Making a difference: examples of the use of repeat LiDAR datasets to guide river management decisions following extreme floods

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Key Points

- Repeat LiDAR surveys are extremely valuable for managing river channel change after large floods
- Initial LiDAR collection should be at the largest spatial coverage possible to provide a baseline dataset.
- Using a DEM of Difference (DoD) repeat LiDAR can be used to determine the amount, position and processes of erosion and deposition after flood events.
- The processes identified by the comparison of repeat LiDAR can assist management decisions.

Abstract

The response to managing the effects of a flood event can be reactive. Landholders often want immediate compensation for soil loss and river encroachment into productive floodplains, and methods to set priorities for river stabilisation are often not available. Without a clear understanding of catchment scale impacts these decisions can be made in a vacuum, usually based on rapid assessments at discrete sample locations. As a result of the Lockyer Creek LiDAR and aerial datasets, pre and post the 2011 and 2013 flooding, recommendations can be made about how to undertake remotely sensed monitoring for management. An initial low flow LiDAR run enables a baseline dataset to be established. Hydraulic models can be created to delineate the bankfull, bed, and in-stream geomorphic features. Evidence of sediment accumulation and relict erosional features can aid process determination and, in concert with existing data, the construction of a model of how the channel is functioning and its likely geomorphic trajectory. Collection of a subsequent LiDAR dataset means a DEM of Difference can be built. Firstly this allows an evaluation of catchment scale patterns of erosion and deposition, identifying hotspots. Subsequently the key drivers of processes can be determined, such as those responsible for riverbank erosion, and the channel trajectory model revisited. In the Lockyer, wet flow mass failures contributed ⅓ of the eroded sediment and in subsequent events were unlikely to erode further, more often becoming depositional features. This alters the traditional management response of remediating existing failures to a programme of rehabilitation of sites without failures. As LiDAR collection will not be instantaneous after the flood, initial management that involves infrastructure/asset protection must occur in the absence of these information. Other channel works should wait until the data is available to avoid undertaking inappropriate management actions.

Keywords

DEM, DoD, LiDAR, Riverbank erosion, River management

Introduction

Large floods can cause channel change and in so doing destroy vital infrastructure (Baker 1988). In the aftermath of these floods there is the potential for government funding to be provided to natural resource managers to remediate damage, and reduce future impacts to communities. To be proactive and prepare for such events the current state of the river needs to be understood along with the rates and causes of processes operating. The geomorphic trajectory of the channel can then be modelled, allowing appropriate management actions to be undertaken (Thorne 1999; Grove *et al.* 2014). The implications of the 'do nothing' approach can also be evaluated.

An understanding of the system dynamics and trajectory of a river system, pre and post flood, has traditionally been based on a combination of: 1) point measurements; 2) collections of mapped data; 3) aerial photographs; and, 3) field observations. The outcome of these assessments is usually a very spatially discrete set of two dimensional changes, such as in the cross-sectional area or the difference in channel centerline position. Surveys, both topographical and aerial, are usually done too infrequently to identify the pre and post flood changes with any confidence.

The development of Light Detection and Ranging (LiDAR) now overcomes the problems of selecting representative cross-sections for re-survey, and mapping uncertainties of aerial photographs produced from Australian evergreen riparian vegetation (Hoyle *et al.* 2012). The penetration of the LiDAR through vegetation enables the channel position underneath the canopy to be determined in three-dimensions. One of the advantages of repeated LiDAR over compiling cross-sections, or a detailed feature survey, is that volumetric calculations can be undertaken quickly over a much larger spatial scale using GIS. This enables the volume of sediment eroded and deposited in a flood to be quantified.

Currently the extent of airborne LiDAR acquisition is a balance between the cost of data collection and volume of data acquired (Johansen *et al.* 2010). Geo-rectification, joining and subsequent viewing of the point data can become very computationally expensive. The point data is much easier to use if it is interpolated into a Digital Elevation Model (DEM). The pixel size of the DEM is guided by the density of ground returns, the more returns in a pixel the lower the errors. DEMs with pixel sizes of 1 m^2 can be produced over scales of 1,000's of kms^2 with elevation errors under +/- 0.2 m. In river systems this pixel scale can be sufficient to monitor geomorphic changes over an event timescale (Lawler 1993).

This paper provides information to aid the collection of LiDAR and high resolution aerial imagery so that it is useful for river management. The sequence of the paper will build on how remotely sensed data becomes available over time, from an initial baseline dataset to a multi-temporal dataset. Using examples of different LiDAR derived data the applications for the management of channel changing floods will be explored.

Initial LiDAR collection

There are many reasons why LiDAR may be collected. If the management of a river system is the priority then a complete coverage of an entire catchment may be useful in order to provide an initial dataset that allows an evaluation of the linkages between hillslopes and channels, as well as flood inundation modelling is to be undertaken. The disadvantage of this approach is that the data collection, processing and storage may be all be expensive financially and logistically. At a minimum the flight lines should be concentrated on the riparian zone and channel, allowing future rates and processes of channel change to be quantified. The swath width should be wide enough to allow the capture of meander migration or anabranch development, and so may need to include the entire floodplain to capture developing anabranches.

The lack of penetration of LiDAR through water means that capture should be undertaken at the lowest flow possible, accounting for both natural and irrigation flows. The periods of minimum vegetation coverage will also provide the most ground returns. To enable an efficient data collection the channel and floodplain spatial configuration needs to be determined before flight lines are set. The blue-line network on previous mapping may not be adequate. This was a particular issue for the 2nd Sustainable Rivers Audit (SRA) of the Murray-Darling Basin (MDB) (Davies *et al.* 2012) where each state had different networks mapped using varying map projections. The joining of these networks resulted in streams not linking across borders. Particular care needs to be taken in the difference between a DEM derived blue-line network and a river with anthropogenic modifications such as inter-basin transfers and irrigation channels.

The following examples show how a baseline LiDAR dataset of 100 to 1,000s of kilometres of a river network may be used for management.

Example 1. Baseline feature delineation

The 3rd Victorian Index of Stream Condition (ISC3) flew 29,000 km of streams in 2009-2010 at the end of the drought (DEPI 2013). The 'main' river network of Victoria was flown so that there was a continuous capture of LiDAR and aerial imagery. This continuity allowed the ability to report river condition at reach scale of 5-40 km, with variability captured at 25-100 m intervals. The collection of the LiDAR in a fairly short temporal period meant that the position of bed and banks is now available as a baseline to compare future morphological changes against or to use for planning purposes.

The LiDAR has been used to report on the condition of riverbank. As only one LiDAR dataset was available the rates and volumes of erosion could not be quantified. Instead the slopes of the riverbanks has been used as a proxy for erosion, with steep slope (>35^o) used as an indicator that erosion may have taken place. Reference conditions for each 100 m section have been constructed, allowing a comparison been observed and expected areas of steep slopes. These data then enable future LiDAR collection to validate the conditions measures with actual rates erosion, and the pre-processing of an extensive single LiDAR dataset means that future data can be focused in areas of likely change.

Example 2. Hydraulic modelling of geomorphic features

In 2010 around 100 km of the Lockyer Creek, Queensland, were captured using discrete LiDAR (>2pts m^{-2}). A HEC-RAS hydraulic model, hydraulic model, and terrain slope, were derived from a 1 m DEM and used to define cross-sections along the extent of the LiDAR (Figure 1). These enabled the delineation of five different geomorphic features: (1) inner channel bed and bars; (2) inner channel banks; (3) benches; (4) macrochannel banks; and, (5) floodplain and/or terrace (Thompson and Croke 2013). These products or maps were made available as GIS polygon features.

The different geomorphic features are likely to operate differently in terms of both hydraulics and sediment dynamics. Not only can changes be detected in the extent of these features following a flood event but they can also be used to guide management after the flood. For example, environmental flows can be targeted to cover different geomorphic features and native re-vegetation projects can use appropriate species for different zones.

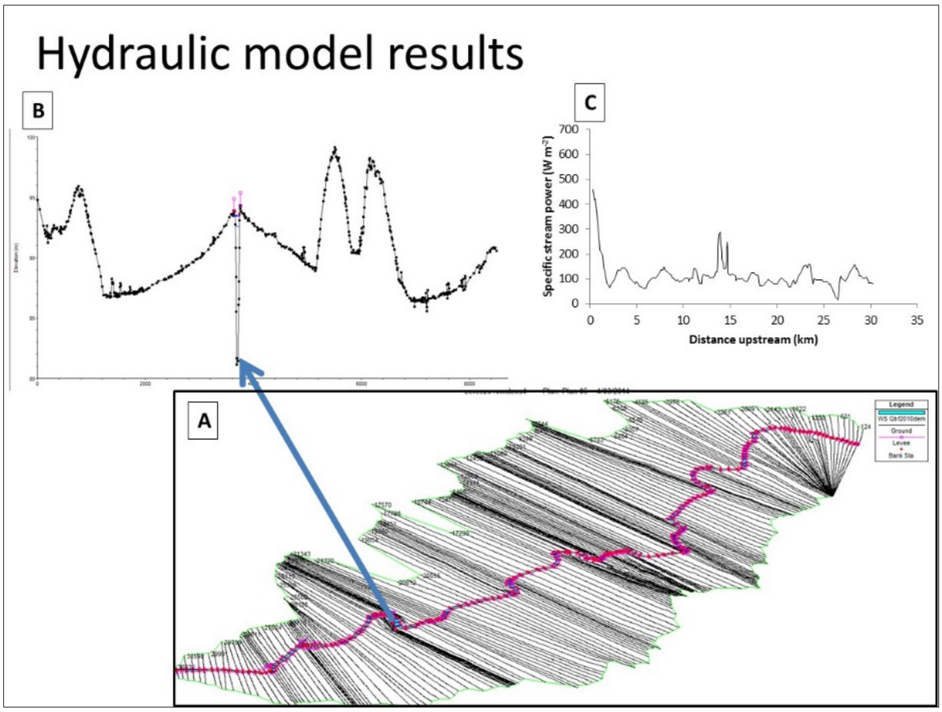

Figure 1. The hydraulic analysis of Lockyer Creek LiDAR data showing: A) the planform position of cross-section; B) a single cross-section in 2D; and 3) the stream power upstream of the example cross-section.

Example 3. Mapping of erosion scars

The 2010 Lockyer LiDAR was also used to map out the spatial position and morphology of riverbank mass failure scars (Thompson *et al.* 2013). The mapping was of the accumulated failures that persisted in the landscape from events preceding the 2010 data collection. There were 234 mass failures identified with an average area of 421 m^2, it was not possible to distinguish the age of the failures from the imagery. The distribution of the failures in the five geomorphic features described above, was then calculated, with 60 % of the area of failures occurring in the macrochannel, 21 % on benches, 11 % across the inner channel banks and 7 % from floodplains.

This baseline dataset allows future erosional events to be placed in context. Whilst it is only identifying features that have persisted, the relative size and distribution suggest that the most failures have occurred within the boundaries of the macrochannel. If future floods cause larger failures or a greater encroachment onto the floodplain then this may alert managers that the system is operating differently than it has in the past than it has in the past.

Multi-temporal LiDAR datasets

Whilst the initial data provided by a baseline dataset of LiDAR can provide some indication off the state/condition of the channel the real advantage of these data comes from change detection. Comparing one DEM time step with another allows a DEM of Difference (DoD) to be constructed (Wheaton *et al.* 2010). The DoD provides the volumetric differences between the two surfaces at a pixel scale, from these the amount and spatial position of erosion and deposition can be determined. The secondary dataset collection following a flood needs to be made in light of the dynamics of the system in question. If change is less than the error in the DoD then there may be little to be gained from the resurvey. If a flood has occurred then a decision must be made about how long it will take for the flow to return to a stage low enough for most of the riverbanks to be visible. Whether the whole of the original DEM spatial extent needs to be recaptured depends on the questions being asked of the data. A focus on areas of change that are causing social concerns may well be misguided if this means that the change is not contextualized against larger scale trends and processes in the catchment. The following examples will highlight what products the DoD was able to produce as a result of the 2011 Lockyer Creek flood.

Example 1. The spatial distribution of erosion and deposition

After the 2011 flood the Lockyer was re-flown to the same spatial extent as previously captured but with a more dense point coverage (>4 pts m^{-2}), this allowed a DoD to be produced with a mean vertical error of +/- 0.067 m and a standard deviation of 0.043 m (Croke *et al.* 2013a). The inundated channel was defined by placing a mask over the area of water where LiDAR could not penetrate, and so excluding it from further volumetric calculations. The channel boundary was the main source of sediment, whereas the areas of flood plain that were inundated contained the greatest volume of deposited sediment. The initial baseline modelling revealed variability in the channel form over the captured extent with changes ranging from confined to unconfined macrochannel (Gupta *et al.* 1999; Croke *et al.* 2013b) to areas with greater connectivity between channel and floodplain. This variability manifested as nine reaches along the Lockyer alternating between flood containing macrochannel and floodplain inundating reaches (Croke *et al.* 2013c). This mapping reveals the variability in sediment routing along the river and an indication of higher and lower risk zones for erosion management. It also suggests the fate of eroded sediment, and any associated nutrients or contaminants. Overall, the LiDAR is a powerful tool for producing sediment budgets.

Example 2. Erosion process determination

The combination of the aerial and LiDAR imagery allowed us to map the position of the mass failures within the Lockyer (Grove *et al.* 2013). The steep backwall of the failures was identified using a 35^{o} slope layer to aid with the delineation of the failures covered by tree canopy. In combination with the DoD and the aerials it was possible to identify the position, morphology and dimensions of mass failures. The failures cut into fresh flood deposits, showing that the collapse occurred on the receding limb of the flood hydrograph. There was no evidence of failure blocks either on the failure floor or in the vicinity of the failures. The morphology was divided three different types: 1) single piping, 2) multiple piping, and 3) sapping failures. These were concluded to be different forms of the wet flow process (Grove *et al.* 2013) resulting from water exfiltrating out of the riverbank as the floodwater receded. The excavated material was entrained and did not accumulate at the toe of the bank.

Once mass failures were defined it was possible to allocate the rest of the erosion to fluvial entrainment, the volume of sediment identified as being scoured by the flow is shown in Figure 2. In terms of planform area only 8% of the riverbank was occupied by mass failures and 33% by fluvial entrainment. The volume of sediment eroded was 695,400 m^3 (41 %) from mass failures and 983,400 m^3 (59 %) from fluvial entrainment. These data allow decisions to be made about what strategies might be used to reduce erosion if it is above an acceptable or target level.

Figure 2. An aerial image of a meander bend from the Lockyer Creek after the 2011 flood. Fluvial entrainment was calculated from differencing the 2010 and 2011 DEM and then highlighted. The darker the colour the greater the volume of erosion in that 1 m^2 pixel. The volume of mass failures has been excluded from the image for clarity.

Example 3. Temporal changes in mass failure spacing and morphology

Multiple time periods of LiDAR allow for the processes of erosion to be determined but also enable morphological changes to be observed in areas that have previously eroded. Questions can be asked about whether failures continue to erode in subsequent flood events, or if mass failures have any spatial organization making them more likely to occur in one region. The effectiveness of management interventions can also be tracked.

The mapping of the existing mass failures in the 2010 Lockyer Creek dataset have been compared with those failures mapped in the 2011 imagery by Thompson *et al.* (2013) (Figure 3). Only 17 % of the failures that occurred after the 2011 floods overlapped with the existing mass failures (Table 1). It is interesting to note that, far from being a source of sediment from the flood, these scallops were a sink of sediment, with material accumulating in them on the flood recession. Failures up to a planform area of 2000 m^2 showed a significant correlation with deposition. This suggests that up to this size the failure is able to form an expansion zone, reducing flow velocities and erosion, and increasing the amount of deposition. The amount of deposition in each scallop after the 2011 event was on average 0.13 m and if this rate continued into the future it would take about 12 events to fill the existing failures. Whilst this constant rate of filling it unlikely it gives an indication of the likely persistence of these failures if the river does not laterally migrate to remove the scar.

Often the management view of riverbank erosion is that once it has started to occur that it will continue into the future. This creates pressure to protect or remediate the eroding sections of riverbank. Landholders often drive this process by demanding that natural resource managers undertake stabilization works when there are signs of erosion. Evidence from the repeat LiDAR suggests that this model of erosion, with failures continuing in the same position, is inappropriate for the wet flows in Lockyer Creek. Spending money to stabilize these features would be a waste of resources.

Table 1. A comparison between mass failures identified along the Lockyer Creek pre and post the 2011 flood.

	Number of Mass Failures	Total Area (m^2)	Average Area (m^2)
Pre-existing (2010 imagery)	234	98,508	421
2011 failures	437	295,350	676
Failures from 2011 that overlap with those from 2010	75	9,040	120

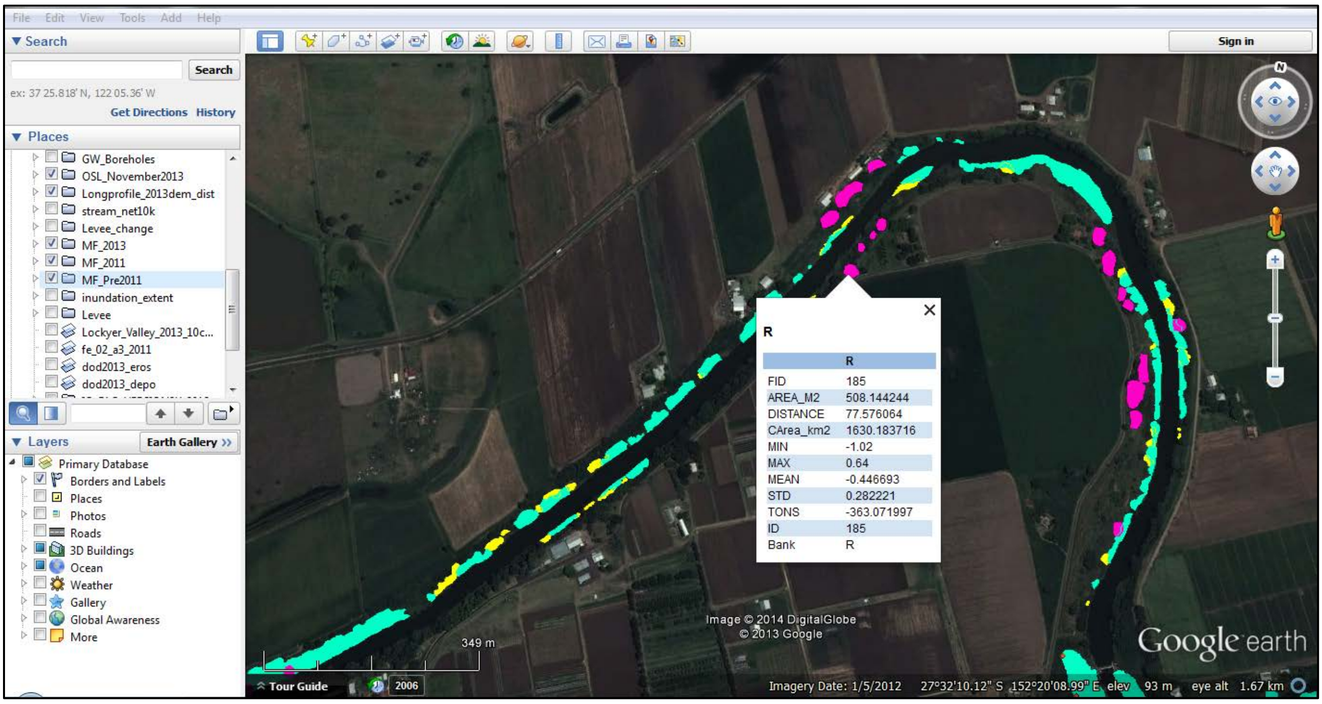

Figure 3. A screen capture of an ARC GIS session showing mass failures from three different flood events on a reach of the Lockyer Creek. The data displayed for an individual failure indicates the spatial position and failure dimensions that can be rapidly acquired for each failure.

Discussion and conclusions

LiDAR and aerial imagery can be commissioned to answer many different questions. It is difficult to justify the collection of such data for a large spatial extent without a clear understanding off the advantages it may provide. The initial justification should be based around the collection of baseline data, in a similar way to an environmental audit. There is a considerable investment of resources needed to make full use of the initial dataset. The temptation is to use the data in a similar way to existing aerial photography and topographic data, filing the data away and using it to visually detect changes in an ad hoc manner. A more structured approach could use the data to delineate features such as the bankfull channel, benches, riverbanks and floodplain. These may not only be used for detecting change in the future but also for current management purposes such as the position of planning zones or the placement of riparian fencing.

Repeating the LiDAR capture and producing a DoD means that data on volumetric change is obtained. This can be a useful management tool as it provides information on the rate, position and processes of change following an extreme flood event. Whilst it could be possible to recapture the previous imagery extent soon after the event in order to maximize the effectiveness of re-flying the LiDAR the flood water must be allowed to recede as much as possible. Depending on climatic conditions this baseflow level might not be reached until several months have passed, which in the case of the Lockyer Creek allowed vegetation growth to obscure aerial photogrammetry. After the data are collected they must then be processed, which introduces another delay before the data can be used. It is evident that that there will be immediate management tasks that must occur subsequent to an extreme flood and before LiDAR will be available as a tool for managers. As a result of the time difference between a flood event and the acquisition of LiDAR and aerial imagery the management steps outlined in Table 2 are suggested.

Understanding the amount, position and processes of change means that the trajectory of channel change can be re-evaluated. Using these patterns of change as a template can provide an indication of where works would be useful in order to manage the system, rather than a band-aid approach that only considers problems in isolation.

Table 2. Examples of the actions that can be taken by managers in the collection and use of LiDAR before, during and after a flood event.

Management Step	Actions
Initial LiDAR data collection	Use the baseline dataset to provide publically available data on the position of geomorphic features and indication of areas that are likely to experience erosion. This can provide an education tool for landholders and manage expectations away from the goal of a stable river system (Florsheim *et al.* 2008).
Allocation of funds for repeat LiDAR	Funding often becomes available after a flood event that damages infrastructure and effects humans. A proportion of this funding should be allocated to the collection of LiDAR and aerial imagery
Collation of field and remotely sensed data	Field data collected subsequent to the flood, such as rapid assessments, surveys and photographs should be georeferenced and added to the baseline DEM and aerial imagery
Acquire 2nd LiDAR and create DoD	Once a DoD has been compiled the areas of erosion and deposition should be delimited, and they should be matched against the expectations of erosion provided by the baseline dataset
Process determination	If the mass failures are large enough, compared to the errors in the DoD, then they should be mapped and their processes described.

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