

INCISION toolbox for the delineation and analysis of incised features within LiDAR data

K. Roots 

*Department of Environment and Science, Queensland State Government, Brisbane, QLD, Australia
Email: Kevin.Roots@des.qld.gov.au*

Abstract: Fine sediments from terrestrial erosion processes pose a major threat to the Great Barrier Reef lagoon and associated coastal ecosystems. An understanding of the spatial and temporal variability of sediment yield from these eroding systems is crucial to their management. The Queensland Government Paddock to Reef Catchment Modelling program was developed to measure and report on progress towards the water quality targets set out in the Reef 2050 Water Quality Improvement Plan. However, while there have been significant improvements in the spatial data inputs for gully erosion, there are still major uncertainties within this modelling program in relation to current sediment yields from gully erosion.

The INCISION toolbox was developed for the automated extraction of geomorphological data from aerial LiDAR data to help validate and improve the accuracy of the modelling inputs. The INCISION toolbox consists of a series of modules, each with a specific landscape analysis focus. The final outputs from the INCISION processing include polygons delineating the boundaries of incised features (gullies and streams) within the landscape, and a raster dataset depicting the depth of each pixel of the DEM within the demarcated incision zones. The comparison of the depth and incision boundary datasets extracted from LiDAR during different temporal periods allows for the quantification of sediment yield per area over time and the identification of erosion hotspots. The INCISION toolbox also allows for the autonomous extraction of cross-sectional data from the incised features, with outputs including cross-sectional area, hydraulic radius, and slope of drainage line where the channel thalweg intersects the transect. Multitemporal analysis of cross-sectional data allows for the quantification of the rates of lateral expansion of channels.

While the primary aim of the INCISION toolbox is the extraction of data pertaining to static dimensions and patterns of change that have already occurred, it is envisioned that multivariant analysis of the derived products may allow for the development of LiDAR-based tools for the predictive modelling of future erosion rates and erosion hot spots within Great Barrier Reef catchments.

Keywords: *Gully erosion, Great Barrier Reef, sediment transport, LiDAR, sediment*

1. INTRODUCTION

Fine sediments from terrestrial erosion processes pose a major threat to the Great Barrier Reef (GBR) and associated coastal ecosystems (Waterhouse et al., 2017) with active gullies identified as a primary sediment source (Wilkinson et al., 2013, Wilkinson et al., 2018, McCloskey et al., 2021). Gullies are known to increase the hydrological connectivity of a landscape, providing an effective link for the transfer of sediments from upland areas to the lower parts of a catchment (Poesen et al., 2003). Climate change related increases in rainfall intensity (Polade et al., 2014) are likely to exacerbate the deleterious impacts of gully erosion (Vanmaercke et al., 2016).

The key to effective management and remediation of eroding landscapes is the appropriate prioritisation of investment (Lu et al., 2001). Rust and Star (2018) identified the volume of sediment yield as being a fundamental metric for the prioritisation of gully remediation effort, while Betts et al. (2003) emphasise the importance of understanding the spatial and temporal variability of gully development. Bartley et al. (2017) identified a clear need for the current Government initiative to evaluate the most cost-effective methods for gully erosion mitigation.

There has been considerable investment from both the Queensland and Australian Government in addressing gully erosion across GBR catchments. The Queensland and Australian Government's Paddock to Reef Integrated Monitoring, Modelling and Reporting (P2R) program was developed to measure and report on progress towards water quality targets set out in the Reef 2050 Water Quality Improvement Plan (State of Queensland, 2018). As identified by Prosser (2018) there have been significant improvements in the modelling program spatial data inputs for gully erosion, however there are still major uncertainties within this modelling program in relation to current sediment yields from gully erosion.

The ever-increasing availability of aerial Light Detection and Ranging (LiDAR) datasets across GBR catchments will help to address some of these data limitations. However, the extraction of meaningful information from this LiDAR data requires significant processing and analysis. Given the sheer spatial extent of the focus area, there is a clear need for an autonomous system of LiDAR analysis that can extract the desired information from large expanses of aerial LiDAR data, with minimal requirement for manual intervention.

The INCISION toolbox was developed for the automated extraction of geomorphological data from aerial LiDAR data to help validate and improve the accuracy of the current P2R Catchment Modelling Program. INCISION was designed for the ESRI ArcMap platform, with the deliberate intention of building a tool that could be used by other users without the requirement for additional plugins or customised software. Written using ESRI ModelBuilder visual programming language, the INCISION toolbox consists of a series of modules, each with a specific landscape analysis focus.

The key deliverables from the primary modules within the INCISION toolbox include:

- Polygons delineating the breakdown of the DEM into landscape units: hillslope, colluvial/deposition, alluvial, and major drainage channels
- Mapping of infrastructure including roads, contour banks and dams
- Polygons delineating the soft and hard (depth > 0.3m) margins of incised landscape features
- Rasters representing the modelled depth of each delineated incision feature

The cross-section module allows for the iterative extraction of cross-sectional data (including width, cross-sectional area, wetted perimeter, hydraulic radius, and slope of the intersecting drainage line) for any number of transects positioned throughout the LiDAR scene.

Where multitemporal LiDAR scenes are available, the INCISION toolbox allows for the calculation of sediment yield and the identification of erosion hotspots.

It is envisioned that multivariate analysis of the derived products may also allow for the further development of LiDAR-based tools for the predictive modelling of future erosion rates and erosion hotspots.

2. STUDY AREA

Preliminary tests of the INCISION toolbox were undertaken over a 1775 km² area of land about 60km west of Rockhampton, Queensland. This site encompasses a complete overlap of LiDAR from 2008 and 2015. The site includes a wide variance of topography including steep mountains, alluvial flats and major river channels. The region encapsulated within the study area contains numerous active gullies in sodic soils and has been identified as a significant source of fine sediment entering the GBR.

3. METHOD

Each INCISION module contains multiple tools linked together within the ESRI ArcMAP ModelBuilder interface. Raster analysis functions used throughout the toolbox were primarily undertaken using Map Algebra within Raster Calculator.

The INCISION modules were designed to run in the following sequence:

1. Preliminary DEM construction and clipping
2. Infrastructure mapping and masking
3. Landscape classification
4. Delineation of incised landscape features
5. Cross -section data extraction
6. Multi-temporal analysis (including sediment yield and erosion hotspot identification)

3.1. Preliminary DEM construction and clipping

The INCISION toolbox contains a preliminary *DEM Prep* module which uses *Natural Neighbor* interpolation to convert pre-classified *.las* files to a DEM. In this study, DEMs were constructed from LiDAR captured in 2008 and 2015. The DEM clipping process in the *DEM prep* module passes each input DEM through a cell statistics function to filter out all areas of the DEMs outside the zone of overlap. The overlapped DEMs were subdivided into three sections (along logical catchment boundaries) to prevent software crashes associated with exceeded memory capacity during the subsequent analyses and processing. Previous testing indicates that memory issues tend to develop when processing DEM extents exceeding 800 to 900 km², although this limitation might be specific to the processing machine and/or associated licence server speeds.

3.2. Infrastructure mapping and masking

Infrastructure such as roads, contour/diversion banks, dams, and mine/quarry sites were identified and masked to exclude these features the subsequent DEM analyses.

Road and tracks polylines were derived from the *Baseline Roads and Tracks* datasets extracted from QSpatial (State of Queensland, 2023a) and manually edited to ensure they were spatially congruent to the formed roads evident in the hillshade LiDAR DEM. The World Imagery basemap (available as a free image basemap within ArcMap) was also used as an aid in this process.

Contour and diversion banks were detected through the construction of a Topographic Projection Index (TPI) raster (Weiss 2001). In this step, a smoothing filter was applied to the DEM to convert the elevation value for each cell to the mean elevation value of all cells within a 3 m radius. Subtracting the smoothed DEM from the original DEM provides the TPI values. TPI values greater than 1 standard deviation from the mean are used to indicate raised topography such as mounded embankments or ridges. *Raster calculator* was used to identify areas of zero flow accumulation and with a TPI value > 1 standard deviation of the TPI mean, with these identified zones then being converted to polygons. When displayed in bright colours against the hillshaded DEM, these potential contour/diversion bank polygons allowed for a quick visual confirmation of their accuracy.

Dams were identified through the digital filling of hydrological sinks in the DEM surface (Mark 1988). The difference in elevation values between the pixels in the original DEM and that of the DEM with filled sinks provided a measure of the depth of each depression. Sinks with a depth > 0.3m and surface area > 100 m² were classified as *Potential Dams* and converted to polygons. These polygons were manually (visually) assessed at a later stage to confirm the validity of the dam classification.

Active mine and quarry sites were identified through desktop analysis using the *1999 to 2017 Land use mapping* dataset (State of Queensland, 2023b).

3.3. Landscape classification

3.3.1 River channels

The Landscape classification process starts with the identification and mapping of the major river channels. Achieving this objective necessitated the construction of a *Relative Height Model* (RHM) modified from Zhang et al., (2020). In this process, the DEM is passed through a focal statistics filter, determining for each cell the minimum elevation value for all cells within a radius equal to the half the distance of the maximum width of river channel present within the LiDAR scene. This statistical filtration process was then repeated to derive the

range of elevation values within this moving pixel window. The outputs from these processes were then used to generate the RHM raster where:

$$RHM = \frac{DEM - \text{Minimum elevation value within moving filter window}}{\text{Range of elevation values within moving filter window}}$$

The RHM raster shows the local fluctuations in the topography whilst detrending the gradual transitions in elevation across the catchments. Any cells with an RHM value < 0.1 were classified as channel beds and were converted to polygons for manual inspection. Only those polygons matching the beds of active channels were retained.

3.3.2 Hillslope, colluvial, and alluvial zones

Hills were classified based on their elevation relative to the surrounding landscape. A combination of *raster calculator* and *cell statistics* tools were used to generate a raster showing all cells outside the RHM Channels layer with Slope $< 5^\circ$. The inverse of the RHM raster was then used to filter out any of the identified low slope pixels from ridgelines and mountain peaks. A series of *zonal statistics* processes were then applied to the remaining low slope cells to establish their relative elevation values. The object of these processes was to retain only cells in lowland, low slope areas. These cells were aggregated into regions of lowland zone and converted to polygons.

A random feature generator was then used to generate points at 50 m spacings within these lowland, low slope polygons. These random points were then assigned the elevation values of the underlying DEM pixels, with *Natural Neighbor* interpolation then applied to create a *Relative Elevation Threshold* (RET) raster surface intersecting all points.

Non-lowland classification was ascribed to any parts of the DEM with an elevation value more than 10 m above the RET, or between 5 and 10 m above the RET and with a Slope value $> 10^\circ$. Non-lowland areas were subsequently reclassified to Hill or Colluvial, depending on their slope and relative position in the landscape. The Colluvial classification was given to low slope ($< 10^\circ$) areas immediately adjacent to the defined Hillslope zones, or within areas of low slope within valleys surrounded by hills.

The Alluvial classification was given, by default, to any areas of terrain between the Hills/colluvial and Channel zones. These defined landscape divisions are used to classify the incision boundary outputs from Section 3.4 as alluvial, colluvial or hillslope incision features.

3.4. INCISION mapping

3.4.1 Hydrologically connected TPI depressions

Incised landscape features (gullies and defined waterways) were delineated via a multi-step process starting with the identification of hydrologically connected depressions within the DEM.

Surface flow drainage lines were modelled with *Flow Direction* (D8 algorithm) and *Flow Accumulation* tools applied to the depression-less (filled sink) DEM described in Section 3.2. Cells with flow accumulation values > 1000 were exported to a new raster and converted to drainage polylines.

Depressions in the DEM were identified through *Raster Calculator* analysis of the TPI raster described in Section 3.2. All cells with an elevation value $< (-0.5 \times \text{the standard deviation of the TPI mean})$ were classified as being depressed relative to the surrounding landscape. These identified zones of depression were then filtered out to include only those within 5m of the surface flow drainage lines.

3.4.2 Shadow modelling

Breaklines in the terrain surface were identified through modelling the spatial distribution of shadows under different scenarios of digital illumination in a technique modified from Yang *et al.* (2017). The *Hillshade* tool was applied to the DEM from all cardinal directions (N, NE, E, SE, S, SW, W, NW) at 25° of altitude. The *Raster Calculator* tool was used to identify and select cells in the DEM that were in shadow whilst having an aspect within 180° of the direction of illumination. Cells were deemed in shadow if they exhibited a modelled shadow value of less than 50, out of a scale ranging from 0 (completely dark) to 255 (fully illuminated). The determination of the aspect of each cell was crucial to ensure that the shadow from (for example) a high creek bank or rock outcrop, was not obscuring the breakline on the opposite bank.

A series of proximity searches were then undertaken to select all shadow cells that were in spatial proximity to the hydrologically connected TPI cells in Section 3.4.1. All other shadow cells were discarded. Similarly, hydrologically connected TPI cells from Section 3.4.1 which were not in spatial proximity to the shadow cells

were also filtered out. The retained TPI and shadow cells were then merged to form a dataset comprising shadow-determined breaklines in association with hydrologically linked depressions. These features were then aggregated into distinct clusters after an iteration of positive and negative buffering to remove gaps of non-data (for example where a cattle ramp had intersected an otherwise steep stream bank, causing a break in the shadow-derived breakline).

3.4.3 Identification of remnant islands

The *Eliminate Polygons* tool was applied to the outputs of Section 3.4.2 to generate the outermost extent of each cluster of polygons. This dataset forms the outer boundary of the soft margin outlined in 3.4.4. However, some of the internal polygons dissolved into this outer extent boundary were artifacts of the shadowing process described in Section 3.4.2 and were caused by remnant pedestals or islands within the channel of the incised features. Such remnant islands play a vital role in the construction of the interpolated pre-incision surface cap (Section 3.4.4). An iterative zonal statistics filtering process was then run where the maximum elevation of each of these polygons were compared to the lowest elevation of the surrounding landscape outside of the defined incision boundary. Polygons exhibiting a maximum depth greater than the lowest elevation of the surrounding landscape outside of the defined incision boundary were classified as “remnant” and were merged into the soft incision margin dataset.

3.4.4 Soft and hard incision margins

The final outputs from 3.4.3 comprise the soft margin of the incision boundary. In a similar process to that used in Section 3.4.2, the vertices of the soft margin polygons were assigned the elevation values of the underlying DEM pixels. *Natural Neighbor* interpolation was then applied to these elevation points to construct a raster representing the modelled pre-incision surface.

The difference in elevation between this interpolated pre-incision surface and the original underlying DEM provides the measure of incision depth for each cell of the DEM within the area bounded by the delineated incision boundary polygons. The outermost extent of all cells exhibiting a depth greater or equal to 0.3 m provides the hard margin of the delineated incisions. The depth threshold value of 0.3m was based on the gully definition of McDonald *et al.* (1990). A final filtering process was applied to these delineated boundary outputs to exclude any incisions that did not exceed 0.3m in depth and/or exceed (in any point of their entirety) a maximum slope of 25 degrees. The 25 degrees slope threshold was based on field observations of walls slopes associated with gullies and streambanks and was implemented to remove features such as shallow linear gilgai and non-incised drainage depressions from the final outputs.

3.5. Cross sectional data

Cross-sectional analysis requires the input of transects manually positioned over the delineated incisions across the DEM. In a series of iterative autonomous processes, these lines of transect are clipped to both the hard and soft margins and used to extract the cross-sectional area, maximum and mean depth, wetted perimeter, hydraulic radius, and slope of thalweg.

3.6. Sediment yield and hotspot analysis

The volume of the void space within each mapped incision or incision subsection is calculated as the volumetric difference (using *Cut/Fill* analysis) between the DEM and the modelled pre-incision surface. Sediment yield is calculated as the difference in the volume of the respective void spaces between each temporal period of LiDAR capture. Erosion hotspot analysis is undertaken via the *Focal Statistics* tool whereby the value of each output raster is the sum of the total volume of sediment yield within a 50 metre radius. When displayed as a semi-transparent layer over the original hillshaded DEM, this raster allows for the visual display of erosion hotspots (Figure 1(d)).

4. RESULTS

The following images provide an indication of the type of outputs generated by the INCISION toolbox. Figure 1(a) shows an example of the hard and soft margins of the delineated incised landscape features. The red polygons indicate the soft margins, with the black polygons indicating the hard margins where the depth of the incision (relative to the interpolated pre-incision surface) exceeds 0.3m. Note the linear depression features evident within the DEM that have not been mapped. Whilst these features were picked up during the TPI and multi-directional hillshading processes, they were autonomously excluded from the final mapped outputs because they did not meet the minimum slope and/or depth parameters defined in section 3.4.4.

Figure 1(b) provides an example of the volumetric calculations derived from the difference between the DEM and the interpolated pre-incision cap.

Figure 1(c) shows the outputs from the landscape classification and infrastructure mapping processes. The red polylines indicate the location of earthworks including contour and diversion banks and dam walls. The blue polygons are dams, while the orange and yellow polygons indicate the areas defined as hill and colluvial zones. Figure 1(d) shows an erosional hotspot analysis map, derived from the multitemporal analysis of sediment yield within the delineated incision areas. In this image, red indicates high erosional activity.

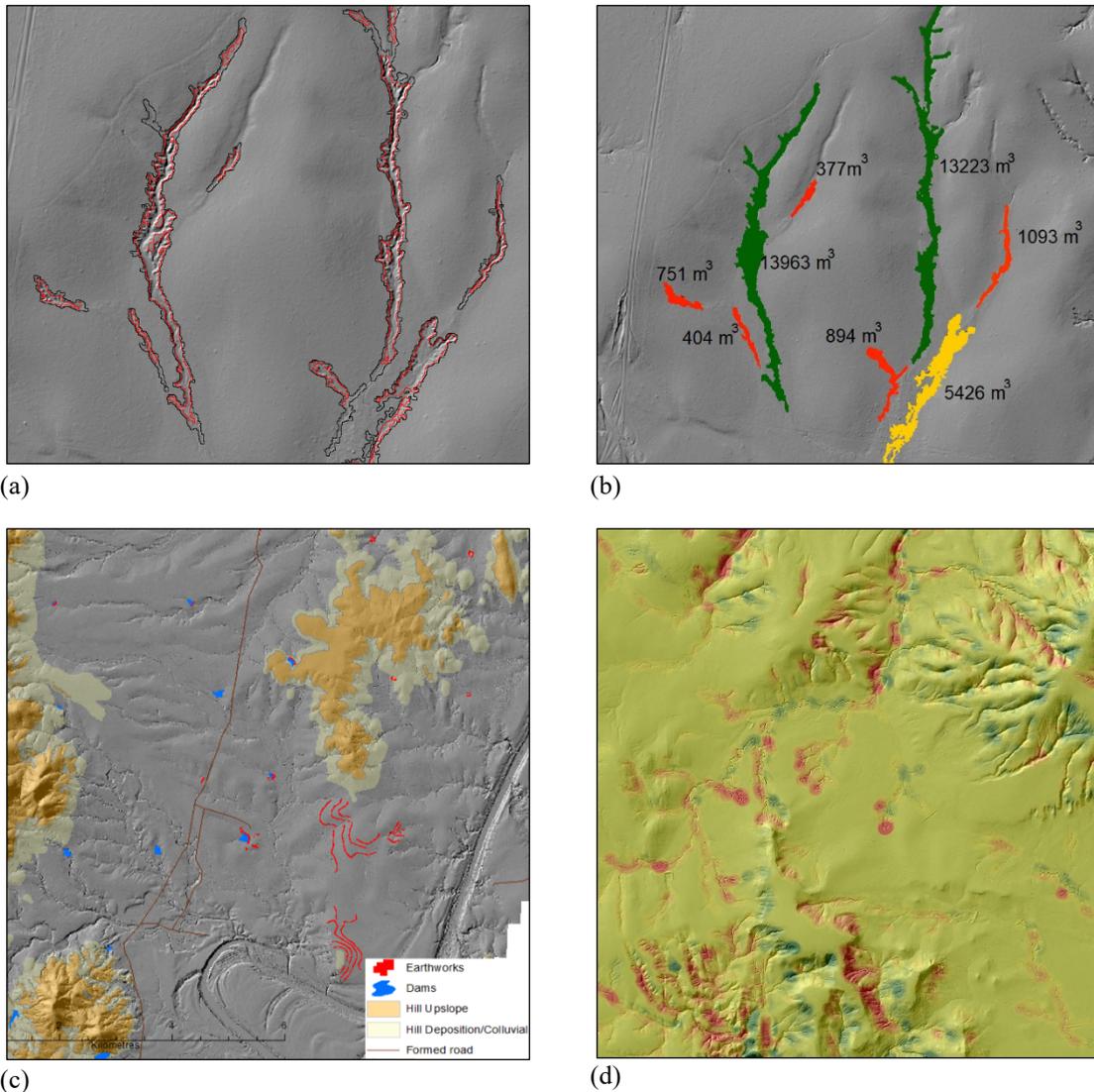


Figure 1. (a) Delineated hard and soft incision margins, (b) static volumes of mapped incisions (soft margins); (c) landscape classification and infrastructure mapping; and (d) hotspot analysis of multitemporal sediment yield

5. DISCUSSION AND CONCLUSION

Preliminary on-ground validation of the INCISION Toolbox outputs suggest it is effective for the delineation of incised features in the landscape, and for measuring other patterns and phenomenon related to gully and streambank erosion.

The decision to write the tool within ESRI ModelBuilder has advantages and disadvantages. The main advantage of this platform is the ubiquitousness of ESRI software within the field of spatial data analysis. The INCISION toolbox is therefore theoretically transferable between users, without the need for additional customised software or plug-ins. However, given the inherent complexity of landscape analysis, the INCISION

toolbox has evolved into a far more unwieldy product than was originally foreseen. Over time, some of the major processes may be migrated out of the ModelBuilder Visual Programming Language to a pure Python environment. The visual nature of the current platform however facilitates the evolution of new modules for the toolbox, especially by developers who do not have a traditional programming background.

Overall, the INCISION toolbox achieves everything it was designed to do. As the extent of LiDAR coverage across the GBR catchment increases, so does the need for a mechanism by which this LiDAR data can be processed and analysed. It is unlikely there will ever be a one-size-fits-all LiDAR analysis package out there; however, the INCISION toolbox is a very workable solution for the Queensland Government Paddock to Reef Catchment Modelling program.

REFERENCES

- Bartley, R., Hawdon, A., Henderson, A., Wilkinson, S., Goodwin, N., Abbott, B., Telfer, D. 2017. Quantifying the effectiveness of gully remediation on off-site water quality: preliminary results from demonstration sites in the Burdekin catchment. NESP Project, 2.
- Betts, H.D., Trustrum, N.A., Rose, R.C.D. 2003. Geomorphic changes in a complex gully system measured from sequential digital elevation models, and implications for management. *Earth Surface Processes and Landforms: The Journal of the British Geomorphological Research Group*, 28, 1043-1058.
- Lu, H., Gallant, J., Prosser, I.P., Moran, C., Priestley, G. 2001. Prediction of sheet and rill erosion over the Australian continent, incorporating monthly soil loss distribution. Land and Water Technical Report. CSIRO, Canberra, Australia.
- Mark, D.M. 1988. Network Models in Geomorphology. *Modelling Geomorphological Systems*, ed. M/G. Anderson. New York: John Wiley. 73-97
- McCloskey, G., Baheerathan, R., Dougall, C., Ellis, R., Bennett, F., Waters, D., Darr, S., Fentie, B., Hateley, L., Askildsen, M. 2021. Modelled estimates of fine sediment and particulate nutrients delivered from the Great Barrier Reef catchments. *Marine pollution bulletin*, 165, 112163.
- McDonald, R.C., Isbell, R.F., Speight, J.G., Walker, J., Hopkins, M.S. 1990. Australian Soil and Land Survey Inkata Press Melbourne.
- Poesen, J., Nachtergaele, J., Verstraeten, G., Valentin, C. 2003. Gully erosion and environmental change: importance and research needs. *Catena*, 50, 91-133.
- Polade, S., Pierce, D., Cayan, D., Gershunov, A., Dettinger, M. 2014. The key role of dry days in changing regional climate and precipitation regimes, *Sci. Rep.*, 4, 4364.
- Prosser, I.P. 2018. Improving how gully erosion and river sediment transport processes are represented in Queensland catchment models. Report to Queensland Water Modelling Network, Department of Environment and Science. State of Queensland, 2018. Reef 2050 Water Quality Improvement Plan 2017-2022, <https://www.reefplan.qld.gov.au/water-quality-and-the-reef/the-plan>
- State of Queensland (Department of Resources) 2023a. Queensland roads and tracks <http://qldspatial.information.qld.gov.au/catalogue>
- State of Queensland (Department of Environment and Science) 2023b. Land use mapping 1999 to 2017, <http://qldspatial.information.qld.gov.au/catalogue>
- Rust, S., Star, M. 2018. The cost effectiveness of remediating erosion gullies: a case study in the Fitzroy. *Australasian Journal of Environmental Management*, 25, 233-247.
- Vanmaercke, M., Poesen, J., van Mele, B., Demuzere, M., Bruynseels, A., Golosov, V., et al. 2016. How fast do gully headcuts retreat? *Earth-Science Reviews*, 154, 336-355.
- Waterhouse, J., Brodie, J., Tracey, D., Smith, R., Vandergragt, M., Collier, C., Petus, C., Baird, M., Kroon, F., Mann, R. 2017. 2017 Scientific Consensus Statement: land use impacts on the Great Barrier Reef water quality and ecosystem condition, Chapter 3: the risk from anthropogenic pollutants to Great Barrier Reef coastal and marine ecosystems.
- Weiss, A. 2001. Topographic Position and Landforms Analysis, The Nature Conservancy. Accessed Feb/2020
- Wilkinson, S., Hancock, G., Bartley, R., Hawdon, A., Keen, R. 2013. Using sediment tracing to assess processes and spatial patterns of erosion in grazed rangelands, Burdekin River basin, Australia. *Agriculture, Ecosystems & Environment*, 180, 90-102.
- Wilkinson, S.N., Kinsey-Henderson, A.E., Hawdon, A.A., Hairsine, P.B., Bartley, R., Baker, B. 2018. Grazing impacts on gully dynamics indicate approaches for gully erosion control in northeast Australia. *Earth Surface Processes and Landforms*, 43, 1711-1725
- Yang, X., Li, M., Na, J., Liu, K., 2017. Gully boundary extraction based on multidirectional hill-shading from high-resolution DEMs. *Transactions in GIS*, 21(6), pp.1204-1216
- Zhang, S., Ma, Y., Chen, F., Liu, J., Chen, F., Lu, S., Jiang, L., Li, D., 2020 A new method for supporting interpretation of paleochannels in a large scale -Detrended Digital Elevation Model Interpretation *Geomorphology*, 369.