arthursleigh and Dixons Ck
Intensity-Frequency-Duration Table

Location: 34.6755° 149.5756° NEAR. Dikons Ck Issued: 9/7/2015

Rainfall intensity in mm/h for various durations and Average Recurrence Interval

<table>
<thead>
<tr>
<th>Average Recurrence Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 YEAR</td>
</tr>
<tr>
<td>Duration</td>
</tr>
<tr>
<td>5Mins</td>
</tr>
<tr>
<td>10Mins</td>
</tr>
<tr>
<td>30Mins</td>
</tr>
<tr>
<td>1Hr</td>
</tr>
<tr>
<td>2Hrs</td>
</tr>
<tr>
<td>3Hrs</td>
</tr>
<tr>
<td>4Hrs</td>
</tr>
<tr>
<td>6Hrs</td>
</tr>
<tr>
<td>12Hrs</td>
</tr>
<tr>
<td>24Hrs</td>
</tr>
<tr>
<td>48Hrs</td>
</tr>
<tr>
<td>72Hrs</td>
</tr>
</tbody>
</table>

(Raw data: 2:22, 4:47, 1:23, 4:34, 3:02, 2:22, 20:00, 17:00, 17:00, 15:30) © Australian Government, Bureau of Meteorology
Appendix C – LiDAR metadata report

The metadata report for the 2012 LiDAR surveys has been included on the thesis disk in a separate folder named “Appendix C”—file name: “Fugro_SCA_metadata”
Appendix D – N and P export calculations

**DIXONS CK**

0.93m avg depth erosion (A horizon avg depth to 0.39 m, 41.9% is A horizon)

**Average N + P per m³**

0.419 m³ A horizon * 1.354 t/m³
= 0.567326 t

0.567326 t * 0.000829 N = 0.119 N
= 0.074 kg

0.567326 t * 0.000130 P = 0.0075 kg

0.581 m³ B horizon * 1.7 t/m³
= 0.9877 t * 0.000366 N = 0.036 N
= 0.15 kg

**Total**

1.48 kg N/m³
0.224 kg P/m³

**SCENARIO A: No separation according to soil horizon**

2855.18 ± 1587.36 m³ sed @ Dixons Ck

2855.18 ± 1587.36 m³ * 1.505 t/m³
= 4297.0459 ± 2388.9768 t

avg N: 690ppm
avg P: 135ppm

= 4297.0459 ± 2388.9768 t * 0.0009 N = 3.86 ± 0.215 t N
= 4297.0459 ± 2388.9768 t * 0.0001135 P = 0.4877 ± 0.02711 P

**SCENARIO B: Assuming that all sediment was lost from the system**

2855.18 ± 1587.36 m³ * 0.419
= 1196.32 ± 665.10 m³ A horizon * 1.354 t/m³
= 1619.82 ± 900.55 t

avg N: 829ppm avg P: 130ppm

= 1619.82 ± 900.55 t * 0.000829 N = 1.34 ± 0.747 t N
= 1619.82 ± 900.55 t * 0.000130 P = 0.211 ± 0.117 t P

1658.86 ± 686.81 m³ B horizon * 1.7 t/m³
= 2820.062 ± 1167.577 t

Avg N: 366ppm Avg P: 147ppm

= 2820.062 ± 1167.577 t * 0.000366 N = 1.032 ± 0.427 t N
= 2820.062 ± 1167.577 t * 0.000147 P = 0.415 ± 0.172 t P

**Total N and P lost:**

2.372 ± 1.174 N
0.626 ± 0.289 P
**SCENARIO C: Assuming that only clay and silt were lost above the dam**

846.8 ± 376.93 m³ total below dam
2008.42 ± 1270.87 m³ total above dam

**Below dam**

846.8 ± 376.93 m³ * 0.419
=354.8092 ± 157.9337 m³ A horizon * 1.354 t/m³
=480.412 ± 213.842 t

<table>
<thead>
<tr>
<th>Component</th>
<th>Below Dam Value</th>
<th>Above Dam Value</th>
<th>Total N and P lost below dam</th>
</tr>
</thead>
<tbody>
<tr>
<td>avg N</td>
<td>829ppm</td>
<td>840.412 ± 213.842 t * 0.000829 N</td>
<td>0.704 ± 0.278 N</td>
</tr>
<tr>
<td>avg P</td>
<td>130ppm</td>
<td>840.412 ± 213.842 t * 0.000130 P</td>
<td>0.185 ± 0.0686 P</td>
</tr>
<tr>
<td>Avg N</td>
<td>366ppm</td>
<td>836.384 ± 277.249 t * 0.000366 N</td>
<td>0.704 ± 0.278 N</td>
</tr>
<tr>
<td>Avg P</td>
<td>147ppm</td>
<td>836.384 ± 277.249 t * 0.000147</td>
<td>0.185 ± 0.0686 P</td>
</tr>
</tbody>
</table>

**Above Dam**

2008.42 ± 1270.87 m³ * 0.419
=841.5279 ± 532.4945 m³ A horizon * 1.354 t/m³

=1139.4289 ± 720.9976 t clay and silt
=319.0401 ± 201.8793 t clay and silt

<table>
<thead>
<tr>
<th>Component</th>
<th>Above Dam Value</th>
<th>Total N and P lost above dam</th>
</tr>
</thead>
<tbody>
<tr>
<td>319.0401 ± 201.8793 t * 0.000829 N</td>
<td>0.264 ± 0.167 t N</td>
<td></td>
</tr>
<tr>
<td>319.0401 ± 201.8793 t * 0.000130 P</td>
<td>0.0415 ± 0.0262 t P</td>
<td></td>
</tr>
<tr>
<td>1166.4721 ± 738.3755 B horizon * 1.7 t/m³</td>
<td>0.649 ± 0.410 t N</td>
<td></td>
</tr>
<tr>
<td>1166.4721 ± 738.3755 B horizon * 1.7 t/m³</td>
<td>0.196 ± 0.124 t P</td>
<td></td>
</tr>
</tbody>
</table>

**Total N and P lost above dam**

0.649 ± 0.410 t N
0.196 ± 0.124 t P

**Combined total**

1.353 ± 0.688 t N
0.381 ± 0.193 t P
SCENARIO D: Assuming only 50% silt and clay were lost above the dam
A horizon: 319.0401 ± 201.8793 t clay and silt/2
= 159.52 ± 100.94

\[
\begin{align*}
159.52 \pm 100.94 \times 0.000829 N &= 0.132 \pm 0.0837 t N \\
&= 0.0207 \pm 0.0131 t P \\
\end{align*}
\]

B horizon: 1050.9914 ± 665.2763 t clay and silt/2
= 525.496 ± 332.638 t

\[
\begin{align*}
525.496 \pm 332.638 \times 0.000366 N &= 0.192 \pm 0.122 t N \\
&= 0.0772 \pm 0.0489 t P \\
\end{align*}
\]

Total:
\[
\begin{align*}
0.324 \pm 0.2057 t N \\
0.0979 \pm 0.062 t P
\end{align*}
\]

Combined Total:
\[
\begin{align*}
1.028 \pm 0.484 t N \\
0.283 \pm 0.131 t P
\end{align*}
\]

**ARTHURSLEIGH**

1.02m avg depth erosion (A horizon avg depth to 0.256m, 25% is A horizon)

**Average N + P per m^3**

0.25 m^3 A horizon * 1.473 t/m^3
= 0.36825 t

\[
\begin{align*}
0.36825 t \times 0.000678 N &= 0.25 kg N \\
&= 0.039 kg P \\
0.75 m^3 B horizon * 1.73 t/m^3 &= 1.2975 t \\
1.2975 t \times 0.0000334 &= 0.040 kg \\
&= 0.043 kg
\end{align*}
\]

Total
\[
\begin{align*}
0.65 kg N/m^3 \\
0.082 kg P/m^3
\end{align*}
\]

**SCENARIO A: No separation according to soil horizon**

13834.79 ± 3944.77 m^3 sediment @ Arthursleigh
13834.79 ± 3944.77 m^3 * 1.58 t/m^3
= 21858.968 ± 6232.737 t

Avg N: 543ppm
\[
21858.968 \pm 6232.737 t \times 0.000543 = 11.87 \pm 3.384 t N
\]

Avg P: 79ppm
\[
21858.968 \pm 6232.737 t \times 0.000079 = 1.72 \pm 0.492 t P
\]
SCENARIO B: Assuming that all sediment was lost from the system

13834.79 ± 3944.77 * 0.25
= 3458.6975 ± 944.7794 * 1.473 t/m³
= 5094.6614 ± 1452.6616 t

Avg N: 678ppm
= 3.45 ± 0.985 t N

Avg P: 105ppm
= 0.535 ± 0.153 t P

10376.093 ± 2958.578 m³ B horizon * 1.73 t/m³
= 17950.641 ± 5118.340 t

Avg N: 300ppm
= 5.39 ± 1.54 t N

Avg P: 33.4ppm
= 0.600 ± 0.171 t P

Total N and P lost
8.84 ± 2.53 t N
1.14 ± 0.324 t P

SCENARIO C: Assuming only clay and silt were lost above the dam

4281.64 ± 1300.2 m³ below dam
9553.15 ± 2646.37 m³ above dam

Below Dam
4281.64 ± 1300.2 m³ * 0.25
= 1070.41 ± 325.05 t A horizon * 1.473 t/m³
= 1576.73 ± 478.80 t

Avg N: 678ppm
= 1.07 ± 0.325 t N

Avg P: 105ppm
= 0.166 ± 0.0503 t P

2704.91 ± 975.15 m³ B horizon * 1.73 t/m³
= 4679.49 ± 1687.01 t

Avg N: 300ppm
= 1.40 ± 0.506 t N

Avg P: 33.4ppm
= 0.156 ± 0.0563 t P

Total:
2.47 ± 0.831 t N
0.322 ± 0.107 t P

Above Dam
9553.15 ± 2646.37 m³ * 0.25
= 2388.29 ± 661.59 t A horizon * 1.473 t/m³
= 3517.95 ± 974.53 t * 0.28 clay and silt
= 985.026 ± 272.87 t clay and silt

985.026 ± 272.87 t * 0.000678 N
= 0.668 ± 0.185 t N

985.026 ± 272.87 t * 0.000105 P
= 0.103 ± 0.0287 t P
7164.86 ± 1984.78 m³ B horizon * 1.73 t/m³
=12395.21 ± 3433.67 t clay and silt
=5677.01 ± 1572.62 t clay and silt

5677.01 ± 1572.62 t * 0.000300 N
=1.703 ± 0.472 t N
5677.01 ± 1572.62 t * 0.0000334 P
=0.190 ± 0.0525 t P

Total above dam:
2.371 ± 0.657 t N
0.293 ± 0.0812 t P

Combined Total:
4.841 ± 1.488 t N
0.615 ± 0.188 t P

SCENARIO D: Assuming only 50% silt and clay were lost above the dam

A horizon: 985.026 ± 272.87 t clay and silt/2
=492.513 ± 136.435 t

492.513 ± 136.435 t * 0.000678 N
=0.334 ± 0.0925 t N
492.513 ± 136.435 t * 0.000105 P
=0.0517 ± 0.0143 t P

B horizon: 5677.01 ± 1572.62 t clay and silt/2
=2838.505 ± 786.31 t

2838.505 ± 786.31 t * 0.000300 N
=0.852 ± 0.236 t N
2838.505 ± 786.31 t * 0.0000334 P
=0.0948 ± 0.0263 t P

Total:
1.186 ± 0.3285 t N
0.147 ± 0.0406 t P

Combined total:
3.65 ± 0.864 t N
0.469 ± 0.148 t P
Appendix E – Nutrient and sediment export rate calculations

RATE OF SEDIMENT YIELD

Gullies drainage area:
Arthursleigh: 8.16 km$^2$
Dixons Ck: 55.5 km$^2$

Study over 325 days

Scenario A
Arth:
\[
(21858.968 \pm 6232.737 \text{ t} / 325 \text{ d}) \times 365 = 24549.30 \pm 857 \text{ t km}^{-2} \text{ yr}^{-1}
\]

Dix:
\[
(4297.0459 \pm 2388.9768 \text{ t} / 325 \text{ d}) \times 365 = 4825.91 \pm 2683 \text{ t km}^{-2} \text{ yr}^{-1}
\]

Scenario B
Arth:
A hor: (5094.6614 \pm 1452.6616 \text{ t} / 325 \text{ d})\times 365 = 5721.69 \pm 1613.45 \text{ t km}^{-2} \text{ yr}^{-1}

B hor: (17950.641 \pm 5118.340 \text{ t} / 325 \text{ d}) \times 365 = 20159.95 \pm 5748.29 \text{ t km}^{-2} \text{ yr}^{-1}

Total: 3172 \pm 904 \text{ t km}^{-2} \text{ yr}^{-1}

(23045.3024 \pm 6571.0016 \text{ t total export})

Dix:
A hor: (1619.82 \pm 900.55 \text{ t} / 325 \text{ d})\times 365 = 1819.18 \pm 1011.38 \text{ t km}^{-2} \text{ yr}^{-1}

B hor: (2820.062 \pm 1167.577 \text{ t} / 325 \text{ d}) \times 365 = 3167.14 \pm 1311.27 \text{ t km}^{-2} \text{ yr}^{-1}

Total: 90 \pm 42 \text{ t km}^{-2} \text{ yr}^{-1}

(4439.882 \pm 2068.127 t total export)

Scenario C
Arth:
Below dam A hor: 1576.73 \pm 478.80 \text{ t}
Below dam B hor: 4679.49 \pm 1687.01 \text{ t}
Above dam A hor: 985.026 \pm 272.87 \text{ t c & s}
Above dam B hor: 5677.01 \pm 1572.62 \text{ t c & s}
Total: (12918.256 \pm 4011.3 \text{ t} / 325 \text{ d}) \times 365 = 14508.19 \pm 4504.99 \text{ t km}^{-2} \text{ yr}^{-1}

Dix:
Below dam A hor: 480.412 \pm 213.842 \text{ t}
Below dam B hor: 836.384 \pm 277.249 \text{ t}
Above dam A hor: 319.0401 \pm 101.8793 \text{ t c & s}
Above dam B hor: 1050.9914 \pm 665.2763 \text{ t c & s}
Total: (2686.8275 \pm 1358.2466 \text{ t} / 325 \text{ d}) \times 365 = 3017.514 \pm 1525.415 \text{ t km}^{-2} \text{ yr}^{-1}

Scenario D
Arth:
Below dam A hor: 1576.73 \pm 478.80 \text{ t}
Below dam B hor: 4679.49 \pm 1687.01 \text{ t}
Above dam A hor: 985.026 \pm 272.87 \text{ t c & s}
Above dam B hor: 5677.01 \pm 1572.62 \text{ t c & s}
Total: (9587.238 \pm 3088.555 \text{ t} / 325 \text{ d}) \times 365 = 10767.21 \pm 3468.68 \text{ t km}^{-2} \text{ yr}^{-1}

Dix:
Below dam A hor: 480.412 \pm 213.842 \text{ t}
Below dam B hor: 836.384 \pm 277.249 \text{ t}
Above dam A hor: 159.52 \pm 100.94 \text{ t c & s}
Above dam B hor: 525.496 \pm 332.638 \text{ t c & s}
Total: (2001.812 \pm 924.669 \text{ t} / 325 \text{ d}) \times 365 = 2248.188 \pm 1038.474 \text{ t km}^{-2} \text{ yr}^{-1}
RATE N + P YIELD

Scenario A

Arthursleigh:
N: \((11.87 \pm 3.384 \text{ t N}/325 \text{ d}) \times 365\)
=13.33 \pm 3.8 \text{ t N}/8.16 \text{ km}^2
=1.63 \pm 0.47 \text{ t N km}^{-2} \text{ yr}^{-1}

P: \((1.72 \pm 0.492 \text{ t P}/325 \text{ d}) \times 365\)
=1.93 \pm 0.55 \text{ t P}/8.16 \text{ km}^2
=0.24 \pm 0.07 \text{ t P km}^{-2} \text{ yr}^{-1}

Dixons Ck:
N: \((3.86 \pm 2.15 \text{ t N}/325 \text{ d}) \times 365\)
=4.34 \pm 2.41 \text{ t N}/55.5 \text{ km}^2
=0.078 \pm 0.044 \text{ t N km}^{-2} \text{ yr}^{-1}

P: \((0.4877 \pm 0.2711 \text{ t P}/325 \text{ d}) \times 365\)
=0.55 \pm 0.30 \text{ t P}/55.5 \text{ km}^2
=0.0099 \pm 0.0055 \text{ t P km}^{-2} \text{ yr}^{-1}

Scenario B

Arthursleigh:
N: \((8.84 \pm 2.53 \text{ t N}/325 \text{ d}) \times 365\)
=9.92 \pm 2.8 \text{ t N}/8.16 \text{ km}^2
=1.22 \pm 0.35 \text{ t N km}^{-2} \text{ yr}^{-1}

P: \((1.14 \pm 0.324 \text{ t P}/325 \text{ d}) \times 365\)
=1.28 \pm 0.55 \text{ t P}/8.16 \text{ km}^2
=0.16 \pm 0.07 \text{ t P km}^{-2} \text{ yr}^{-1}

Dixons Ck:
N: \((2.372 \pm 1.174 \text{ t N}/325 \text{ d}) \times 365\)
=2.66 \pm 1.32 \text{ t N}/55.5 \text{ km}^2
=0.048 \pm 0.024 \text{ t N km}^{-2} \text{ yr}^{-1}

P: \((0.626 \pm 0.289 \text{ t P}/325 \text{ d}) \times 365\)
=0.70 \pm 0.32 \text{ t P}/55.5 \text{ km}^2
=0.012 \pm 0.005 \text{ t P km}^{-2} \text{ yr}^{-1}

Scenario C

Arthursleigh:
N: \((4.841 \pm 1.488 \text{ t N}/325 \text{ d}) \times 365\)
=5.44 \pm 1.67 \text{ t N}/8.16 \text{ km}^2
=0.67 \pm 0.20 \text{ t N km}^{-2} \text{ yr}^{-1}

P: \((0.615 \pm 0.188 \text{ t P}/325 \text{ d}) \times 365\)
=0.69 \pm 0.211 \text{ t P}/8.16 \text{ km}^2
=0.085 \pm 0.026 \text{ t P km}^{-2} \text{ yr}^{-1}

Dixons Ck:
N: \((1.353 \pm 0.688 \text{ t N}/325 \text{ d}) \times 365\)
=1.519 \pm 0.772 \text{ t N}/55.5 \text{ km}^2
=0.027 \pm 0.013 \text{ t N km}^{-2} \text{ yr}^{-1}

P: \((0.381 \pm 0.193 \text{ t P}/325 \text{ d}) \times 365\)
=0.428 \pm 0.216 \text{ t P}/55.5 \text{ km}^2
=0.0077 \pm 0.0039 \text{ t P km}^{-2} \text{ yr}^{-1}

Scenario D

Arthursleigh:
N: \((3.65 \pm 0.864 \text{ t N}/325 \text{ d}) \times 365\)
=4.10 \pm 0.97 \text{ t N}/8.16 \text{ km}^2
=0.50 \pm 0.12 \text{ t N km}^{-2} \text{ yr}^{-1}

P: \((0.469 \pm 0.148 \text{ t P}/325 \text{ d}) \times 365\)
=0.527 \pm 0.166 \text{ t P}/8.16 \text{ km}^2
=0.065 \pm 0.02 \text{ t P km}^{-2} \text{ yr}^{-1}

Dixons Ck:
N: \((1.028 \pm 0.484 \text{ t N}/325 \text{ d}) \times 365\)
=1.15 \pm 0.543 \text{ t N}/55.5 \text{ km}^2
=0.021 \pm 0.009 \text{ t N km}^{-2} \text{ yr}^{-1}

P: \((0.283 \pm 0.131 \text{ t P}/325 \text{ d}) \times 365\)
=0.318 \pm 0.147 \text{ t P}/55.5 \text{ km}^2
=0.0057 \pm 0.0027 \text{ t P km}^{-2} \text{ yr}^{-1}
Appendix F – Uncertainty analysis results

### Dixons CK

<table>
<thead>
<tr>
<th>Uncertainty Analysis Method</th>
<th>Total Net Volume Difference</th>
<th>± Error Volume</th>
<th>% Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw (no uncertainty analysis)</td>
<td>-29,954.92</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.20m MinLoD</td>
<td>-6,107.51</td>
<td>9,344.09</td>
<td>-152.99</td>
</tr>
<tr>
<td>0.20m MinLoD w 95% CI</td>
<td>-2,855.18</td>
<td>1,587.36</td>
<td>-55.60</td>
</tr>
<tr>
<td>0.30m MinLoD</td>
<td>-4,074.82</td>
<td>6,280.35</td>
<td>-154.13</td>
</tr>
<tr>
<td>0.30m MinLoD w 95% CI</td>
<td>-2,023.48</td>
<td>999.81</td>
<td>-49.41</td>
</tr>
<tr>
<td>Prob 0.95 w FIS error</td>
<td>-6,730.62</td>
<td>3,934.10</td>
<td>-58.45</td>
</tr>
</tbody>
</table>

### Arthursleigh

<table>
<thead>
<tr>
<th>Uncertainty Analysis Method</th>
<th>Total Net Volume Difference</th>
<th>± Error Volume</th>
<th>% Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw (no uncertainty analysis)</td>
<td>-87,026.50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.20m MinLoD</td>
<td>-30,474.44</td>
<td>15,211.38</td>
<td>-49.92</td>
</tr>
<tr>
<td>0.20m MinLoD w 95% CI</td>
<td>-13,834.79</td>
<td>3,944.77</td>
<td>-28.51</td>
</tr>
<tr>
<td>0.30m MinLoD</td>
<td>-21,144.31</td>
<td>10,221.46</td>
<td>-48.34</td>
</tr>
<tr>
<td>0.30m MinLoD w 95% CI</td>
<td>-9,294.08</td>
<td>2969.86</td>
<td>-31.95</td>
</tr>
<tr>
<td>Prob 0.95 w FIS error</td>
<td>-26,449.52</td>
<td>7,330.10</td>
<td>-27.71</td>
</tr>
</tbody>
</table>
Appendix G – Raw change detection maps
Appendix H – GIS data

The GIS data produced in this study has been included on the thesis disk in a separate folder named “Appendix H”