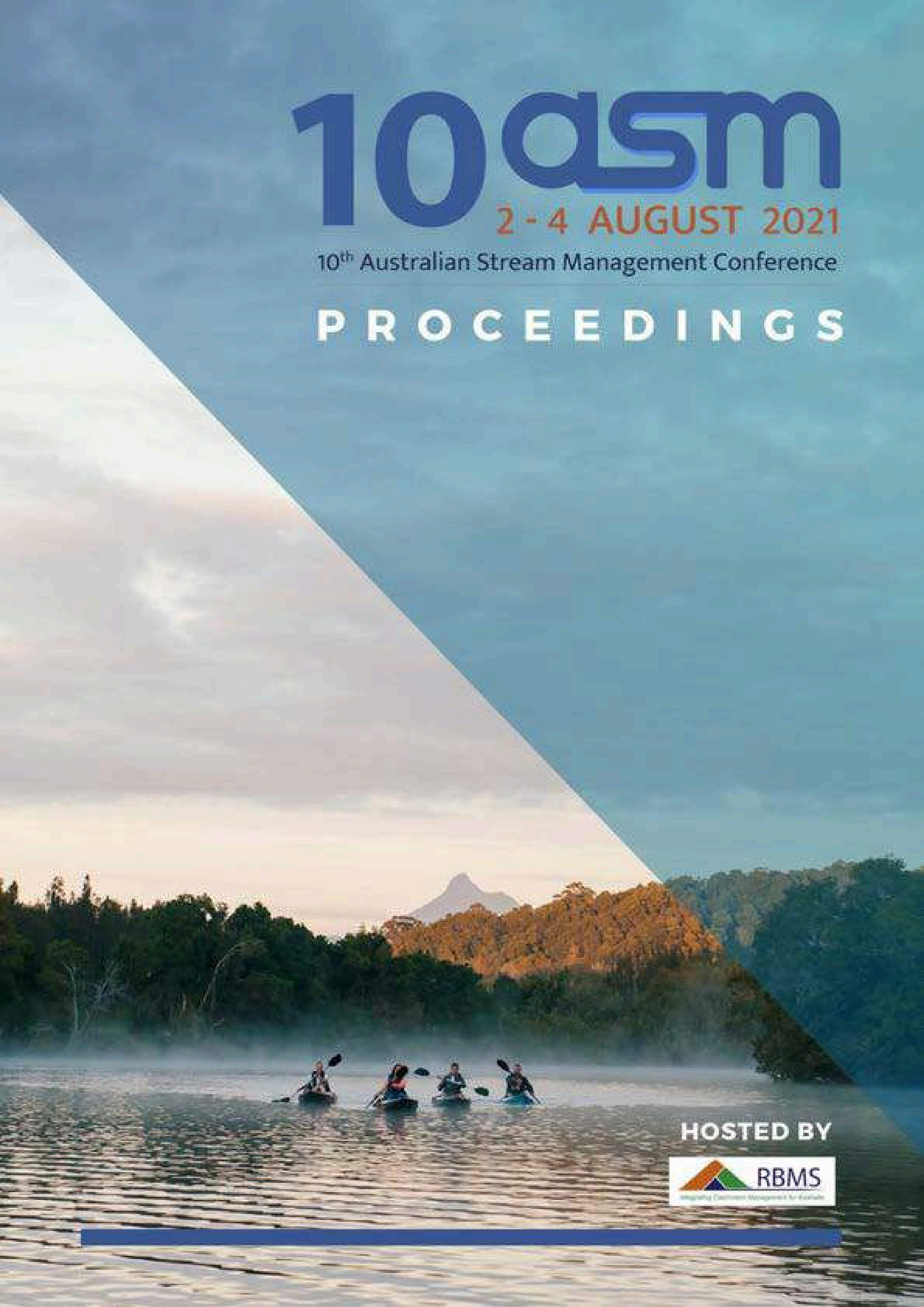

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Integrating Catchment Management for Australia

If there's something strange in your neighborhood: informing management of fluvial erosion and deposition using multiple LiDAR captures?

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Key Points

- River management should include an understanding of river and floodplain geomorphic processes.
- DTMs of Difference (DoDs) can be used to set SMART geomorphic targets.
- Clusters of erosion and deposition allow scoping of large datasets, areas of disturbance to be identified, and rehabilitation efforts tracked.

Abstract

Assessment of a rivers physical form has typically been based on an observation of a single point in time to infer processes, or analyses of discrete cross-sections. The assumption often made is that observed processes will continue, such as riverbank erosion. Management decisions have been based on this assumption. Assessments of condition have also been made without consideration of geomorphic river types, with the channel and floodplain managed separately.

A 10-step process has been devised to guide managers through diagnosing physical form problems and set appropriate objectives. The method scopes a perceived problem, using a basic river typology to consider likely river and floodplain trajectories. To inform on these trajectories an analysis was undertaken on how multiple LiDAR DTMs of Difference (DoDs) can be used to provide data on volumes of erosion/deposition. Regions of clustering in these data were also examined, identifying high volumetric changes that may be management concerns.

A case study on the King River, Victoria showed that a standardized approach should be taken when interpreting LiDAR DoDs. Data can be reported for each time period on the areas, volumes, and rates of erosion/deposition. The total time available, from first to last LiDAR capture, should also be reported. To identify clusters the erosion and deposition data should be considered separately. Rather than setting threshold volumes or rates of change as a trigger for management clustering is a more objective approach.

Future river management needs to include a consideration of volumes of erosion and deposition, with the channel and floodplain combined.

Keywords

LiDAR, DoD, Cluster analysis, Hotspot, Geomorphic objective, River disturbance.

Introduction

Remotely sensed data at scales applicable for whole of catchment management has become readily available creating vast quantities of information for river managers. New techniques are required to make best use of these data so that they are informative. This paper will explore whether spatial variability in erosion and deposition derived from the differences between two Digital Terrain Models (DTM) can be used to highlight where geomorphic problems may exist or show responses to management inventions. Using the analogy of human temperature over time, we know the expected range of variability of this easily measured variable, understanding the periods that extend above and below this range may be diagnostic of a complaint or disease.

Whilst the focus of this paper is how to make use of LiDAR flown over rivers and floodplains to set geomorphic management targets over 100's of kms, the rationale behind why these targets are needed will also be outlined. What is the knowledge gap that exists and why do we need to know this sort of information? A review was undertaken of the existing use of geomorphic objectives and targets in Victoria's ten Catchment Management Authority 2014-2022 Regional Waterway Strategies (RWS) to understand how geomorphology was incorporated (Grove 2018). Whilst there were geomorphological considerations in the strategies, there appeared to be a lack of overt inclusion of river geomorphologic typologies to guide management. A generic approach can lead to misleading or erroneous objectives for the river type. The geomorphic interaction of the channel with its floodplain was also often neglected with a concentration instead on the hydrological connection. There was also a lack of a consistent approach across the regions.

Objectives described for rivers included: (1) A stable system; (2) A channel connected with its floodplain; (3) Reference loads of large wood in the channel; and (4) Resilience to flooding. These were often not Specific, Measurable, Achievable, Realistic and Timely (SMART). For example, what does geomorphic resilience to flooding constitute? Is it a static concrete channel or a channel that can re-establish features after disturbance in a certain timeframe? Without this being articulated it is difficult to determine how resilience can be achieved or monitored? The review (Grove 2018) recommended that the variability in river - floodplain forms and processes across Victoria be better described so that objectives could be set that allow for expected levels of river and floodplain geomorphic dynamism. It would also allow changes because of disturbance and its management to be articulated over planning timeframes of 5-20 years.

This paper will introduce the overall approach to frame geomorphic objectives in Victoria followed by an investigation into using volumes/clusters of sediment movement in the King River, Victoria. Recommendations will be made on how to best report DTMs of Difference (DoDs) to set targets.

An approach to setting physical form objectives and targets in Victoria

This approach for setting management objectives and targets was designed around managing known or perceived physical form issues, rather than identifying where issues may arise across a management area. The latter is seen as a future goal. Ten steps, presented in the form of questions, have been created to help river managers either work through the process or know what to ask of others.

1. What are the physical form values in the reach or catchment, why do you care in the first place?
2. What is the extent of the reach or catchment that is being managed for the value(s)?
3. What are the spatial extents of functional river types currently in the reach?
4. What is the disturbance and management history of the reach and its catchment?
5. What is the trajectory of the value/reach without management?
6. Reassess: are the values and threats in the area of interest the same as initially thought?
7. What is the management strategy: restoration, rehabilitation, remediation, or conservation?
8. What is the long-term management objective: passive or intervention?
9. What is the managed trajectory of the stream, including short-, medium- and long-term outcomes?
10. What are the measurable targets for objectives?

By the end of asking these questions either a set of management objectives and targets can be produced, or the missing pieces of information laid bare.

Geomorphic river-floodplain types used to guide objective setting

An initial set of five river types have been defined for the State of Victoria (Table 1). The types needed to be mappable so that they could be clearly communicated. Confined streams were delineated using the BOM

Geofabric (BOM 2020) MRVBF values >99.9%. For unconfined streams approximate total stream power was calculated based on BOM geofabric attributes of modelled discharge and slope. In the places where LiDAR existed the bed and bankfull widths have been mapped and reported every 25 m. These average bankfull widths over 100 m sections were used to estimate the specific stream power. The stream power ranges could then be used in the broad classification ranges of Nanson and Croke (1992) dividing into high, medium, and low energy types. Anabranching streams were separately classified using the Geofabric ANABRANCH ID.

The Geofabric variables were closer to the current condition than a pre-European settlement condition and so better equate to managing the existing streams rather than setting restoration targets.

Table 1. Five physical form and process references or functional types that could be used on Index of Stream Condition (ISC) streams in Victoria

Functional river types	Specific stream power (Wm^{-2})	Expected riverbank material	Flood resilience (Resistance + Recovery)	Likely proportion of the ISC network	Likely connection with the floodplain	Likely connection with groundwater
1. Confined	N/A	Hillslope/rock	High	Medium	N/A	N/A
2. Unconfined: high energy	> 300	Non-cohesive sediment, gravels and larger	Low	Low	High	Low
3. Unconfined: medium energy	10- 300	Non-cohesive	Medium	Medium	High	High
4. Unconfined: low energy	<10	Gravels-Sands	High	High	Medium	Medium
5. Unconfined: anabranching	<10	Cohesive sediment	High-threshold dependent	Low	Low – threshold dependent	Low

For each of these river types the overall geomorphic setting has been described, common threats articulated, management actions suggested, with targets described that are able to be monitored (Grove 2021). Finally generic geomorphic objectives have been described for Short (1-3 yrs), Medium (4-8 yrs), and Long-term (5-20+ yrs) for the management of different disturbances.

Moving from setting targets with cross-sections to using volumetric change

Historically, river channel change has concentrated on planform change over large reaches. Spatially concentrated repeat cross-sections have allowed the determination of volumetric changes of erosion or deposition over smaller areas, which have been extrapolated for use over larger reaches. With more than one LiDAR capture a DTM of Difference (DoD) can be created by subtracting the elevations, allowing the calculation of volumetric change above the water surface. In areas of repeat LiDAR in Victoria, DoDs have been created that report volumetric change at a m^2 scale with vertical errors of approximately +/- 0.4 m.

The difference in elevations above the waterline can show the extent of erosion or deposition both in area and volume. It is also possible to show where there has been limited or no change, which is important when the channel may appear active with bare banks, but the rates of change are extremely low. The DoD can also be used to investigate where there may be clustering of erosion and deposition. The negative values used to denote volumes of erosion can cluster in cold spots, whilst hotspots result from volumes of deposition. The position of the clusters can be compared against reference conditions for the channel type. For example, we would expect erosion on the outside of a meander bend but not on both sides of a channel, or in the inside of a bend.

Whilst a DoD can be a significant improvement over previous estimates of channel erosion and deposition, current data has allowed reporting to be based around the understanding of one period of change in Victoria. We do not currently have a good indication of how sediment volume fluxes may vary over multiple time periods that may be different lengths or contain varying hydrological conditions. For example, are volumes of change relatively consistent spatially and temporally also can different data processing techniques produce changes greater than the error of the data?

A case study of cluster analysis on the King River, N.E. Victoria

The King River was chosen as it contained overlapping LiDAR data for 2010 (T1), 2014 (T2), and 2018 (T3). Two DoDs were produced showing change over 4-5 year intervals (T1-T2 and T2-T3), and another DoD for the entire time period (T1-T3). Each DoD was clipped by the extent to the banks for the entire time period with the extent of the riverbed removed. This was undertaken so that only the area where erosion and deposition had occurred were considered, excluding areas where the water surface changes could register as volume change. The main processing operations for each DoD were:

1. DoD = most recent DTM – older DTM so that erosion was negative and deposition positive.
2. Clip DoD to the extent of channel changes in that epoch, the widest extent of bankfull in both times.
3. Remove the area occupied by the bed for over both time periods.
4. Reclassify the DoD raster for each dataset into: 1 = erosion, 2 = error (> +/-0.4 m), 3 = deposition.
5. Exclude error from each DoD.

The hydrological data from the King River at Cheshunt gauge showed that although the first LiDAR capture (T1) was taken at the end of the millennium drought there were still winter peaks of over 2 m before T1. The highest stage on record (27/06/1967 – to date) was 3.5 m on the 23rd of September 1998. The 17th and 18th ranked highest daily stages were in the period between T1 and T2 (Figure 1). This suggests the durations of the DoDs should capture a large event in the period between T1 and T2, and then moderate flow events between T2 and T3.

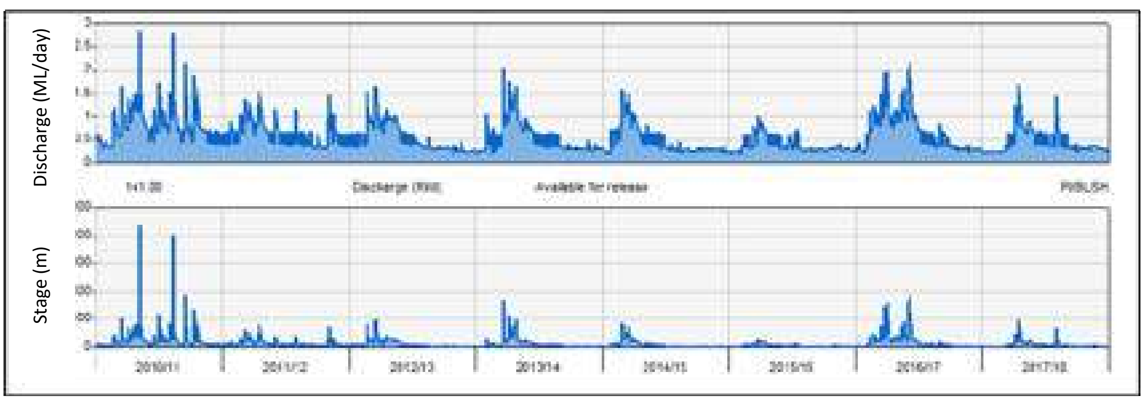

Figure 1. Stream water levels (m) and discharge (ML/day) on the King River at Cheshunt from T1 (03rd May 2010) until T3 (08th April 2018).

Expected geomorphic changes during the LiDAR capture period

The LiDAR extent was over a single river type that would be classified as an unconfined medium energy stream based on the specific stream power of 108 W m-2 (Stout 2017). More specifically in the Nanson and Croke (1992) classification it would be a 'wandering gravel-bed river floodplain', because of the presence of gravels in the channel, abandoned channels on the floodplain and abundant sediment load. The sinuosity in 2010, calculated from ISC3 data, was around 1.48 which put it at the upper end of a sinuous stream and just below that of a sinuosity of 1.5 found in meandering streams.

The erosion and depositional processes for this type of stream were described by Nanson and Croke (1992), these included overbank vertical accretion, minor lateral and abandoned channel accretion. It would be expected that this stream should move laterally after the significant flood event in 2010. The reach should be net erosional with a significant flux of sediment both within and out of the reach. The channel may move to new positions on the floodplain and may even avulse across the floodplain.

In the second DoD epoch (T2-T3) continued adjustment would be expected to occur as there were high flow events. The relative change would be expected to be lower than the first epoch (T1-T2). Net erosion would still be expected. Because of the expected lower rates of change, it may be that there were shorter step lengths for sediment in the reach. This could result in deposition being relatively higher compared to erosion with reworking of previously deposited sediment from epoch 1.

Signs of disturbance include erosion on both banks which may indicate widening, incision or both. Long reaches with little deposition or conversely little erosion would not be expected and straightening, shown by a reduction in sinuosity, or an increased number of channels would also be indicators of geomorphic disturbance.

The method used to determine clusters of volumetric change

The DoD provides volumetric change, and results in a long thin strip of polygons of known areas and volumes of change along the river. Clustering of these polygons may indicate, along with other variables, areas of high erosion or deposition. These clusters may be easier to spatially locate and visualize than trying to determine which parts of the channel have widened significantly or deepened for example.

The determination of clustering was based on the ARCGIS Getis-Ord local statistic. For each polygon of erosion or deposition the volume of change is weighted and compared to its immediate neighbour. In the ARCGIS Hot Spot Analysis tool there is an input field of the 'conceptualization of spatial relationships'. This allows the user to determine how neighbours are dealt with in the analysis. In this trial the fixed distance band was used, this is where neighbours within a certain distance are weighted and outside of this distance they are not. The distance was automatically generated so that each polygon has at least one neighbour. The Euclidean distances generated were in the order of 50 – 150 m.

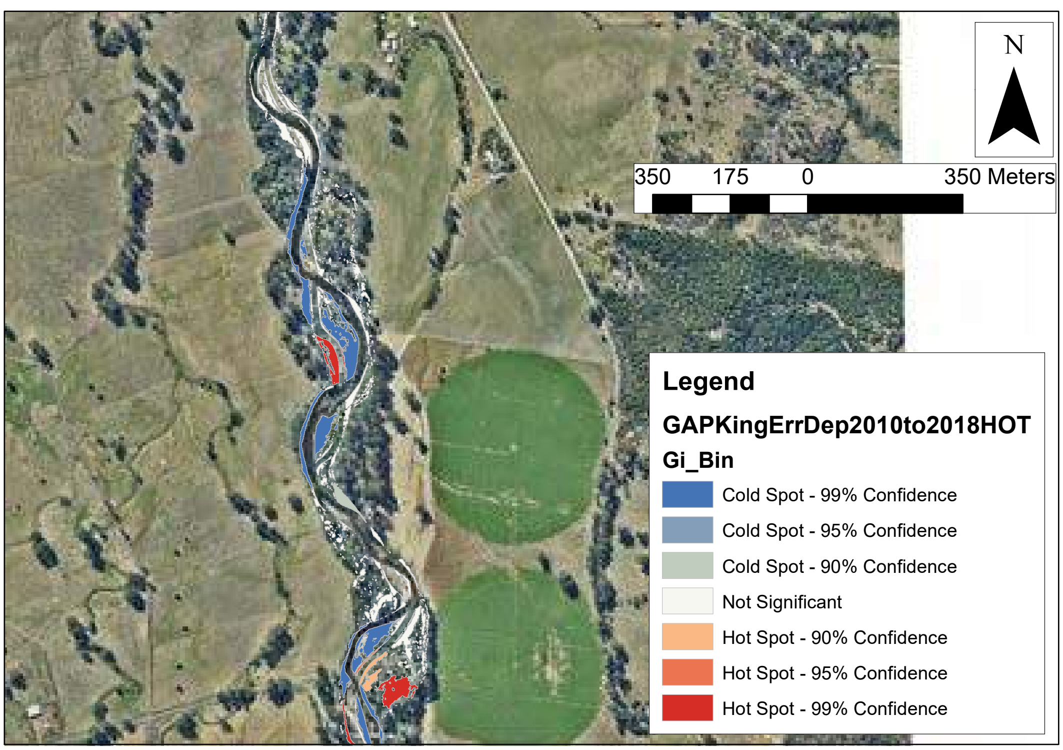

Figure 2. An example of clustering on part the King River showing both hot and cold spots.

Each time the polygon weight/neighbourhood comparison was undertaken it compared the reach average weight against the target and neighbours. This means that the polygon becomes clustered when the neighbourhood of polygons have significantly higher or lower values than the average clustering of the whole sample. Data comparisons will, therefore, be internal to the considered reach for the time period of interest. Therefore, clustering can potentially occur in both low and high flow periods.

When the error was removed from the data and the cluster analysis applied there were hotspots of high values (deposition) and cold spots of negative values (erosion) (Figure 2). Each polygon was attributed a level of statistical confidence that it was part of a cluster. Initially the clustering analysis was performed using the whole dataset of change polygons. This produced hot and cold spots that included values of erosion in hotspots of deposition and vice versa. The inclusion of polygons of deposition in an area of erosion was not considered useful for determining management strategies. Cluster analysis was, therefore, performed separately for each type of volumetric change to see the differences.

The position of clusters would need to be considered relative to the stream type before a decision was made about whether they were a sign of disturbance. We might expect erosion (cold spots) on the outside of meander bends and deposition (hot spots) on the inside of the bed. Whereas erosion on both sides of the channel can often be used as an indicator of poor condition.

Analysis and findings

Contrasting setting a threshold of change vs. clustering

The first question asked was if cluster analysis was needed at all? Setting a threshold volume of erosion was compared to using cluster analysis. The histogram of polygons of erosion was examined between T1-T3. A threshold of >1000 m^3 delineating the tail of the distribution. Those areas that eroded between 2010 and 2018 were clustered with the Getis Ord analysis, and the 99% significant clusters chosen.

Clustering the erosion polygons from T1-T3 produced 99% confidence polygons containing 94,848 m^3 of erosion over an area of 87,818 m^2. If a threshold of 1000 m^3 was used this gave 191,154 m^3 of erosion over 182,459 m^2. This means that clustering was identifying an average depth of -1.08 m m^{-2} of erosion and the threshold setting was giving -1.04 m m^{-2}. The clustering was identifying a smaller area and more polygons with the average the depth of erosion being greater than using an arbitrary threshold.

Comparing two epochs (T1-T2) (T2-T3) to the whole period (T1-T3)

As new DTM datasets become available it is possible to report on the changes between the new data and the last timestep. It is also possible to report the total difference between the oldest and newest dataset. The differences in volume and clustering were examined using different time lengths to see how they may inform on management.

The total planform area of change outside of error (T1-T3) was 569,945 m^2. When undertaking the same calculations for two periods, Epoch 1 had 492,561 m^2 of change and epoch 2 had 387,605 m^2. This means that when the epochs were considered separately there was 310,221 m^2 (54 %) more than when considering the whole period DoD (T1-T3). There was clearly erosion and deposition overlap in the two epochs making the total area of change not equal to the sum of the two component epochs.

The same was not true for the total volume of change where the two epochs are only just greater than the whole period. The whole period (T1 – T3) was -304,402 m^3 compared to -309,640 m^3, the sum of Epoch 1 (-131,833 m^3) and Epoch 2 (-177,807 m^3). This was unexpected at the prediction had been that the channel change would have been greater in Epoch 1 because of the high flow in Epoch 1.

The percentage of erosion to deposition in the total volume of sediment moved changes over time and suggests that Epoch 1 deposited sediment that was later mobilized in Epoch2. Epoch 1 had 67 % erosion and 33 % deposition, Epoch 2 had 82 % erosion and 18 % deposition. The ratio of erosion to deposition for the whole period (T1-T3) was 82 % erosion to 18 % deposition. The results indicate that finer detail may be gained from reporting each timestep individually but information for the whole period can inform on gross changes to the system.

The 99 % confidence erosion cold spots for the whole period were relatively consistent in volume to the combination of epoch 1 and 2. The same is true of the 99 % cold spots of deposition. This means that despite the different relative proportions of erosion and deposition over time the clustering is consistently identifying significantly high-volume areas of change.

Comparing including or excluding gaps in the bed (T1-T3)

The King River was laterally mobile. This means that the process of removing the water surface in each time step can leave gaps in the channel if the channel has moved outside of the original riverbed position. These gaps can be removed, losing data, or they can be left in the data. The effect of these options has been investigated on the production of hot and cold spots.

During the total time period (T1 – T3) the area of change excluding error was 592,475 m^2 with gaps included and 569,945 m^2 with them excluded, a 4 % increase with gaps included. A slightly higher volumetric change occurred with a 6 % increase when the gaps were included, going from -304,402 m^3 to 323,047 m^3. These relatively small changes meant that the ratio of erosion to deposition stayed consistent with both methods as did the average depths of change.

The clustering analysis did show greater differences with the 99 % significant cold spots reducing by 11 polygons and the volume or erosion increasing from -75,060 m^3 to -188,294 m^3. This 251 % volume increase suggests that including more bed enables the clustering analysis to identify more regions of high erosion. However, the same was not true for deposition. This may be because of the more confined spatial extent of erosion, such as a thin strip along the outside of the meander bend. This would make it more sensitive to the distance and volume of changes in surrounding polygons.

Modelling management intervention on cold spots

The cluster analysis has the potential to reveal where management interventions may be required. However, it was unknown if they could be specifically used to derive a management target at the 10 -100 km reach scale rather than at a specific work site. One potential target was a reduction in the number and/or volume of highly significant clusters in disturbed streams as the volume changes become more evenly distributed across the reach. To investigate this the epoch 1 (T1-T2) cluster analysis of erosion only was compared with the epoch 2 (T2-T3) cold spots with and without an example of management.

The hypothetical management was modelled by removing 45 large polygons of erosion in the second epoch that would be likely management candidates. These includes erosion on point bars and areas where there was erosion on both banks. It was assumed management had occurred after T2 and successful before T3.

In the management simulation the eroded area in epoch 2 was reduced by 45 polygons, an area of 16,130 m^2 and volume of 12,359 m^3. The clustering result was a decrease of 31 cold spots with the largest difference in the 95 % significance polygons.

The combined volume of erosion in the 99, 95 and 90 % significance polygons reduced by 3,533 m^3 when management was included in epoch 2, this is much less than the 12,359 m^3 removed. The anticipated shift in the relative volumes in different significance clusters in the managed vs unmanaged cases did not occur. The high volume and 17,189 polygons of erosion over the reach mean that targeted interventions may not yield a large change relative to the whole population volume.

A more laborious, but realistic and informative, approach would be to highlight those clusters that were in positions showing degradation such as incision. The clusters would be used to compare pre and post management. Another alternative is if the management is less diffuse over the reach, concentrating on an area of high erosion or deposition, then the reach length could be shortened for the analysis of change.

Conclusions

Understanding the geomorphic type and disturbance history of a river and its floodplain provides a much clearer context for setting management objectives. Whilst the terms stability and resilience have often been used to describe management objectives a more detailed set of measurable targets need to be included to allow effective management. LiDAR based DoDs allow the areas and volumes of erosion and deposition to be calculated over 100's of kilometres and these data can be used in target setting.

The analysis of volumes of change over time on the King River showed that: (1) The reach was net erosional during both epochs, (2) There was only slightly less erosion in epoch 2 than in epoch 1, and (3) The volume of deposition in epoch 1 was over half that compared to epoch 2. This information can be used to gauge the overall character of the stream, refining expectations and objectives.

The processing of the DoDs can be undertaken in many ways, it is recommended are that:

1. The stream type should be the same and for a distance long enough to provide a large population of polygons over varying processes. In a meandering river several meander bends should be included.
2. DoDs should be created for the both the shortest time interval and longest time interval available from the LiDAR DTMs, providing both detail and information on overall changes.
3. The maximum extent of the bed and banks should be delineated for the time period of interest, and the minimum amount of the bed be extracted from the merged bankfull polygon.
4. Polygons should be created from volumetric change outside DoD error using the automated process with no modification of size or shape. This maintains consistency and maximises available data.
5. Clustering analyses should be used rather than defining an area or volumetric threshold of concern.
6. Data should be analysed split into a dataset of erosion and one of deposition.

The clustering approach allows for a quicker scan of large datasets to scope likely issues. However, it should be combined with an initial understanding of the stream type to consider where clustering would be expected. Modelled management interventions at a number of high erosion locations did reduce the number of highly significant cold spots. It did not, however, decrease the volume of significant clusters. A reduction in significant cluster volumes may be a better target when management includes long reaches, compared to the total reach length, of interventions such as fencing and revegetation.

Acknowledgments

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