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The use of ground based LiDAR in rehabilitation performance and landform stability monitoring

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Abstract

Quantitative assessment of rehabilitation performance is one of the most critical aspects in mine closure and in obtaining sign-off and relinquishment from the relevant regulatory authorities. All current and widely used rehabilitation monitoring techniques require some degree of subjectivity, whether it is in the selection or location of monitoring sites or in the capturing of rehabilitation data. This subjectivity often results in the incorrect measurement or understanding of the specific processes operating in rehabilitation, and it is generally responsible for the continuation of monitoring programmes over a protracted time period and for the discrepancies between monitoring data and actual field observations. Without quantitative and objective data, it is difficult for regulators to approve mine closure and remove the liability on mining companies.

This paper will present an alternative rehabilitation monitoring technique that allows for the quantitative measurement of key rehabilitation performance measures, and provides additional landform information that can be used to effectively plan and direct future rehabilitation and mine closure activities. The monitoring technique utilises a ground-based LiDAR (Light Detecting and Ranging) system, which is similar to that often used to assess pit wall stability, to accurately capture quantitative data on floristic parameters (e.g., plant height and growth rates, foliage cover, plant density), surface soil parameters (e.g., percentage of rock and exposed soil cover) and landform attributes (e.g., slope shape, angle and length, berm / setback width). Unlike existing monitoring techniques, whereby these data are captured at specific locations on the post-mine landform, the LiDAR technique can rapidly and accurately measure these parameters over the entire landform, thus removing the subjectivity in selecting sites for monitoring.

Post-processing of the LiDAR point cloud enables vegetation growth rates from year to year to be assessed, as well as foliage cover and plant density. A highly accurate Digital Elevation Model (DEM) is created from the point cloud, and terrain analysis can be undertaken to identify areas of concavity (e.g., areas of potential water convergence) and all stages of rilling and gullying. The DEM can be input directly into surface flow and erosion modelling software (e.g., WEPP, SIBERIA), so that long-term surface runoff and sediment yields can be determined. Given the ease of use and rapidity of measurement, the ground-based LiDAR system can also be used to audit all rehabilitation and mine closure earthworks to ensure that it is undertaken to design, and scans of general minesite areas can determine volumes of soil materials that can be directly input into any cost estimator software to accurately determine mine closure costs.

This paper will highlight the use of the ground-based LiDAR technique and contrast it to other commonly used rehabilitation monitoring techniques. Case studies will be presented showing the successful application of the LiDAR technique to rehabilitation and mine closure monitoring.

1 Introduction

Awareness of mine closure and the importance of effective rehabilitation monitoring to achieve closure has gained prominence over the last five years. A driving factor in this increased awareness and attention has been the global financial crisis, which has forced mining companies to 'look inward' and become cognisant of their financial liabilities and money tied up in closure (or more specifically, money tied up in unclosed sites). With the addition of increased environmental awareness and regulatory pressures, mine closure has

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now become a crucial aspect to the success of any mining operation. In Western Australia, new Mine Closure Planning (MCP) Guidelines have been implemented through legislation that now requires every new mining operation to submit a detailed MCP prior to any activity (i.e., along with the Mining Proposal), and this plan must be accepted by the Department of Mines and Petroleum (DMP) for the operation to be granted approval. For all existing sites, a detailed MCP must be prepared and reviewed every three years.

Closure of a mine site, and obtaining regulatory signoff, requires that rehabilitation meet specific stakeholder-agreed completion criteria or performance indicators that are site-specific, scientifically supported and capable of objective measurement or verification (ANZMEC/MCA, 2000). Monitoring data must therefore be quantitative so that an objective and independent assessment can be made. Unfortunately, obtaining such data is laborious and costly, with most common methods requiring assessment of particular rehabilitation attributes (e.g., soil or vegetation parameters) at specific locations across a post-mine landform (e.g., waste rock landform (WRL) or tailings storage facility (TSF)). To ensure that these measurements are scientifically valid and reflect the functioning and performance of the entire landform, a considerable number of replicates are generally needed, which adds significantly to the time and cost of monitoring, to the point where, for some mining companies, monitoring becomes a hindrance and is either ignored or poorly executed such that the data collected are not defensible.

All commonly used rehabilitation and closure monitoring techniques involve the assessment of specific rehabilitation attributes at either:

- Specific points or sites (e.g., surface soil sampling).
- Within quadrats of varying dimensions (e.g., 1 × 1, 5 × 5 or 10 × 10 m).
- Along transects aligned perpendicular or on the diagonal to the contour ripping.

For all monitoring techniques utilising the above approaches, the actual positioning of the point, quadrat or transect is subject to considerable experimenter bias, such that positions are often selected that portray a positive image for a site (e.g., rarely is a transect located within an erosion gully or narrow overtopping berm). Even if the monitoring approach is statistically developed and is implemented soon after rehabilitation earthworks (i.e., when there are no erosional features), most monitoring programmes do not have sufficient flexibility to add or remove sites to accurately reflect the developing and changing rehabilitation ecosystem. Nevertheless, most soil and vegetation monitoring programmes generally only involve a handful of sites (strategically) located over a post-mine landform that often exceeds 100–200 ha; hence the same fundamental question always arises: where to locate monitoring sites?

Rehabilitation attributes that are typically measured during monitoring can be grouped into the following categories:

- Soil and stability parameters (e.g., physical, chemical and / or biological fertility, soil erosion).
- Vegetation parameters (e.g., species richness, plant density, foliage cover, plant height).

Whilst soil physical and chemical (and even biological) properties, as well as vegetation attributes, can be easily measured, actual soil stability and erosion and sediment rates are difficult to measure, especially on a routine basis. These parameters are typically the most important attributes to measure in the early stages of rehabilitation, as the influence of vegetation on stability are negligible. Common methods for erosion monitoring include:

- Direct measures of sediment loss and deposition (e.g., erosion troughs and silt fences).
- Indirect elevational measures (e.g., change in elevation overtime).

No routine rehabilitation monitoring techniques include these measures, with sediment loss estimated from direct measurement of cross-sectional areas of erosional features that are intersected by soil or vegetation monitoring transects.

Through the use of ground-based Light Detecting and Ranging (LiDAR) technology, the problematic aspects of subjectivity and the inability to quantify soil loss are removed.

2 LiDAR technology and capability

LiDAR technology has traditionally been used for broad-scale remote sensing and aerial photography applications to capture elevation data. Given the minimum altitude requirements for aerial surveys, capturing ground-based data (e.g., topography, plant height and cover) is generally restricted, as the level of accuracy is typically only 2–5 m, and subsequently a 5×5 m quadrat would only contain at most two to three measurement points. This lack of resolution limits the use of any aerial survey technique for accurate monitoring of developing rehabilitation and stability process on mine sites.

To overcome these resolution limits, ground-based LiDAR systems have been developed, which allow for millimetre-scale measurement accuracies. Over the last 10 years, this high-resolution ground-based LiDAR system has been used to monitor open pit (and underground) wall stability, as its accuracy is capable of detecting even the smallest bulging of pit walls, which often precedes mass failure of the slope – thus providing sufficient time to remove personnel from the area. Minesite surveyors are only now starting to use this technology to survey large areas on-site, including ore stockpiles and mine pit excavations, to determine month-end volumes balances; however, no application of this technology to post-mine landform construction or rehabilitation auditing and monitoring has been undertaken to date.

All LiDAR systems utilise an electromagnetic distance measurement device that emits a light pulse and measures its return or reflection back to the scanner. The distance to any specific object is then simply calculated by multiplying the time of flight of the pulse by the speed of light according to Equation 1 (Uren and Price, 2005).

$$\text{Distance to object} = (\text{Speed of light} \times \text{Time of flight})/2 \quad (1)$$

Using this approach, ground-based LiDAR systems are capable of capturing 8800 points per second, with an accuracy of 8 mm over a 100 m scan distance (Maptek, 2010). When scanning a pre-mine or post-mine non-vegetated landsurface, the light pulse detects subtle variations in landsurface elevation, which may be due to a rock or gravel cover (able to detect individual rocks) or by a specific rehabilitation management strategy (e.g., contour ripping or backsloping of berms) (Figure 1). In vegetated systems, the light pulse can also detect not only the height of the vegetation but also the width of the foliage and the corresponding stem height (Figure 1).

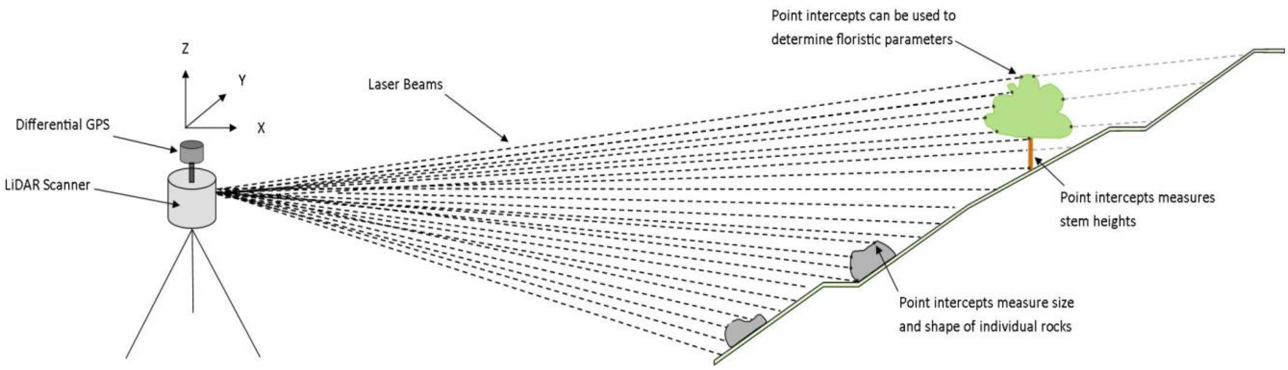


Figure 1 Functioning of a ground-based LiDAR system for rehabilitation and closure monitoring

Given that LiDAR detects individual points of all features across a landsurface, its output is an x (Easting), y (Northing), z (Elevation) point cloud of the surface (Figures 2 and 3). These points can then be imported into any raster-based gridding or triangulated irregular network software to create a detailed, high-resolution digital elevation model (DEM) (Figure 4). In addition to the elevation point cloud, a high-resolution digital image is also captured during a scan. Using this image, each data point is then attributed a colour within the visible range, which can then be filtered to remove certain aspects of the surface (i.e., remove 'green' vegetation to determine percentage exposure of the ground surface). Ground-based LiDAR systems utilise both a rotating mirror and a scanner to enable scanning over a full 360° horizontal area (i.e., 360° rotation), with an 80° vertical scan region.

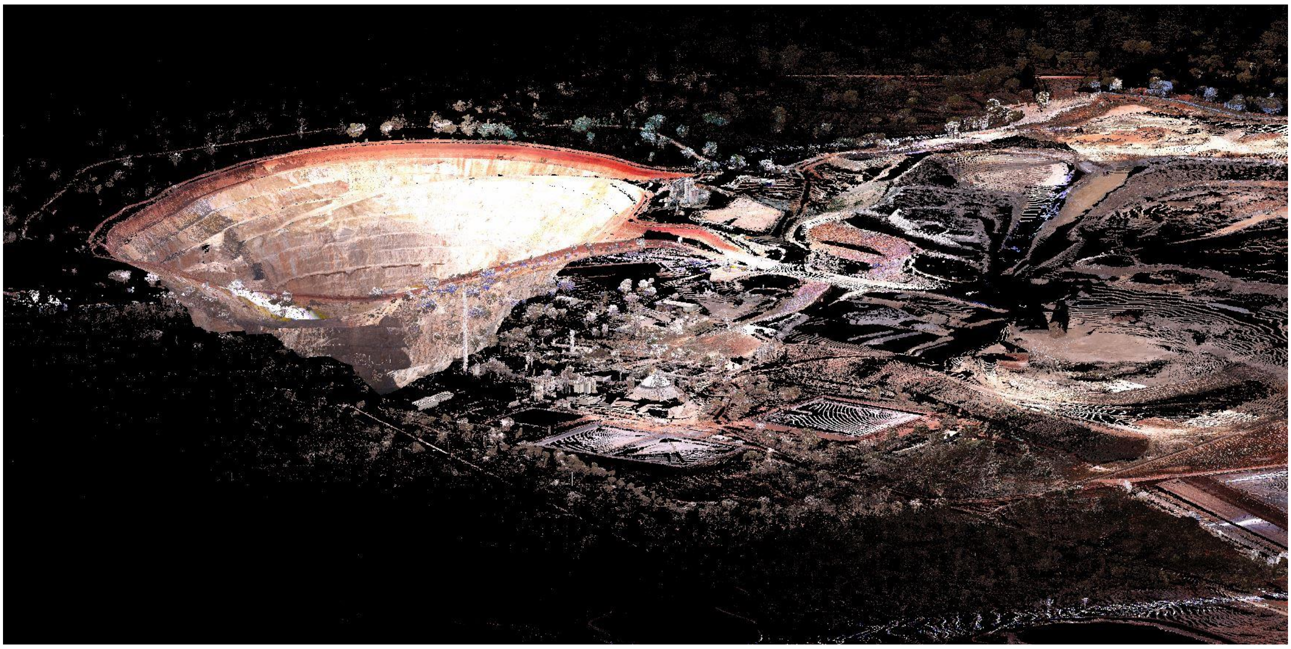


Figure 2 Point cloud (> 118 million points with ±8 mm accuracy) generated for an entire minesite

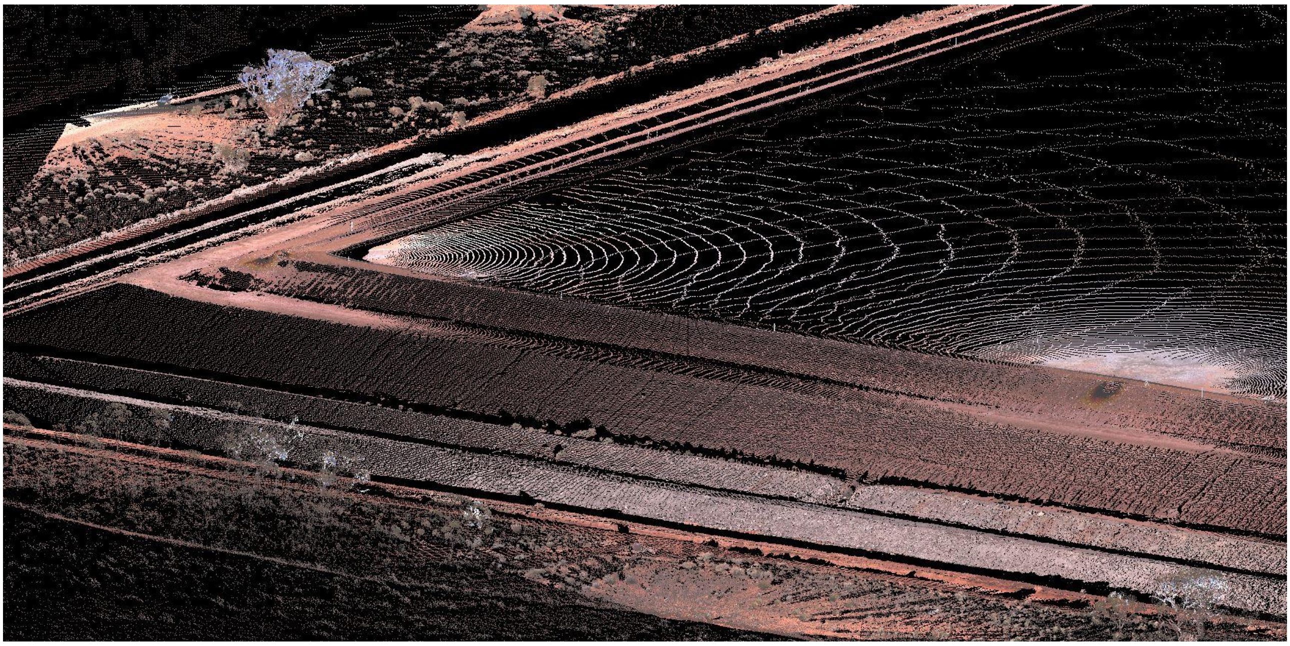


Figure 3 Point cloud of a 1 km section of a TSF

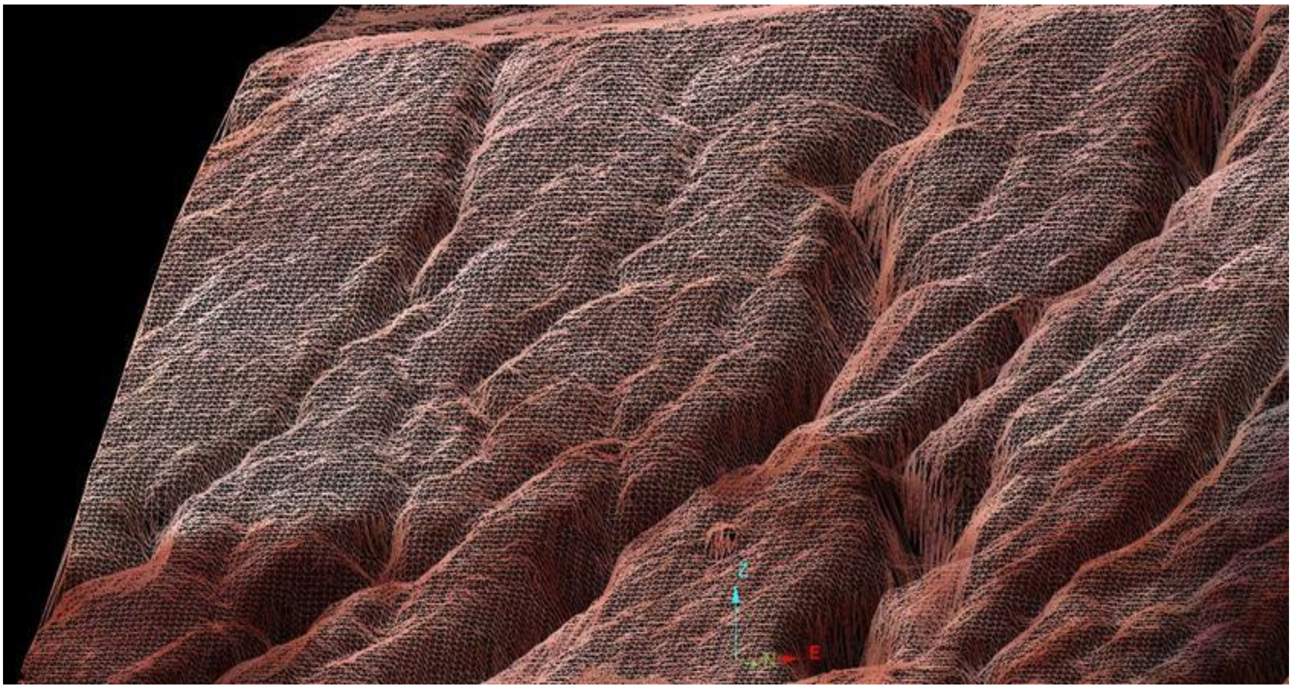


Figure 4 Detailed, high-resolution DEM generated from a LiDAR scan point cloud (large gullies approximately 1 m in width)

LiDAR scanners typically have a range of scanning resolutions, which can be varied to suit the application and time available for the project. Common scanning resolutions are provided in Table 1. Based on a scanning resolution of 8 and 16, a typical 5×5 m rehabilitation monitoring quadrat will contain 13,650 and 27,300 measuring or data points, respectively, whilst a 10 m long line transect will contain upward of 450 individual measurement points.

Table 1 Common LiDAR scanning resolutions

Scanning Resolution	Point spacing (mm @ 100 m; ± 8 mm)	Points/m^2 @ 100 m Scanning Distance
1	349	69
2	175	137
4	87	276
8	44	546
16	22	1,092

Given the large amount of data collected for each scan, designated computer software developed to deal with large (10 GB file size) point cloud data is required to process the information collected. MapTek (developer of Vulcan) have a proprietary software (I-Site) that has been specifically developed for processing of ground-based LiDAR point clouds and generation of high-resolution DEMs. Through the use of this software, and with a hard drive with a minimum specification of 1TB 7200 rpm, an Intel 64 CPU processor and a 8 GB RAM or more, detailed images and 3D landscape models can be rapidly constructed to aid in rehabilitation and closure planning.

3 Application of ground-based LiDAR for rehabilitation and closure monitoring and planning

An image showing the application of a ground-based LiDAR system is shown in Figure 5. The system consists simply of a scanner placed on top of a tripod, whose exact location and elevation is known by using a differential GPS. Optimally, a LiDAR scan should be taken at the toe of the post-mine landform (looking up) and again at the crest or top of the landform (looking down). This is typically required as construction of these landforms often contains backsloping berms and contour riplines, which would result in unacceptable shadowing if only one scan per slope was undertaken. Depending on extent of revegetation on the post-mine landforms slopes, surface complexity (e.g., multiple lifts, access ramps or corners) and prevalence of vegetation surrounding the landform, multiple scans are often required along a batter slope to ensure sufficient overlap of scans and to reduce the shadowing effects; this is shown in Figure 6.

Figure 5 Scanning of a rehabilitated waste rock landform using a ground-based LiDAR system

Given the amount of data collected and ease of use, ground-based LiDAR systems can be used for the following rehabilitation and closure applications:

Stability and compliance applications:

- Audit of as-built post-mine landforms.
- Input and validation of landform evolution models.
- Identification and quantification of erosional features, sediment yields and soil loss.
- Determination of filling rates of surface water management features (e.g., berms, contour riplines).

Revegetation applications:

- Measurement of floristic parameters, including plant height, plant density and foliage cover.
- Monitoring of floristic parameters over time.

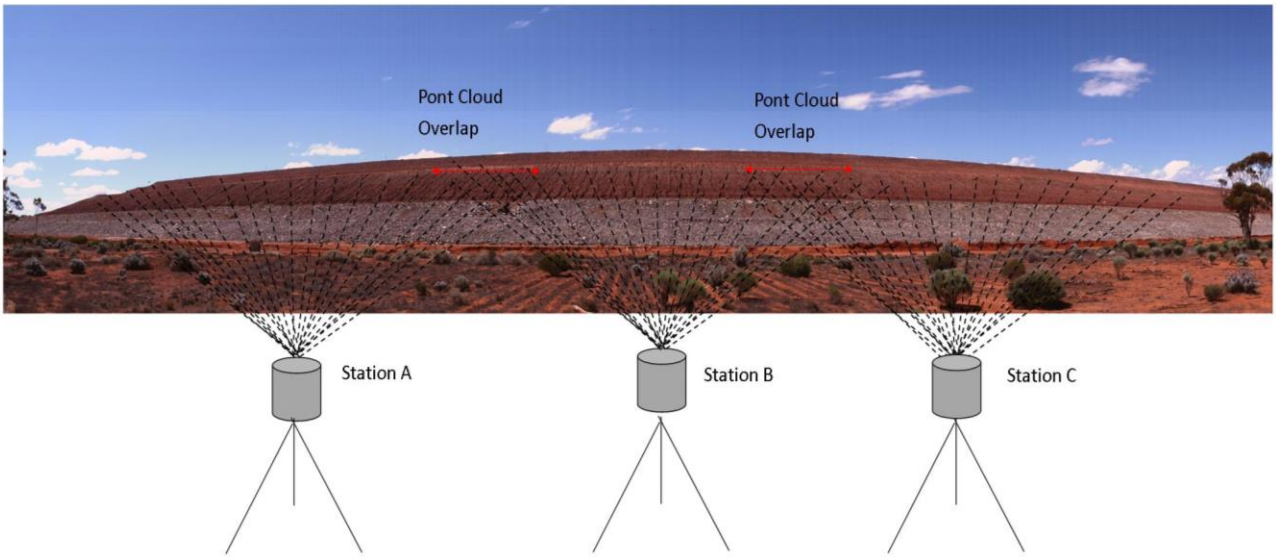


Figure 6 Multiple LiDAR scans of a TSF slope to ensure overlap of point clouds and reduce shadowing effects

3.1 Stability and compliance applications

3.1.1 Audit of as-built post-mine landforms

Given the ease and rapidity to which the ground-based LiDAR can be utilised, it is possible to use this system as an auditing tool for post-mine landforms to determine whether they have been constructed to design. From multiple scans, an accurate (± 8 mm) 3D image of a post-mine landform can be established, which can then be compared with the original design. Using terrain analysis on the DEMs generated from the point clouds, it is possible to determine the following critical surface elements that have a significant impact on the stability and function (i.e., surface water movement) of the newly constructed landform:

- Elevation of each batter / berm crest and toe.
- Batter / berm slope angle and length.
- Areas of profile and planimetric concavity (water convergence) and convexity (water divergence).
- Contour ripping crest height and trough depth and frequency or spacing.

Areas of the post-mine landform that do not conform to the original design can be highlighted and specific remedial earthworks undertaken to rectify the issues before they impact on the overall stability of the landsurface and prior to seeding of revegetation species. An image of a recently constructed WRL, with a rock cover to stabilise the surface, is presented in Figure 7.

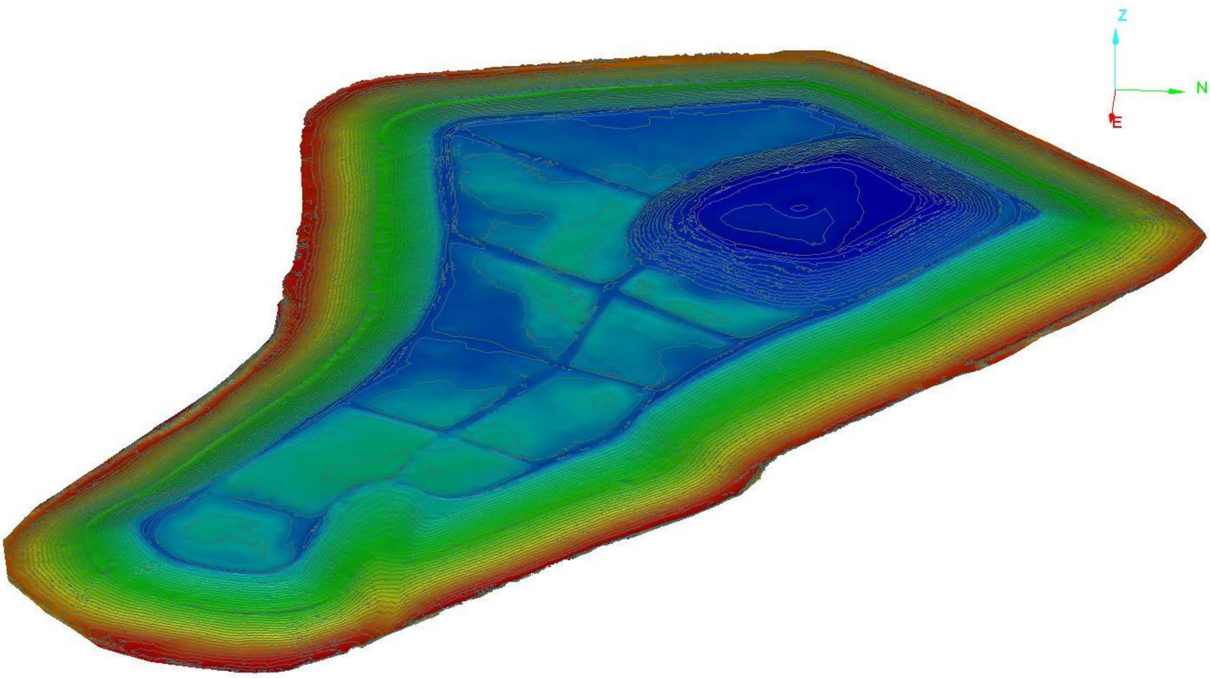


Figure 7 High-resolution DEM of a recently constructed WRL to determine its conformity to the original design

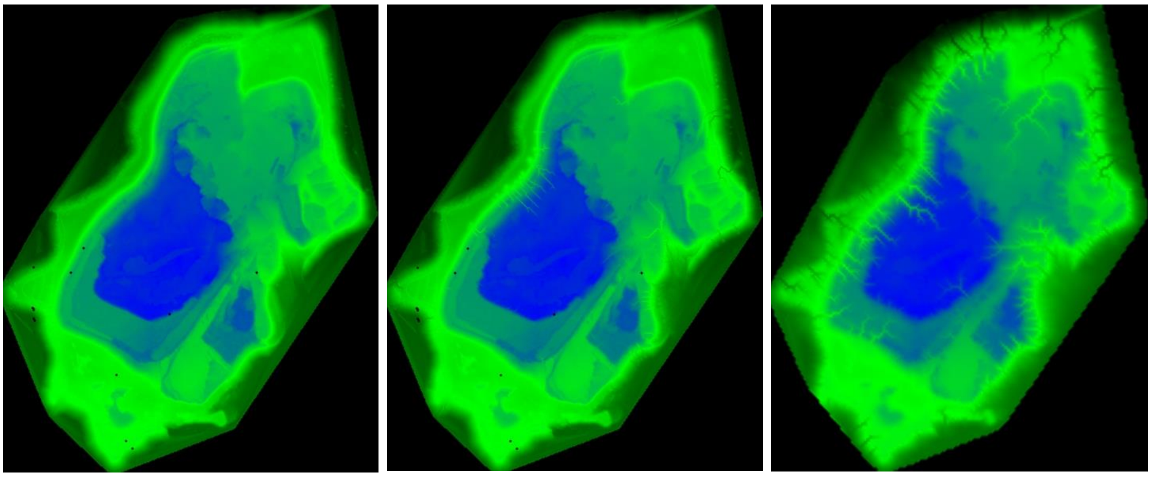
3.1.2 Input and validation of landscape evolution models

The high-resolution point cloud obtained from the LiDAR system or generated DEM can be imported directly into a number of landscape evolution models, such as SIBERIA, CAESAR, CHILD and CASCADE (Figure 8). The predictive nature of all these models depends ultimately on the accuracy of the input DEM or point data; thus, capturing high-resolution elevation data using the LiDAR system greatly improves the validity of these models.

In addition, LiDAR scans of batter surfaces or entire post-mine landforms over consecutive years can be used to validate predictions from landscape evolution models. This is a critical aspect, as all too often model predictions go untested due to the difficulties in capturing annual high-resolution topographic data.

3.1.3 Identification and quantification of erosional features and sediment yields

Given the high resolution and accurate nature of the LiDAR scan data, these can be used to identify even the smallest erosional feature that, with time, may develop into major gullies. Figure 9 shows a detailed DEM for a portion of a WRL batter slope showing areas of concavity that will become and have become problematic with time, whilst Figure 10 shows a typical scan of a TSF embankment wall highlighting the extent and frequency of rills and gullies that have developed on the first lift of the TSF. Due to the accuracy of the point cloud data, a detailed DEM can be constructed and the volume of either one, two or all rills and gullies determined with precision. For the image below, the rills and gullies in a 10×10 m quadrat have an average volume (loss) of 16.723 m^3, which equates to approximately 30 t (3,000 t/ha) or 17 cm over the entire 100 m^2 quadrat. The scanned TSF was constructed 15 years prior to the scan, with thus an annual erosion rate or sediment loss of 200 t/ha/yr. This is significantly higher than the 5 t/ha/yr commonly used by regulatory agencies, and it highlights (and quantitatively proves) the instability of this landform.



(a) (b) (c)

Figure 8 SIBERIA model results derived from LiDAR for; (a) an as-built 200 ha WRL, after; (b) 100 years; and (c) 1,000 years of weathering and erosion

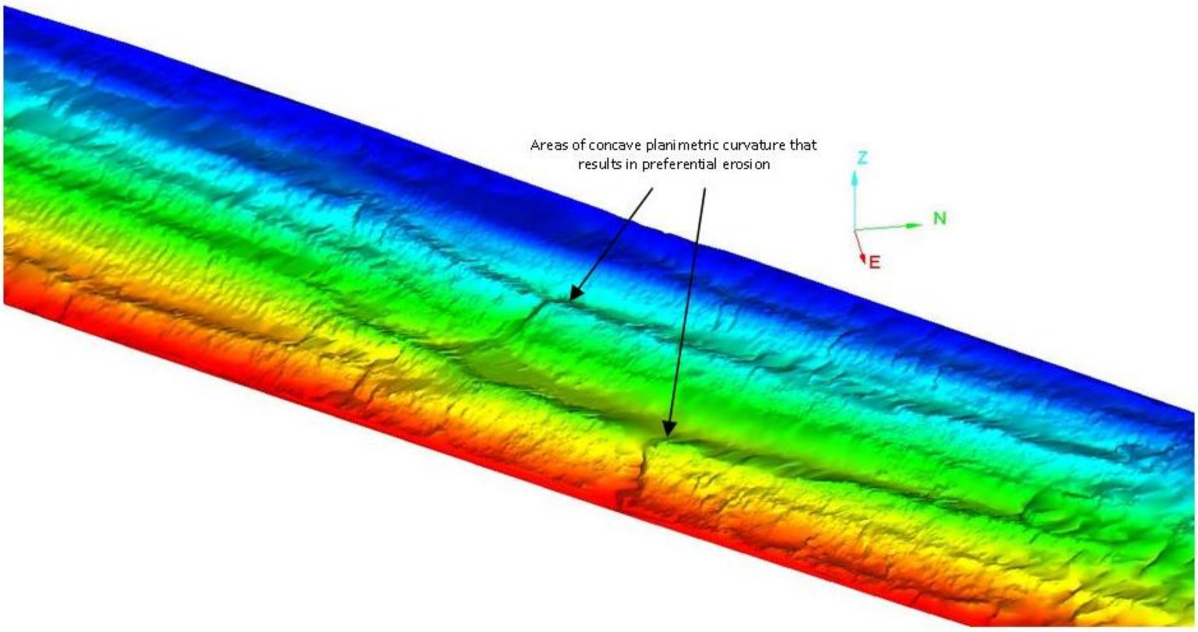


Figure 9 Detailed DEM of a WRL batter surface shows problematic areas of concavity

From the DEM constructed with the point cloud data, accurate measurements of rill / gully dimensions and change in surface elevation (i.e., from soil loss and subsequent deposition downslope) can be rapidly obtained (Figure 11).

Figure 10 LiDAR point cloud of a typical TSF embankment wall showing frequency of rilling

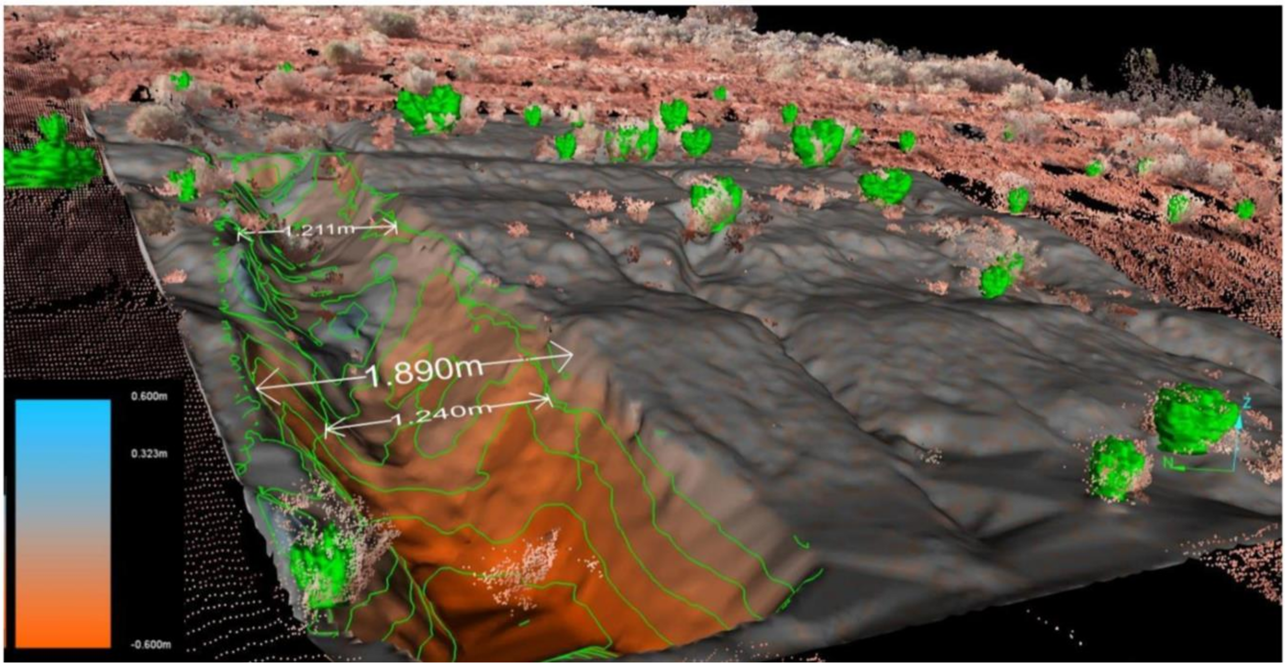


Figure 11 Accurately measuring the change in gully dimensions over time

3.1.4 Determination of filling rates of surface water management features

In the design and construction of post-mine landforms, surface water management features are typically incorporated to control surface water flows and to stabilise the landform surface. Over time, these features fill with sediment; hopefully before they completely fill (and their control over surface water diminishes), the re-established vegetation has grown sufficiently to stabilise the soil surface. LiDAR can be easily used to 'track' the filling of surface water features on an annual basis, such that the rate of filling and the time to overtopping can be accurately calculated; using this information, remedial earthworks can be planned to either minimise upslope sediment loss or clean out the management features. Figure 12 shows a LiDAR scan of a typical contour rip line system on an unstable post-mine landform, whereby all troughs have been filled with sediment. Figure 13 shows a DEM constructed from this scan.

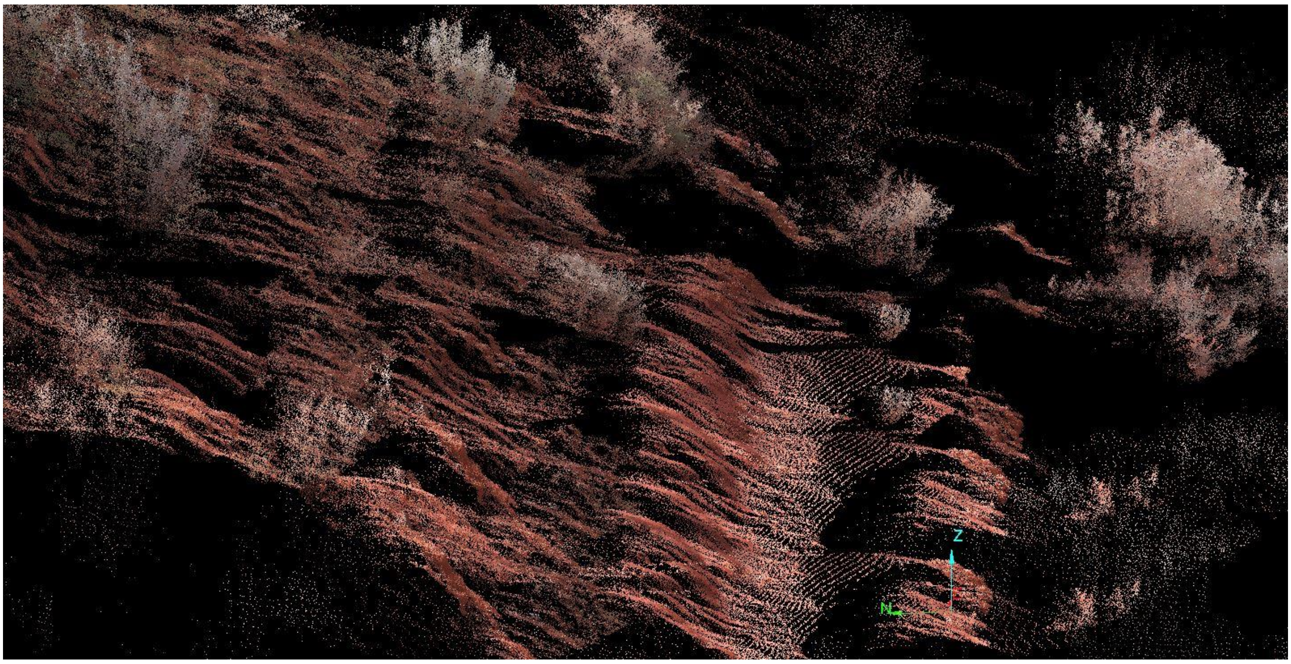


Figure 12 LiDAR point cloud of filled riplines on an unstable waste rock landform

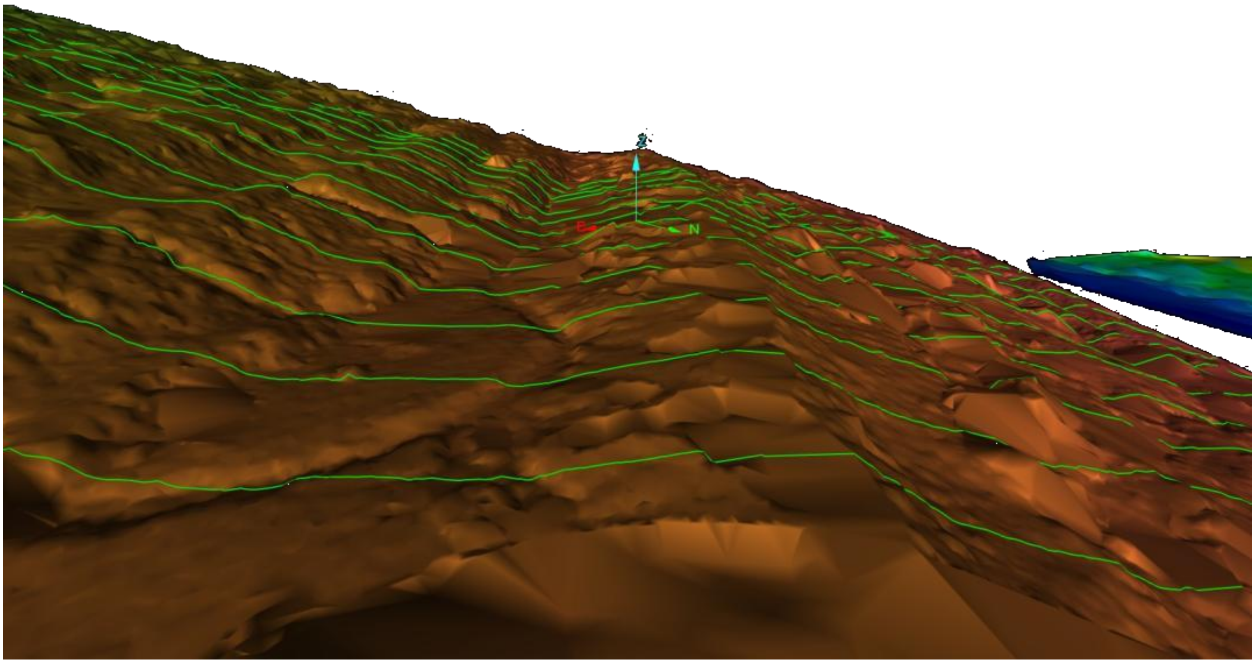


Figure 13 DEM of filled riplines on an unstable waste rock landform

3.2 Revegetation applications

3.2.1 Measurement of floristic parameters

The ground-based LiDAR system can be used to measure rehabilitation floristic parameters, such as plant height, plant density and foliage cover. These parameters are critical to successful rehabilitation of post-mine landforms, particularly in stabilising the surface soils, and are often used as completion criteria to assess performance.

Floristic parameters are generally measured and monitored using a quadrat or point / line transect approach, such that they can be expressed on a per unit area basis. Given that a LiDAR scan can measure over 1,000 surface points/m^2, the resulting point cloud can be used identify the majority of emerging and establishing species; this is clearly shown in Figures 14 and 15.

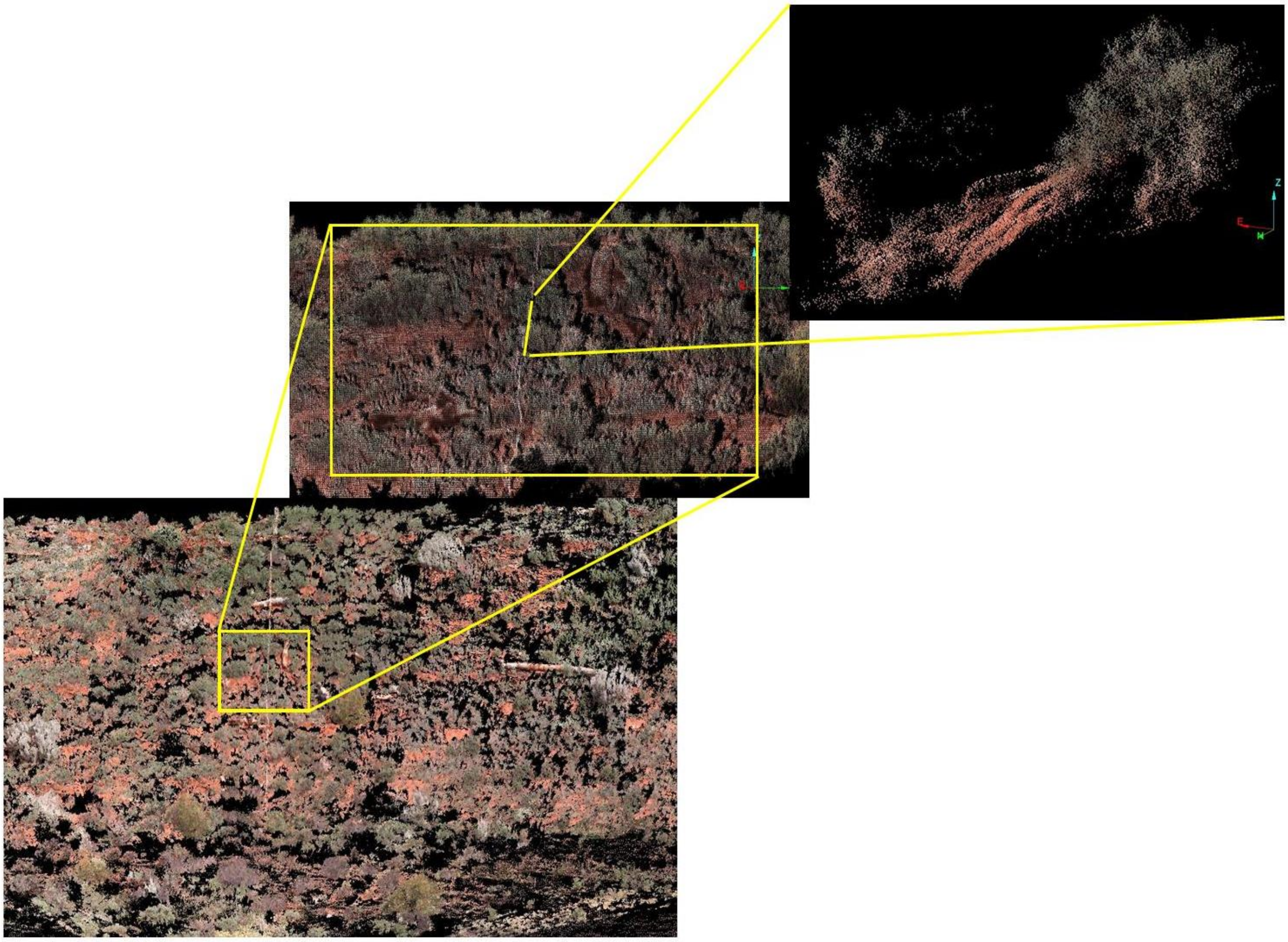


Figure 14 Application of ground-based LiDAR to assess revegetation growth and establishment (yellow box represents a 5 × 5 m quadrat, whilst the yellow transect line is approximately 1.5 m in length)

From the point cloud shown in Figure 15, the parameters of plant height, density and foliage cover can be estimated. Ground validation is generally required initially; however, once this is established the LiDAR scan data can be used to routinely and accurately measure these floristic parameters. In addition, total groundcover (i.e., rock + vegetation) can also be estimated from the high-resolution LiDAR point cloud, as can be seen in Figure 16.

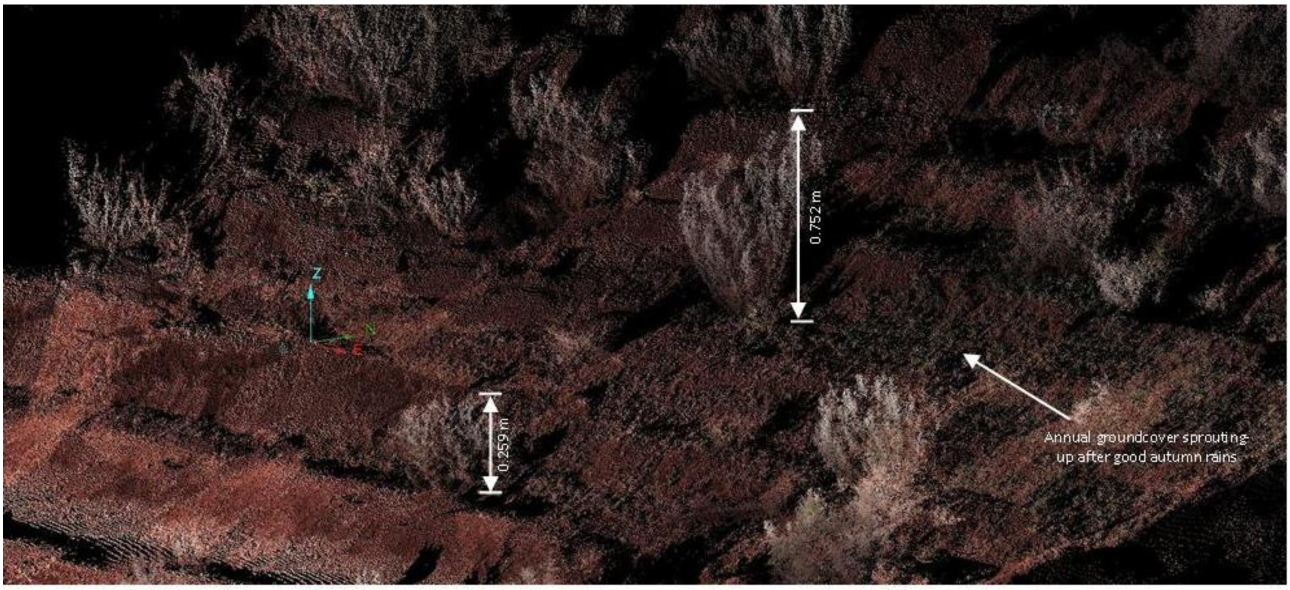


Figure 15 Application of LiDAR to measure floristic parameters

Figure 16 Application of a LiDAR point cloud to measure total groundcover over the surface of a post-mine landform

3.2.2 Monitoring floristic parameters over time

With the level of accuracy that can be achieved using the ground-based LiDAR, the condition and evolution of a rehabilitated post-mine landform surfaces can be easily monitored over time. The growth and establishment of revegetation species can be clearly viewed and accurately measured, with the corresponding change in foliage cover also easily assessed.

4 Limitations to the use of ground-based LiDAR for rehabilitation and closure monitoring

As with all remote sensing and laser techniques, the application of the ground-based LiDAR system is affected by vegetation and corresponding shadowing. The ground-based scanner has a scanning height of only 1.8 m: hence, vegetation > 1.5 m in height can result in appreciable shadowing, as the light pulse is not able to penetrate through vegetation. When scanning from the toe of a post-mine landform (i.e., from the ground looking up) the scanning angle exacerbates the shadowing and thus vegetation > 0.75 m in height can result in significant shadowing of the upslope surface. Initial calculations undertaken during ground-truthing of the LiDAR system identified that when scanning from 100 m from the base of a landform, a 0.5 m high plant will result in a shadow of 2.2 m upslope; scanning at distances > 100 m will result in less shadowing.

In addition to the vegetation effects, constructed surface water management features, such as contour ripping and backsloping surfaces, do result in 'blind' sections of the surface, which are recorded as shadows. For example, when scanning from the base of a landform, it is often not possible to 'see into' deep contour troughs as they are not visible to the scanner. To overcome this and the shadowing effects by vegetation, it is often necessary to perform multiple scans across a slope to minimise the percentage of the surface in shadow. This can be done rapidly, as the ground-based system is mobile and with a DGPS setup nearby, the user can scan from any position on the surface. Work is currently being undertaken to determine if a relationship between vegetation shadowing and foliage cover can be established, as the greater the foliage cover, the greater the extent of shadowing.

The effects of shadowing can be reduced by increasing the scanner height using a telescopic pole or nearby elevated landsurface. The use of a DGPS-controlled drone or unmanned aerial vehicle (UAV), with a high-resolution LiDAR system attached, would produce the highest level of coverage; however, a range of other issues (e.g., weather, locator software, safety and acceptance on mine sites) need to be considered – hence the portability and robust nature of the ground-based scanner make this system effective, implementable and affordable for most sites.

5 Conclusions

This paper highlights the capability and benefits of using a ground-based LiDAR system for rehabilitation and closure monitoring. Although it does not negate the need to undertake a detailed soil and vegetation survey across the post-mine landform, if used in conjunction with them (i.e., before such surveys, to identify the most appropriate sampling sites, or after, to monitor the evolution of the landsurface), it can be used to accurately monitor changes in rehabilitation performance, obtaining quantitative data that can be directly compared with specified completion criteria to facilitate sign-off and relinquishment of the landform.

Acknowledgement

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