Emerging solutions for hydrological modelling from LiDAR

Stefanie Lumnitz, Grant D. Pearse, Jonathan P. Dash and Michael S. Watt

Abstract

This article summarises recent advances in methods for extracting hydrological features such as channel networks from light detection and ranging (LiDAR) derived terrain data. These techniques have the potential to support forest managers seeking to better plan and monitor compliance with emerging environmental standards like the National Policy Statement for Freshwater Management (NPS-FM) or the National Environmental Standard for Plantation Forests (NES-PF). In this article, we introduce new tools for extracting hydrological information from LiDAR data using a case study carried out in Geraldine Forest, Canterbury, New Zealand (see Figure 1). Our intention is limited to making forest managers aware of the availability of these tools, comparing them to existing tools such as ArcGIS, and providing some guidance on the technical aspect of these tools and the type of LiDAR survey that would be sufficient for their use.

Introduction

Light detection and ranging (LiDAR) offers an alternative approach to traditional methods for obtaining high-precision elevation data over large areas. LiDAR is particularly beneficial in forested areas, where the laser penetration through the forest canopy allows fine resolution (<1 m accuracy), high-quality digital terrain models (DTMs) to be developed (Hyyppä et al., 2005; Meng et al., 2010). DTMs represent a topographic model of the Earth's surface with a series of raster cells containing the elevation value of the terrain (Tarolli, 2014). Numerous studies have shown that the resolution and accuracy of input DTMs is a critical factor in the performance of subsequent topographically-based analyses (Zhang & Montgomery, 1994; Dietrich & Montgomery, 1998; Tarolli, 2014). Channel network extraction is one example application that is heavily dependent on the quality of the input DTM. The process of identifying stream networks represents an essential step towards studying catchment hydrological responses to rainfall events, sedimentation flows, flood forecasting, and efforts aimed at mitigation of pollution discharge into rivers (Zhang et al., 2009; Tarolli, 2014). The use of high-resolution DTMs facilitates the automated detection of channel initiation points directly from topography, reducing the need for expensive field surveys. This approach provides the opportunity for determining actual streams from all possible flow paths within the landscape (Pirotti & Tarolli, 2010). As a result, access to high-resolution LiDAR-derived DTMs allows forest managers to accurately map channel heads and channel networks within a geographic region (Lashermes et al., 2007; Sofia et al., 2011; Passalacqua et al., 2012).

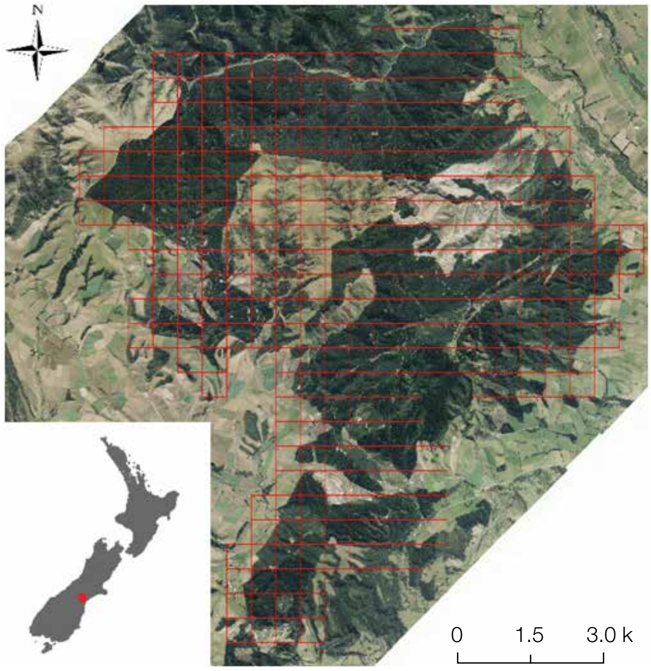

Figure 1: Aerial imagery of the study area with the LiDAR survey coverage shown as red tile outlines

In New Zealand, the recent National Policy Statement for Freshwater Management (NPS-FM) and the impending National Environmental Standard for Plantation Forests (NES-PF) will greatly impact the management of planted forests in hydrologically sensitive, steep or erosion-prone areas. Improving freshwater quality and controlling erosion risk are key goals of these policies and standards. Forest managers in New Zealand will require improved knowledge and tools to reduce and monitor hydrological impacts from forest operations as part of their compliance activities. At present, national sources of topographical and hydrological information are limited by a reliance on historic data with low spatial and temporal resolution.

For example, a recently updated national DTM, derived from existing contour data, has a coarse resolution of 25 m (Barringer et al., 2002). Other national-scale DTMs include the 'Geographx' re-interpreted DTM at 20 m and 8 m resolutions; however, this dataset is only intended for visualisation purposes. Otago University's School of Surveying provides the 'NZSoSDEM' at 15 m resolution. This dataset includes accuracy assessments across the extent (Columbus et al., 2011), but remains too coarse for many hydrological applications. National-level datasets for stream centre lines are similarly restricted, with their intended use limited to environmental reporting activities (Snelder et al., 2010). LiDAR-derived high-resolution DTMs, in combination with new channel network extraction methods, present an opportunity for forest managers to obtain detailed information on hydrological features within forested areas to enhance their management activities. By our estimation, over 450,000 ha of private LiDAR is scheduled for collection in the near future. Many regions such as Northland, Auckland, Bay of Plenty, Wellington, Waikato and Canterbury have existing publicly or Crown-licensed LiDAR (approximately 3.5 M ha) and many regional authorities have indicated an intention to collect or update these data in the future.

Emerging channel extraction methods

Most classical channel extraction methods using DTMs follow a similar workflow. First, pits within the DTM are filled. Second, flow direction and the contributing area for drainage into every grid cell are computed. Finally, flow paths are determined across the surface (Sofia et al., 2011). In an additional step, a unique accumulation threshold must often be chosen to convert the drainage flow paths to a meaningful network (Sangireddy et al., 2016). As such, the definition of the network relies heavily on one chosen threshold value pertaining to previously calculated flow path values that determine if each grid cell is part of the channel or not (Sangireddy et al., 2016). Two main disadvantages associated with these methods include the inability to operate effectively in flatter areas and the inability to fully reproduce the actual channel network using a single uniform accumulation threshold. These disadvantages mean that classical approaches, using lower resolution DTMs, are unable to predict channel heads accurately as channel initiation naturally depends on different processes resulting in varying topographic signatures that are not represented by the choice of a single uniform accumulation threshold (Sofia et al., 2011). Several studies point out that stream network extraction based on the direct detection of channel head morphology from high-resolution DTMs can effectively avoid the thresholding issue of classical methods and a range of algorithms have been proposed for this task (Table 1) (Lashermes et al., 2007).

Case study: channel extraction with GeoNet

Study background and objectives

A case study was implemented to investigate the utility of emerging channel extraction software for use with a high-resolution LiDAR-derived DTM in a commercial plantation forest. The resolution of the DTM that can be produced from LiDAR is proportional to the number and spacing of returns from the ground surface. This is primarily determined by campaign planning and sensor settings. To achieve higher pulse density, and therefore higher spatial resolution, LiDAR providers typically fly lower, slower and with more overlap. This increases the cost of data collection and typically results in a trade-off between the acquisition cost and the quality of the dataset produced. Ideally, the dataset acquired should be just precise enough in resolution and accuracy to meet the survey objectives.

In this case study, we applied a thinning algorithm to a high-density LiDAR dataset to simulate lower-density LiDAR data. Our objectives were: 1) to investigate the use of emerging channel extraction methods in a realistic environment; and 2) to test the feasibility of channel extraction from different resolution DTMs.

Table 1: Modern hydrological feature extraction algorithms capable of handling high-resolution LiDAR-derived DTMs. All methods except Sofia et al. (2011) were trialled for use with the case study data. GeoNet was selected for the final analysis and comparison

Study	Method	Software implementation
Clubb et al. (2014)	Drainage Extraction by Identifying Channel Heads method (DrEICH)	Open source – LSDTopoTools
Pelletier (2013)	A method using an optimal Wiener filter and a user-defined contour-curvature threshold for channelisation	Open source – LSDTopoTools
Passalacqua et al. (2010a)	GeoNet combines local non-linear diffusion filtering with a global geomorphologically-informed geodesic cost function to automatically identify channel initiation points and extract channel paths from LiDAR DTMs	Open source – MATLAB (licence required) or Python (free)
Sofia et al. (2011)	A statistical approach based on normalised topographic attributes, such as openness and minimum curvature, as a weight for the upslope area	Contact: G. Sofia (giulia.sofia@unipd.it) – ESRI ArcGIS (licence required)
Tarolli & Dalla Fontana (2009)	Uses curvature to assess the capability of high-resolution topography to recognise the convergent hollow morphology of surveyed channel heads	Contact: P. Tarolli (paolo.tarolli@unipd.it) – ESRI ArcGIS (licence required)

Study site and LiDAR data

This study was completed in Geraldine Forest in Canterbury in the South Island of New Zealand (Figure 1). The forest is located in the foothills of the Southern Alps and is characterised by steep and broken terrain with elevations ranging from 203 to 780 m above sea level (asl). The site is planted with single-species stands that predominantly comprise radiata pine (*Pinus radiata* D.Don) and Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco), with the remainder made up of small areas of other species. Airborne laser scanner data was captured over the study forest at a pulse density of 21.1 pulses m^{-2} on 13 and 14 June 2016 using a Riegl Q1560 two-channel scanner system. A laser pulse rate of 330 kHz and scan angle of 14° from nadir were used and flight planning ensured substantial overlap across the entire area of interest to remove the possibility of data voids.

Data thinning

The obtained dataset was thinned to assess the impact of resolution and pulse density on channel network extraction. For the purposes of this project, a custom algorithm was developed to simulate changes in pulse density that may vary due to flight planning. The algorithm systematically marks pulses for removal and then excludes all returns associated with these pulses to achieve a specified final target pulse density. Table 2 provides a summary of the LiDAR datasets produced to assess the impact of reduced pulse density on channel extraction. The DTM resolutions associated with pulse densities of 21.1 and 5.3 pulses m^{-2} were, respectively, 0.4 and 1.0 m.

Operating GeoNet

A range of modern algorithms (Table 1) were trialled for use in this study as well as common tools such as the hydrological toolbox from ArcGIS. Most of the algorithms were unable to process the very high-resolution DTMs due to the large amount of temporary memory needed to process the data at once. The exception was the GeoNet algorithm (Passalacqua et al., 2010a), which could process data from all resolution DTMs across the entire area of approximately 80 km². To enable comparison against other methods at all DTM resolutions we chose a suitable sub-catchment covering approximately 300 ha for further analysis. GeoNet combines local non-linear diffusion filtering with a cost function to automatically identify channel initiation points and extract channel paths from LiDAR DTMs. This specific filtering method has the advantage of smoothing the high-resolution input DTM for improved data processing, while enhancing the hillslope-to-valley transitions, thus preserving the location of features of interest (Passalacqua et al., 2010b).

GeoNet is a published methodology available to implement in MATLAB (ca. NZ$9,000–$12,000 for software and toolboxes) or in Python using open-source GDAL and GRASS GIS software libraries. In this project, the final results were computed with the MATLAB version due to the improved user documentation and installation guidance provided on the project website for this version (https://sites.google.com/site/geonethome). It is important to note that implementing the Python version of GeoNet requires some basic Linux skills. The latest version of GeoNet (22/02/2017) requires a single user-defined input parameter. This parameter defines the contributing area threshold and can be estimated from the terrain information by identifying the smallest channel initiation area in the landscape and selecting a threshold area slightly below this. It was noted that the contributing area threshold significantly impacted the results, and fine-tuning of this parameter was carried out through the iterative generation of hydrological features within the chosen sub-catchment. A value of 100 m² was selected as the best fit for this site. Other optional parameters were noted to be less influential and were kept as the defaults chosen by Sangireddy et al. (2016) as suitable values for a range of terrain types.

A direct quality assessment of GeoNet's performance was not possible without a detailed field survey of the site to identify channel heads and water-courses across the area of interest. An intensive field survey was not possible within the budget and timeframe of this study as many channels would be obscured by forest or snow and may only be obvious at specific times of the year. However, in relation to forestry applications, channel head and network extraction is primarily of interest for lifting environmental performance and improving compliance with national water quality legislation. Therefore, a relevant visual comparison could be made against the information currently available to forestry companies without access to improved elevation data through LiDAR. A sub-catchment was selected and the high-resolution hydrological features extracted by GeoNet were overlaid onto the existing resources. This included the current national river layer contained in the NIWA River Environment Classification (REC) geo-database (Snelder & Biggs, 2002).

Results and discussion

LiDAR-derived DTMs for the selected sub-catchment provided elevation data of sufficient accuracy and quality to run all recent algorithms for hydrological feature extraction (Table 1). Figure 2 shows a relief shaded image generated from various resolution DTMs within a subset of the area of interest that is partially covered by forest. Visually, there was little difference between the 0.4 m DTM (A) and the 1 m DTM (B). However,

Table 2: Summary of original and thinned datasets from the Geraldine LiDAR survey

Target pulse density (pulses m^{-2})	All return density (returns m^{-2})	All return spacing (m)	Pulse density (pulses m^{-2})	Pulse spacing (m)	Implied DTM resolution (m)
5	9.1	0.3	5.3	0.4	1.0
un-thinned	36.5	0.2	21.1	0.2	0.4

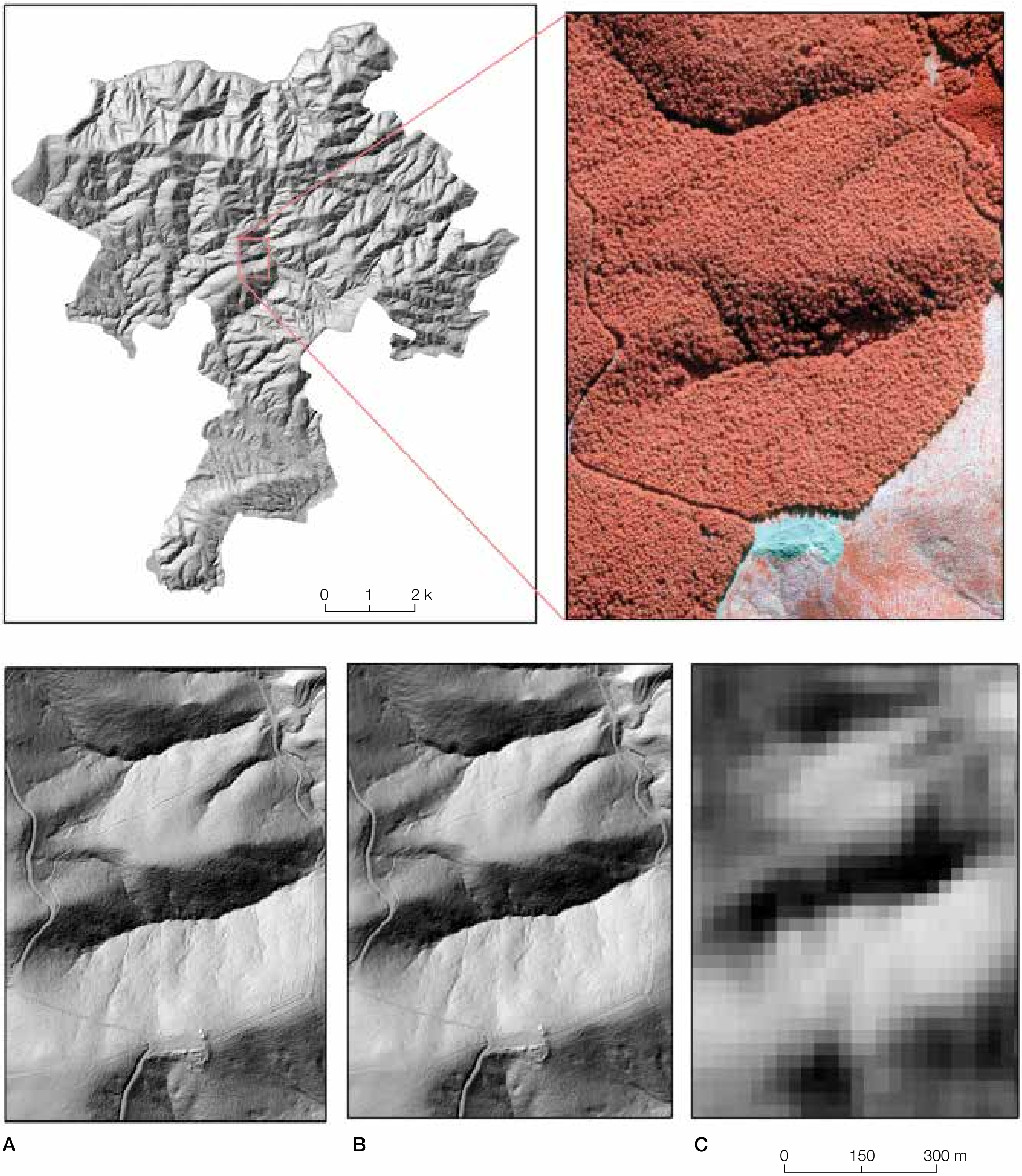

Figure 2: Relief shaded DTMs generated from LiDAR data over the Geraldine study area. Top panels show the area of interest with partial forest cover. The lower panels show detail from the DTMs at resolutions of (A) 0.4 m, (B) 1 m and currently available national elevation DTM at 25 m resolution (C)

the improvement over the national elevation data at 25 m resolution was evident and expected given the increased resolution. Importantly, there were no obvious differences in quality between open and forested areas. This highlights the ability of LiDAR pulses to penetrate through the canopy. By contrast, the relief image from the reference national elevation data at 25 m resolution includes significantly fewer features. It is clear from the image that this data would be less suited to extracting channel networks or identifying channel heads with modern tools. DTM quality strongly impacted the processing time and pre-processing required to extract channels. For most of the tested algorithms (Table 1), the very high-resolution DTMs (<1 m) required excessive computational time and this led to the need to select a sub-catchment to generate results. The MATLAB version of GeoNet provided the easiest path to implementation and produced results within an acceptable timeframe. A single basin in the north of the test area was selected for fine-scale comparison of hydrological feature extraction (Figure 3).

Use of the highest resolution DTM (0.4 m) with GeoNet introduced uncertainties in the channel detection process, with main road lines occasionally included in the extracted channel network (Figure 3). The delineation of channels connected to roads was not as severe as that observed in the results from ArcGIS, where long sections of road network were merged into unlikely channel paths – Figure (4B). GeoNet specifically includes methods to avoid the influence of engineered features on channel network extraction and is capable of extracting features at this resolution. A possible explanation for this issue was inadequate tuning of the optional GeoNet parameters. However, roads can be hydrologically connected to the channel network and we could not rule out actual interconnectedness within the identified areas (Wemple et al., 1996). The 1 m resolution DTM did not contain these effects and provided adequate extraction of channel networks. Data at this resolution is also more realistic outside of research applications and we chose to use the 1 m resolution DTM for all further comparisons.

Figure 4 (A) shows the comparison between the river centre lines (blue) and channel heads (points) extracted by GeoNet overlaid alongside the river lines from the NIWA REC geo-database (red lines). Mismatches between the REC river lines and the DTM were evident in several areas, with the REC river lines appearing to follow paths diverging from the lowest points of the catchment based on the DTM elevation values. Although the REC data were not intended for use at this fine scale, it was clear that significant differences in length and channel location were present between the GeoNet river lines and those contained within the REC geodatabase, with several hundred metres difference across the area. GeoNet also extracted river lines for all sub-catchments and from each channel head detected in the area, providing fine-grained information for even small catchments. GeoNet also estimated channel head locations, with many initiation points detected across the region. The total number of channel heads within the area appeared high, but no testing of these results was possible without detailed ground survey information. Nonetheless, channel heads indicated initiation points for the channels that appeared to align very well with the expected locations based on visual examination of the LiDAR DTM and orthophotography.

The results of channel extraction using the hydrological toolbox from the widely-used ArcGIS 10.4 software package (ESRI, Redlands, California, USA) in combination with the sub-catchment 1 m DTM are shown in Figure 4 (B). The ArcGIS approach relies solely on slope, derived from the DTM, to detect channel networks. This is in contrast to GeoNet and other modern algorithms (Table 1) that attempt to integrate more complex morphological and topographical signatures into the extraction process. The ArcGIS process required the selection of a single threshold (T) influencing the sensitivity of the extraction process. It proved to be a difficult task to find a value that balanced fine-scale channel detection against a strong tendency to detect roads as channels. Ultimately, the value of the threshold was set at T=1000 for the ArcGIS extraction. However, some spurious results can still be seen in Figure 4 (B), where channels consistently flow along or towards roads visible in the DTM.

Ground truth data would be required to assess the absolute accuracy and reliability of all these

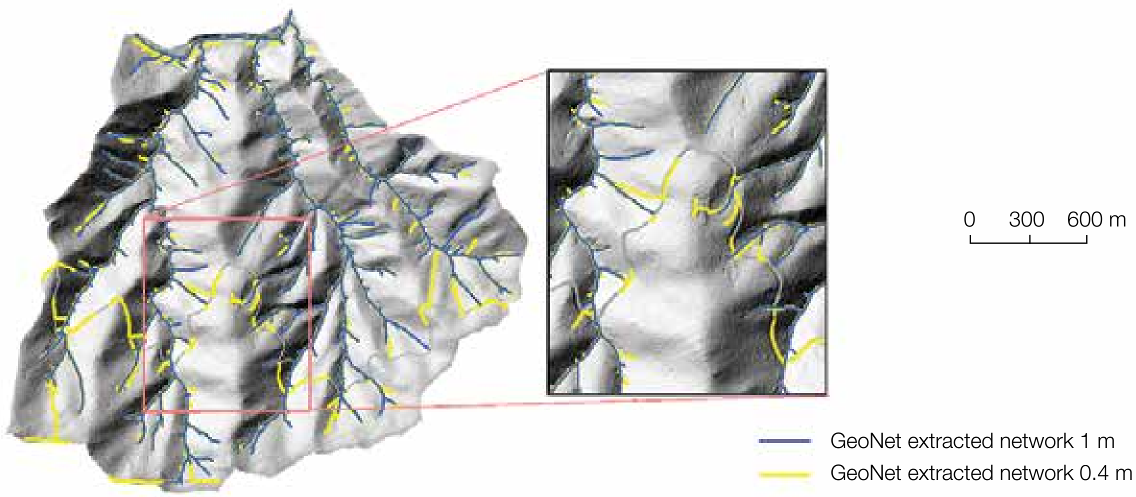

Figure 3: Relief shaded sub-catchment from the Geraldine study area selected for hydrological analysis. Comparison of GeoNet channel networks extracted from 1 m and 0.4 m resolution DTMs. The higher resolution DTM was associated with an increase in detection of roads as part of the channel network as highlighted in the magnified region

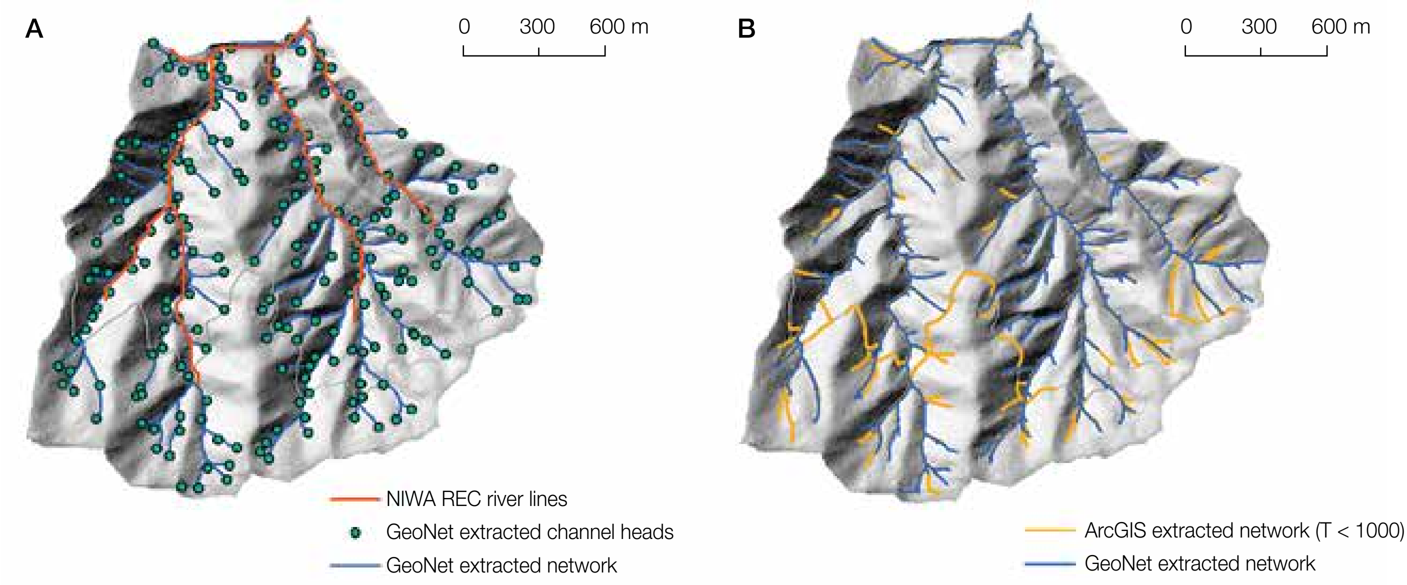

Figure 4: A. GeoNet extracted channel network is shown in blue. GeoNet detected channel heads are shown as mauve points and represent the upstream point of origination for channels. The NIWA River Environment Classification (REC) geo-database river lines are overlaid (red lines) for reference. B. Comparison of GeoNet extracted channel network and ArcGIS extracted channel network. An ArcGIS tolerance threshold (T) of 1,000 provided the best results. Spurious detection of roads across the central spur is evident

methods. However, in the context of forestry, the currently available data sources such as REC provide a more relevant comparison, and hydrological feature extraction may be most valuable in the planning stages of forest operations where results could guide labour-intensive field inspection. In this context, the information available from GeoNet appeared to surpass the level of detail available from the widely-used NIWA REC river lines. Furthermore, GeoNet was able to provide an indication of channel head locations across the area. The availability of these data may offer significant advantages with respect to improving environmental performance. Knowledge of channel locations and channel heads is particularly important for applications relating to sediment inputs, nitrogen inputs and other downstream water quality issues (Henkle et al., 2011), and provides the opportunity to accurately assess environmental compliance with new policies in New Zealand. Accurate delineation of water-courses is also likely to offer significant benefits to forest engineers who may be able to better plan roads and drainage features to minimise sediment and debris run-off during road and harvest planning operations (Passalacqua et al., 2012; Tarolli, 2014). Future research into the application of new channel network extraction techniques is especially needed for the modelling of engineered landscapes with distinct features related to human activities, such as forest roads and harvest infrastructure.

Conclusion

Rapid developments in channel network extraction methods in combination with high-resolution LiDAR-derived DTMs provides the means to extract hydrological features with more detail than currently available data sources. A key challenge to implementing these new technologies is to balance the trade-off between the acquisition cost and the quality of the required dataset so that long-term monitoring can be undertaken as cost-effectively as possible. This paper shows that DTMs with 1 m resolution, generated from LiDAR with a pulse density of 5 pulses m^{-2}, were adequate for hydrological channel extraction tasks. Higher resolutions greatly increased the computational burden. To define the absolute performance of all tested algorithms it is recommended that future results be compared against field collected reference data from a range of forested landscapes in New Zealand. Ambiguity between road and channel networks should also be addressed. The channel network extraction methods described here may provide managers with a useful means of identifying hydrological features to assist with monitoring and mitigating potential impacts from forest operations as part of their compliance activities within the new NES-PF and NPS-FM.

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Stefanie Lumnitz, Grant D. Pearse, Jonathan P. Dash and Michael S. Watt are all researchers in the Geomatics group within the Forest Science team at Scion. Stefanie Lumnitz is also an undergraduate student at the Ludwigs-Maximilians-University in Munich, Germany. Corresponding author: grant.pearse@scionresearch.com.