Spatial Analysis Approaches to the Terrestrial LiDAR Monitoring of Slopes: an example from Minnis North, Co. Antrim, Northern Ireland

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Summary: Terrestrial Laser Scanning (TLS) is becoming increasingly useful for characterisation and monitoring of landforms. There is a need to ensure spatial analysis approaches develop in line with technological advances. TLS is used in this case study as a tool for the temporal analysis of slope morphology to detect slope movements for three locations in Northern Ireland. The high resolution LiDAR derived DEMs were used to calculate difference maps, slope, curvature and topographic roughness parameters. The results demonstrate that temporal analysis of TLS data with appropriate tailored spatial analysis approaches can be a viable technique to investigate slope stability issues.

KEYWORDS: Spatial analysis, Terrestrial LiDAR, GIS, Slopes, Roughness

1. Introduction

Light detection and ranging (LiDAR) based high resolution Digital Elevation Models (DEMs) are becoming increasingly useful for characterisation and assessment in geomorphology (Teza et al. 2007; Buckley et al. 2008). Ground based LiDAR, commonly known as Terrestrial LiDAR Scanning (TLS), is becomingly a popular surveying technique for slope characterisation and monitoring (Oppikofer et al. 2009). The application of TLS for landslide and slope studies is becoming increasingly accessible with studies relating to mass movements (Avian et al. 2009, Baldo et al. 2009), geological characterisation (Buckley et al. 2008; Nguyen et al. 2011), structural analysis (Dunning et al. 2009; Jaboyedoff et al. 2009) and monitoring (Teza et al. 2007; Oppikofer et al. 2009; Prokop and Panholzer 2009).

This research implements the use of Terrestrial LiDAR derived DEMs to analyse the morphology of 3 sites in Northern Ireland, United Kingdom. The application of multiple spatial analysis approaches using TLS derived DEMs will be evaluated for the analysis of slope stability. This encompasses interpretation of different interpolation techniques and spatial analysis approaches to classify different parameters of slope. Interpretation of DEMs will be assessed for the most suitable approach to characterise slope stability issues. Temporal analysis of one of these ongoing slope monitoring projects is presented to demonstrate the various spatial analytical methodologies.

2. Study Areas

The ongoing slope monitoring project currently involves two coastal road sections: Minnis North (Irish Grid Reference (IGR): J333413) and Straidkilly Point (IGR: J330416) and a railway cutting at Craigmore (IGR: J306329), Newry, Northern Ireland. The field location at Minnis, which is described in more detail here, is a mudflow slide with an area of 3,500m^2 is located on the main Antrim Coast Road, Northern Ireland which lies between the large-scale rotational slump features of the Antrim Plateau and coastal plain (Betts et al. 2008). The mudflow slide is a result of the Creteaous Chalk rotated backwards exposing the Lias Clays and superficial glacial tills (Smith and Warke, 2001). The outcome is an active slope failure with a movement cycle linked to the pore water pressure of the underlying geology. Slope failures periodically affect the main road running along the coastline.

Figure 1. Location of Minnis North, Co. Antrim. Inset shows mudflow slide feature proximity to road

3. DEM Generation and Spatial Analysis Approaches

3.1 LiDAR Surveys

Terrestrial LiDAR Scanning of the field sites was carried out using a Leica HDS3000 (Lecia Geosystems, 2006) terrestrial laser scanner with 6mm accuracy at 50m. Targets are acquired in the field and georeferenced to site specific rigid geodetic networks to allow accurate long term monitoring of the landform. Five temporal data acquisitions have been taken to date from February 2011 to August 2011. Leica Cylone 5.4 (Leica Geosystems, 2006) was used for the post processing of the TLS data including registration, georeferencing and operator based removal of non-ground points. Vegetation on the Minnis North site is minimal therefore a filtering scheme was not deemed necessary at this stage.

3.2 Interpolation Approaches

Post processed LiDAR datasets covering the slopes were imported into ArcGIS 10 (ESRI 2010) for interpolation to elevation surfaces. A number of approaches were investigated to generate DTMs including Inverse Distance Weighting (IDW), Spline with Tension (SPT) and Ordinary Kriging (OK) interpolation techniques. The root mean square error (RMSE) has been shown to give a quantification of error values for interpolated surfaces (Aguilar et al. 2005; Hohle and Hohle 2009). The RMSE results from the interpolation techniques, for the initial scan at Minnis North, are summarised in Figure 2 below. Cross validation of the interpolated surfaces indicate that spline with tension, with 32 neighbours gives the lowest RMSE. Grid size for Minnis North was 0.3m, chosen as a compromise between the fine resolution of the generated, point spacing and the scale of the landform.

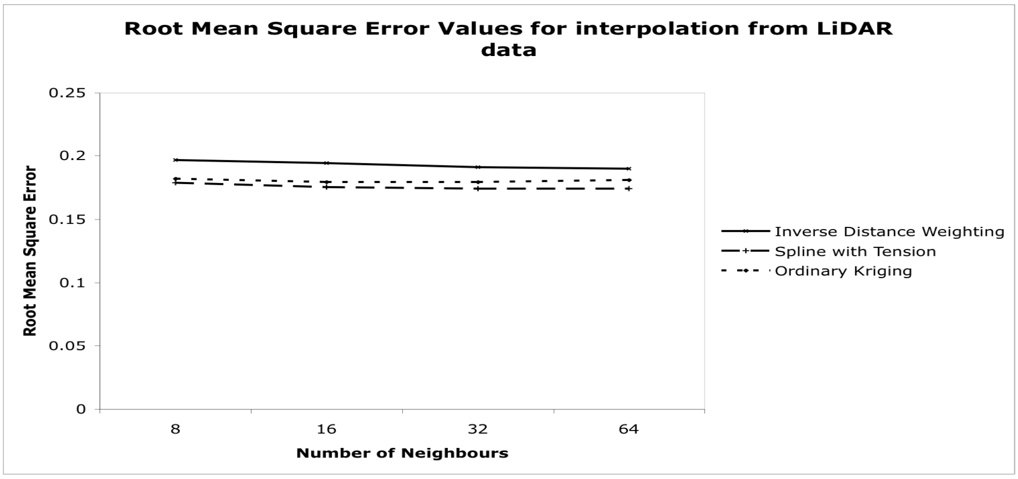

Figure 2. RMSE values for diffferent interpolation approaches to the generation of the DEMs

3.3 Spatial Analysis Approaches

Convexity and concavity are indicators of slope stability, steeper slopes with higher curvature are potentially more prone to failure (Theilen-Willige, 2010). Curvature can be classed as profile curvature, rate of change of maximum slope, and plan curvature, perpendicular to the rate of change of slope (Chang 2008). Positive values for curvature indicate surface is upwardly convex at the cell whereas negative values indicate surface is upwardly concave, with values of zero corresponding to a flat surface (Cavalli and Marchi, 2008).

The surface of most landslides tends to be rougher on a local scale than the surrounding smoother more stable terrain (Mc Kean and Reoring, 2004) with higher roughness values generally associated with evidence of recent movement (Cavalli and Marchi, 2008). Roughness cannot be defined by a single parameter; instead it is a combination of factors (Li et al. 2005). Hobson (1972) proposed that roughness can be defined as the ratio between surface area and plan area of an object or the dispersion of the unit vectors calculated from the slope and aspect derivatives. Roughness as a geomorphic descriptor has been used for several studies evaluating LiDAR data as an approach to map landslides and detect potential failing or recently failed terrain. Studies of topographic roughness use a number of approaches including: local topographic variability (McKean and Reoring 2004, Glenn et al. 2006), standard deviation of residual topography (Cavalli and Marchi, 2008) and orthogonal distance regression (Pollyea and Fairley, 2011).

This study implements GRASS GIS (GRASS Development Team, 2010) functionality using roughness scripts (Grohmann 2006) developed for the spatio-morphological roughness assessment of slopes. Difference maps were calculated using the DEMs and surfaces generated for analysis of the morphological change (Avian et al. 2009; Prokop and Panholzer 2009). Area ratio roughness and inverted Fischer's K parameters were used. Area ratio is the ratio of the real surface to the orthogonal projection therefore it is sensitive in local variation of slope. Fischer’s K defines the dispersion of unit vectors and is sensitive to variation in slope aspect (Grohmann 2004; Gallay et al. 2010). The parameters were calculated on a 3x3 moving window neighbourhood.

4. Results for Minnis North coastal road location

4.1 Convexity and concavity

The DEMs show distinct changes between the short survey intervals. Interpretation of the DEMs during the monitoring period indicate that there has been movement of the toe of Minnis North highlighted in Figure 3. The area of greatest movement highlighted equates to around 50m^3 of material which has been shifted due to slope process of the actively failing slope. A cut and fill analysis of the slope indicates areas of net gain and net loss of material between February 2011 and August 2010. Overall there is a net gain of 468m^3 of material. The spatial pattern of net gain suggests slumping, creating more surface area.

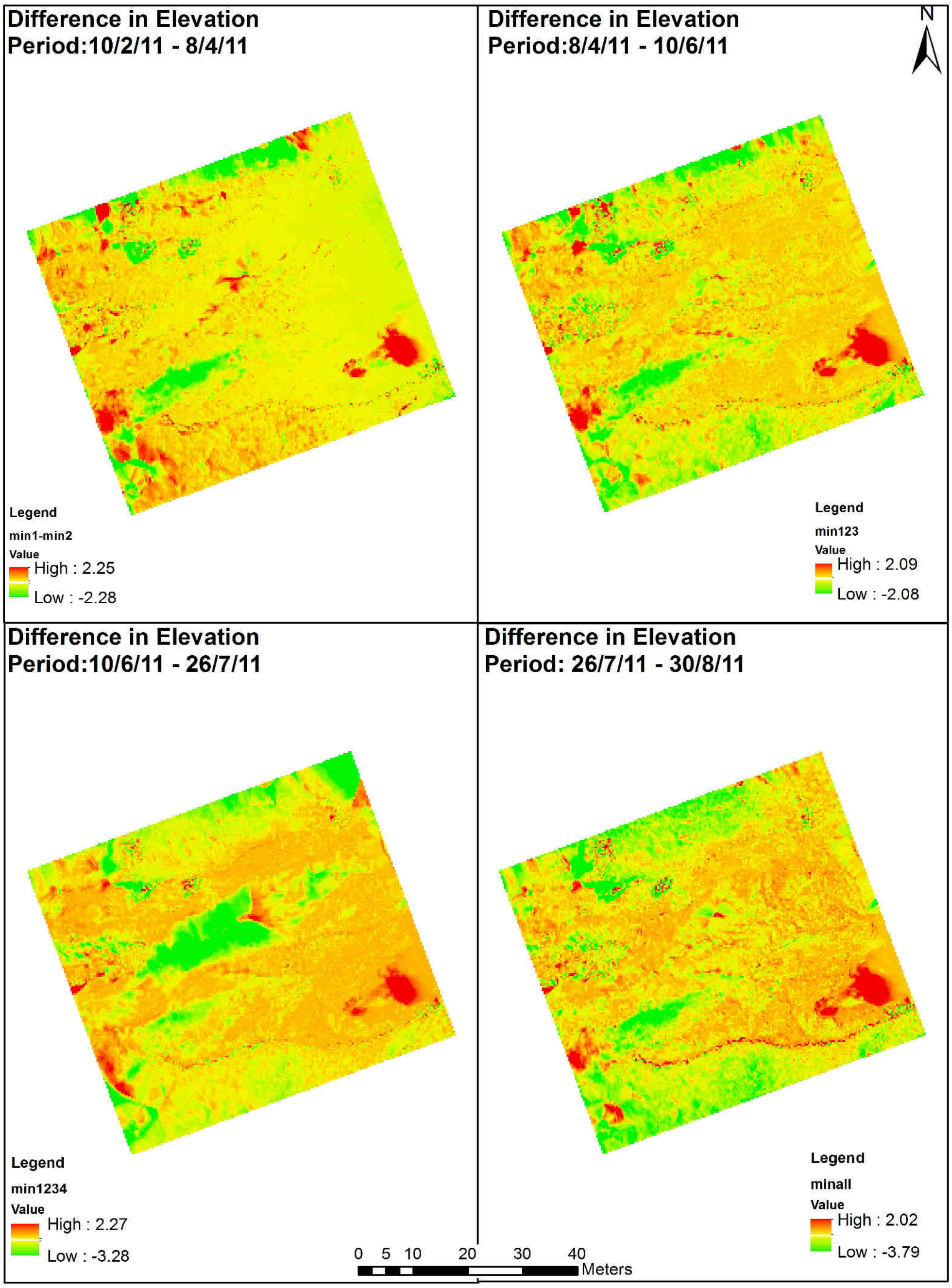

Figure 3: Difference in elevation maps showing areas of accumulation and areas of erosion

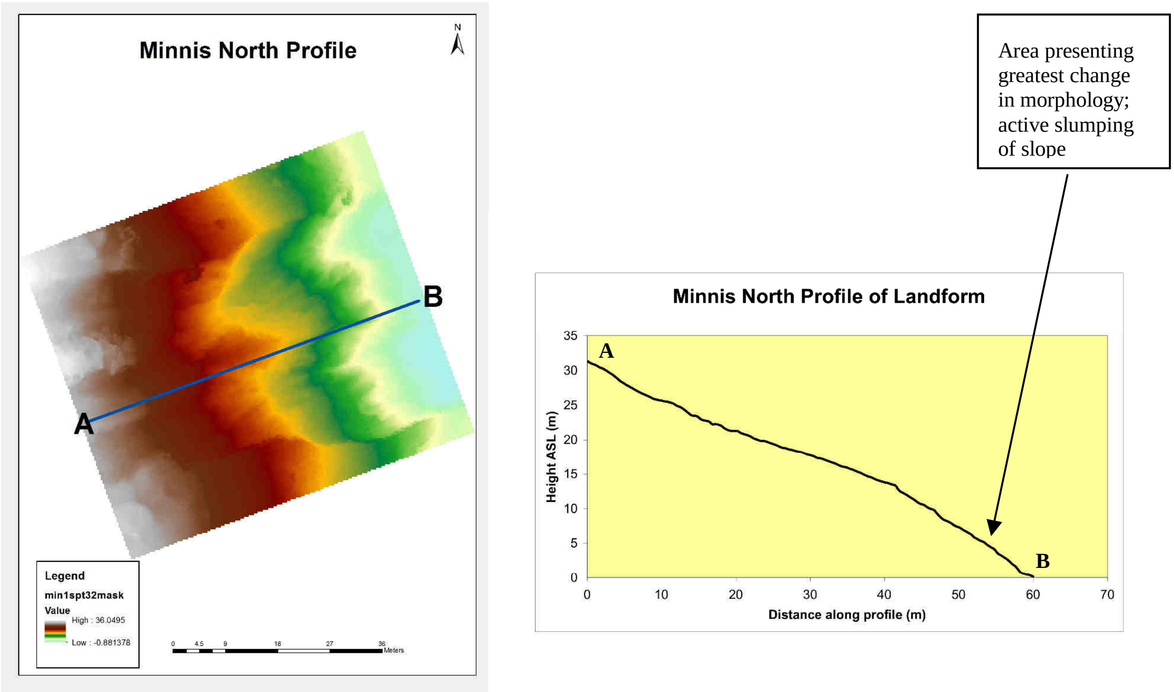

Figure 4. Minnis North Profile of Landform

The spatial pattern of change in slope (Figure 6) highlights areas where the terrain has moved with areas displaying a change in slope. Profile curvature maps are a reasonable indicator of specific slope morphology both in profile and plan format, giving an indication of areas upwardly convex in nature therefore more susceptible to failure. This indicates areas where the slope was most likely to fail; this is supported by the difference elevation maps which present changes in the slope morphology. Changes in curvature over the monitoring period suggest the failing nature of the slope is parameterised by the curvature maps. Morphological change can be recorded by the change in profile curvature.

Profile Curvature Maps for Minnis North Scan 1, 5 and Difference Map

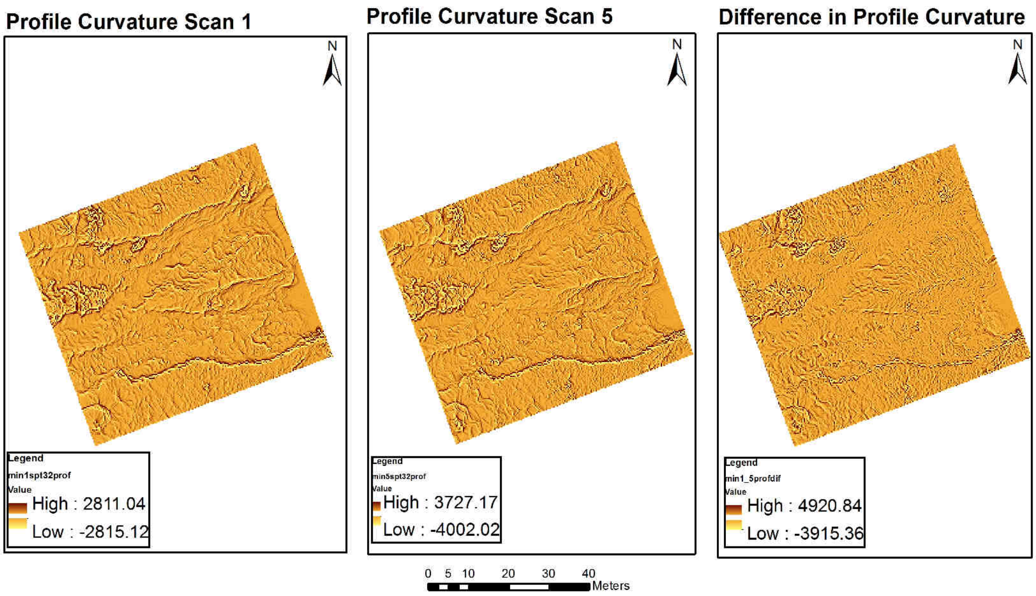

Figure 5. Profile Curvature maps of Minnis North and change in curvature

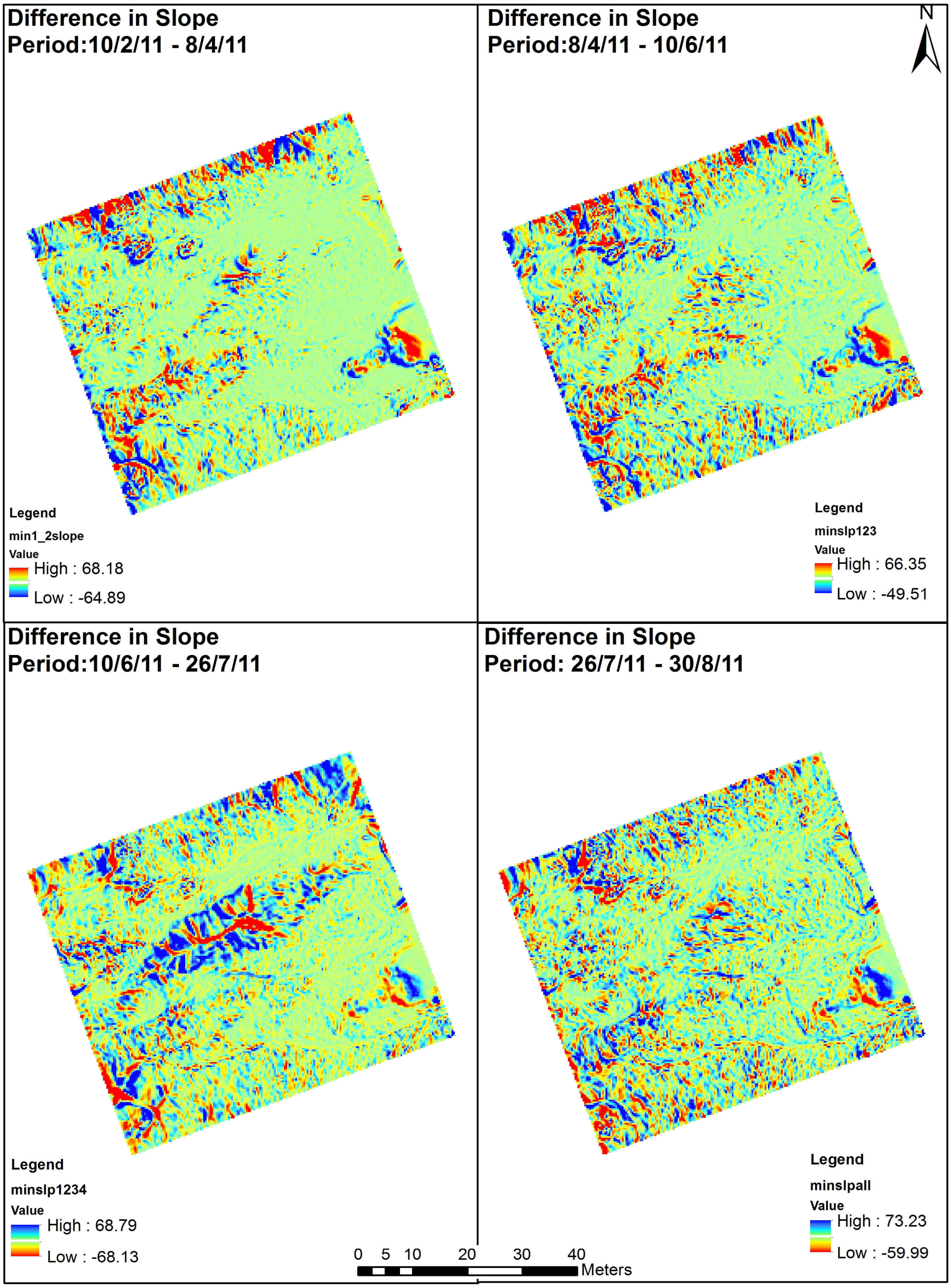

Figure 6. Difference in slope over the period Feb 2011- August 2011

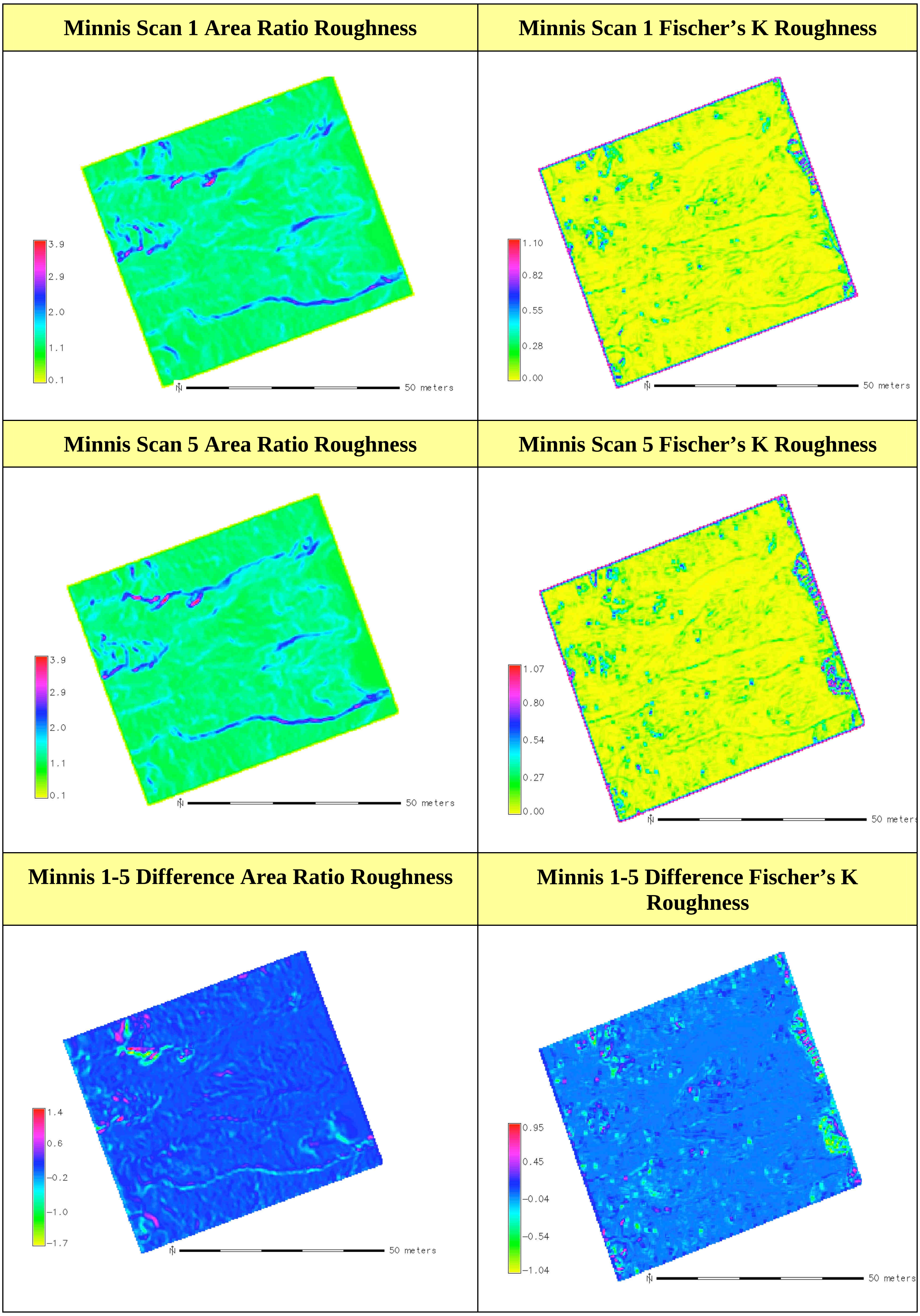

Figure 7. Area ratio roughness and Fischer's K Roughness parameters for Scan 1, Scan 5 and change between scans

4.2 Roughness

The area ratio roughness identified the roughest areas of the landform coinciding with the highest difference between the DEMs. The failed area identified with the difference and curvature maps is mapped by an increase in roughness with the southern edge of the mudflow slide exhibiting an increase in area ratio roughness from the resultant slope failure. Fischer's K roughness shows the main body of the landform to be smooth with the highest area relating to the accumulation zone of the failed material at the base of the slope. The potential for artefacts relating to vegetation and other anomalies has yet to be classified. This classification can be carried out by the application of a minimum filter during the post processing stage, with the difference in heights generating a residual surface.

5. Conclusions

The results show that multi-temporal comparison of the TLS derived DEMs provides useful high-resolution data for calculation of areas of accumulation and depletion of an actively failing slope. This research shows that the application of multiple spatial analysis approaches parameterize slope stability issues, with measures of roughness giving an indication of recent change in morphology. Curvature and slope maps give an indication for potential areas at risk from failure. The complex issue of spatial analysis approaches to slopes requires a multi-faceted approach to identify the potential for slope stability issues. ArcGIS and GRASS GIS have been used in characterise slope stability issues, however, there is further potential to incorporate physical geotechnical monitoring and to improve predictions for slope failures. Future work for the continued monitoring of the slope (s) will focus on the ranking and weighting of potential destabilizing factors. The application of filtering to the LiDAR DEMs and impacts of residuals from the datasets will also be considered.

Acknowledgements

Ordnance Survey of Northern Ireland, Crown Copyright © for the use of base maps. The Department of Employment and Learning Northern Ireland for funding research project.

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Biography

Andrew is a second year postgraduate research student researching spatial analysis approaches to slope stability. The PhD involves the application of Terrestrial LiDAR monitoring of slopes with the aim for developing an improved spatial analytical approach to slope stability. Research interests include GIS, LiDAR, Earth Sciences and spatial technologies.