Tracing shallow lateral preferential pathways of fluid movement using electrical geophysics

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SUMMARY

Assessment of gullies is essential in understanding the effects soil erosion has on resource management, urban planning, agricultural productivity and local environmental conditions. Commonly, prediction of gully head cut retreat has been disregarded due to the inherent complexities; this study proposes a method of analysing data to interpret potential pathways of Gully retreat. Through the implementation of electrical geophysics (Electrical Resistivity Imaging & Frequency Domain Electromagnetics) surveys positioned uphill of existing gullies shallow conductor's representative of Lateral Preferential Pathways (LPP) will be detected. ERI results detected conductors uphill of the head cut at varying distances showing resistivity values of 1-40 Ωm; these identified anomalous zones were confidently linked to form an LPP. Integrated geophysical datasets were generated allowing for interpreted traces of LPP to be drawn which are representative of the future pathway of head cut retreat. Through comparing currently existing gully assessment techniques it is suggested that a combination of geophysical prediction of LPP and LiDAR data is necessary for a complete understanding of existing gullies. Based on the results of this integration, informed and targeted management decisions can be developed to remediate current landforms and mitigate future gullying.

INTRODUCTION

There has been recent focus placed on near surface groundwater and surface run-off flows as they have been attributed to erosion of consolidated and unconsolidated material resulting in incised surface channels referred to as gullies, which pose significant issues for agricultural productivity and local infrastructure (Beavis, 2000, Wu and Cheng, 2005). To effectively manage these erosional features through mitigation an understanding of the occurrence and future erosional pathways is required, although prediction is difficult when topographic variations are not obvious.

Local hydrological conditions will determine the nature of surface flows and groundwater movement including the infiltration depth, flow direction and rate of movement, although it is generally understood that water flows through physical or chemical channels known as ***preferential pathways*** (Clothier et al., 2007). Pathways develop within a medium due to the heterogeneities in the physical properties of the material that the water is flowing through.

Prediction and visualisation of preferential pathways is problematic as it would require witnessing real-time surface flows uphill from an existing gully to trace an expected pathway, which is neither feasible or economical (Valentin et al., 2005). It can be assumed that water flowing through a preferential pathway will saturate the soil leading to a higher conductivity relative to the surrounding soil profiles (Clothier et al., 2007). If this is the case, then electrical geophysics has the ability to measure and detect these anomalous zones uphill of an existing gully feature. To this affect there is potential to trace these ***preferential pathways*** to predict the occurrence of physical channels prior to their erosional formation, specifically this study focuses on the prediction of Gully Head-cut Retreat (GHR).

Gully Head cut Retreat

Gully related studies have focused on lithology, topography, climate and anthropogenic factors that affect initiation and rate of erosion, although a critical feature of gullies is a dynamically retreating head-cut. It involves a dramatic increase in slope relative to the surrounding topography leading into the channel (Collison, 2001). Head cut retreat is the main form of uphill gully extension for continuous gullies but isn't a common focus or analytical feature in assessments of gully erosion. This form of erosion is driven by surface run-off concentrated towards the head-cut through preferential pathways resulting in the release of kinetic energy as water flows into the channel of the gully (Samani et al., 2016, Wells et al., 2009). Force exerted by concentrated flows results in intense erosional force leading to continual incision of the head-cut uphill extending the length of the existing gully (Stavi et al., 2010). The process of head cut retreat is continuous cycle of excess energy from overland flow incising into soil resulting in a material to break off into the channel which is then removed by channel flow. For a detailed outline and depiction of GHR refer to Collison (2001) and Stavi et al. (2010).

Consequences of Soil Erosion

Development of surface channel features pose significant concerns to agricultural productivity, sustainable land management, environmental conditions and structural damages to infrastructure (Beavis, 2000). Gullying is understood as one of the most detrimental and destructive forms of erosion for any agricultural industry as it involves; the removal of the top soil, reduction in soil fertility, destroying agricultural croplands, reduction in land/paddock connectivity and altering local hydrological conditions (Sidorchuk, 1999, Valentin et al., 2005). Removal of productive lands has severe economic consequences as reduction in productivity results in a net loss as well as the effort and finances required to mitigate further damage from gullying. Other major damages caused by gully extension is the undermining of existing infrastructure such as fences, buildings, roads and utilities (Perroy et al., 2010). Similarly, this poses significant economic loss through repairs for structural damage as well as costs associated with health risks from building failure (Frankl et al., 2012). Erosional features such as gullies pose significant risk and are extremely difficult to reverse so it is imperative to mitigate future erosion through timely and effective management based on confident prediction models.

Lateral Preferential Pathway

Surface run-off on a broad scale is determined by major topographic contours although minor topographic variations within these govern localised flows resulting in feeding of water through non-obvious channels, typically uphill of obvious features such as rivers and/or gullies (Frankl et al., 2012, Melliger and Niemann, 2010). Figure 1 represents a hydrology model in which surface run-off is focused to the lowest point (shown as purple arrows) as a non-obvious channel, represented as the blue arrow, is developed due to the **heterogeneities** in the landscape represented as the red contour lines.

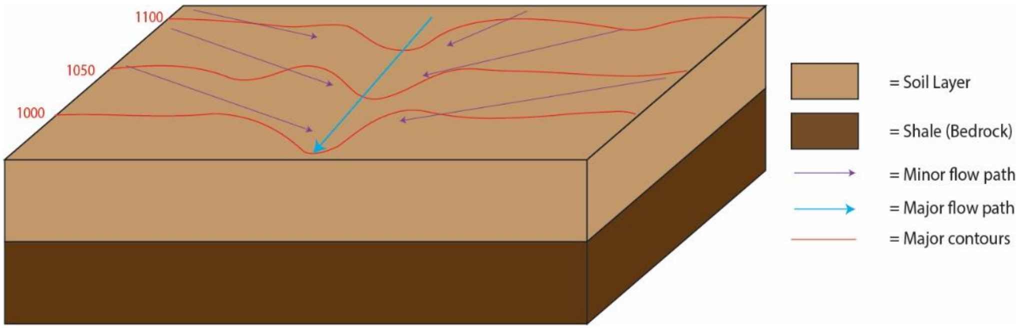

Figure 1. Model depicting the flow paths of water leading to a singular non-obvious channel (blue arrow) caused by topographic variations in the surface Solid red lines represent major topographic contours which are indicative of a broad flow direction, Purple lines show minor flow paths.

As surface run-off is channelled as singular streams across a slope, the erosional force of water movement will eventually incise into the surface resulting in gullying. These non-obvious channels represent the zone of the main body of water movement down a slope which can be inferred as a preferential pathway of water migration, which is represented as the blue arrow in Figure . Preferential pathways follow the dominate flow path of surface run-off from an uphill point to an existing surface feature, within this study these pathways are referred to as '***Lateral Preferential Pathways (LPP)***'.

As LPP represent the dominate zones of water migration due to surface run-off from topographic highs to lows which is illustrated in Figure , this will inherently be associated with higher soil saturation percentages relative to the surrounding area. Zones of saturation occur due to higher quantities of water infiltration associated with LPP after a rainfall event. This leads to extended water retention in the soils (saturated area represented as the blue arrow in Figure) associated with LPP relative to the surrounding soils, which indicates that uphill of gullies water is retained for longer periods of time (Vanmaercke et al., 2016).

Rainfall events incorporate heterogenous saturation of soils due to vegetation cover, soil type, soil depth and rainfall intensity, overall soils would experience fluctuations in apparent conductivity due to water content (Clothier et al., 2007). Non-obvious channels represented as an LPP initially form on the soil surface as Figure depicts as a 'Major Flow path' following the fluctuations of topography; this is then attributed to the heterogeneities in soil saturation (Clothier et al., 2007, Melliger and Niemann, 2010). The concept of an LPP is associated with a larger quantity of water infiltration in the near-surface compared to the surrounding soils which would indicate that the soils within a LPP would be relatively more conductive. Differences within physical properties such as water content of soil can be exploited by geophysical investigations to identify variations in conductivity between LPP and topographically higher soils. Integrating geophysical surveying into hydrological studies provides an insight into the behaviour of fluid movement within the subsurface which is crucial to understanding LPP (Robinson et al., 2008).

Justification of Geophysical Analysis

To address this inability to predict GHR to allow for targeted management decisions to be developed alternative technologies to already known methods needs to be assessed. Geophysical investigations of physical properties of the earth has repeatedly proven its applicability and accuracy as a non-invasive technique for imaging of near surface and subsurface features (Zhou et al., 2001). Hydrological investigations incorporate analysis of water movement as surface run-off and infiltrated groundwater; characterisation of these is difficult as they cannot be visually assessed effectively. Integrating non-invasive geophysical techniques into hydrological assessments ("*hydrogeophyics*") allows for fluid migration patterns to be visualised and analysed in a spatial context (Robinson et al., 2008). Recent investigations have shown that integration of geophysics and hydrology (Corwin and Lesch, 2005b) results in a significant increase in site specific understanding of hydrological processes and interactions, which is required for assessment of LPP being a localised surface feature.

Assessment of LPP requires an adequate measuring and mapping of the variations in water content that exist across a soil profile associated with a slope. To measure these variations electrical geophysical investigations can be implemented to exploit the relative changes in resistivity/conductivity between saturated and unsaturated zones within the subsurface (Corwin and Lesch, 2005a). The most commonly implemented electrical technique to measure the distribution of resistivity/conductivity of soils is '***Electrical Resistivity Imaging*** *(ERI)*'. It incorporates an analysis of the resistivity of the subsurface by measuring specific points at different depths within a profile (Robinson et al., 2008). Another common technique used is soil mapping is '***Frequency Electromagnetic*** *(FEM)'* which induces electromagnetic currents within the near-surface (0-6m depth) to measure the bulk conductivity. These geophysical techniques are implemented within numerous industries to target shallow sub-surface variations in resistivity/conductivity based on heterogeneities of physical properties associated with the soil (Corwin and Lesch, 2005b).

Previous studies have implemented combinations of geophysical techniques including ERI and FEM for identification of near-surface features; these include an investigation on detecting cavities by Carrazza and Helene (2016) as well as another study into cave systems associated to urban hazards conducted by Lazzari et al. (2010). Carrazza and Helene (2016) conducted a near surface geophysical investigation implementing ERI for the detection of cavities. It was hypothesized that the piping phenomenon of soils generated these air-filled cavities related to material failure. Typically gully formations within their study area were caused by rapid material loss; leading to the cut back of the gully into the hillside. ERI profiles were conducted in close succession (5m line spacing) back from the edge of the zone of failure, gullies development was based on rapid large movements of material away from slope edge. It was found that cavities filled with air were detected as zones of high resistivity values (>15,000 Ωm) and were concluded to be associated with areas of slab failure. The study also detected large conductive anomalies ranging from 0-300 Ωm which were interpreted to be highly saturated soil/rock but were considered unrelated with gully formation for the study area. Lazzari et al. (2010) also implemented a near-surface geophysical investigation to detect cave systems using ERI and Ground Penetrating Radar. The aim of study was to develop a hazard map for the site as it was known for its subsurface cave systems which posed significant hazards to an urban context. Results of ERI found that cave systems were typically identified as zones of high resistivity exhibiting values of >1000 Ωm. Other observable features were large conductive anomalies that were interpreted as saturated zones of soil/rock exhibiting values of 1-60 Ωm.

RESEARCH BREAKDOWN

Hypothesis

The hypothesis for this investigation is that shallow anomalous conductive features within a 1-40 Ωm range with no obvious topographic association will exist uphill from the head cuts of continuous gullies.

Research Aims

The findings presented in this Master of Research thesis are intended to address the following research aims:

(1) Investigate the ability for electrical resistivity imaging and frequency electromagnetic field methods to detect shallow conductors uphill from existing gullies illustrative of higher water saturation

(2) Investigate the potential association between identified shallow conductors uphill from head cuts as a Lateral Preferential Pathway for water movement representative of a potential prediction method for Gully Head cut Retreat

Tasks Undertaken

Task to be undertaken to address the research aims stated previously include:

- Identification of appropriate gullies through satellite imagery (Geographic Information Science)
- Field observations through visual assessment and GPS positioning
- Geophysical surveys across the head-cut of the gully with subsequent surveys uphill from that location at various distances
- Data processing and identification of anomalous shallow conductive zones which can be associated and linked to the gully as a LPP.
- Assessment of applicability and confidence in the field method through direct comparisons of current literature detailing other forms of gully assessment for effective management

METHODS

Tracking of LPP and prediction of future gully extension uphill from existing features involves visual field assessment, as well as the implementation of electrical geophysics and the collection of accurate positional data. Fieldtrips to the 'Tamworth Waste Management facility' were conducted in Mid-February and then late April; timing of the fieldtrip affected the soil moisture of the area as the first fieldtrip involved extremely dry conditions compared to the second fieldtrip. Geophysical surveys were divided into primary and secondary sites labelled as sites A to E, these were determined based on the locations of existing gully features which are shown in Figure. Primary sites incorporated at least 4 ERI surveys, FEM and GPS positioning while secondary sites only involved 2 ERI surveys and GPS data. Targeted gullies matched the size of moderate to well-developed channels and represented similar formations as depicted in the centre and right models of **Error! Reference source not found.**.

Electrical Resistivity

Electrical resistivity surveys involved the use of 'Dipole-Dipole' electrode arrays with varying lengths of either a 100m (105 measurements) or 200m (257 measurements) having electrode spacings of 5m. Survey locations were based on the locations of known/located gully formations, shown as the solid red lines on Figure. Watering of electrodes occurred prior to measuring cycle to improve the contact. Measurements incorporated a maximum value of 'n'=7, so survey depth extended to approximately 15m. Equipment consisted of an 'ABEM Terrameter SAS 4000' for measurements and calculations of apparent resistivity and an 'ABEM LUND' to control current/potential electrode positions based on pre-set protocols; both connected to 12v batteries with a current input range of 20-200mA.

Frequency-Domain Electromagnetic (FEM)

Frequency Domain Electromagnetic surveys were conducted using a Dual EM system with a 4m Boom. Measurements were taken every 2m along the survey line ensuring the centre of the boom was placed at the 2m interval, transmitter and receiver were kept North to South with the transmitter being more northerly. Approximate depth of penetration is ~4-6m and measures the bulk conductivity of the soil directly beneath the centre of the boom. Lengths of FEM surveys varied depending on the location of the survey and extent of the surface expression of the gully, Figure depicts all FEM surveys as solid green lines.

GPS

To correlate geophysical data with gully positions, GPS data on the surface expressions of gullies was taken from the 'Head-cut' to a well-established point within the main channel. GPS information was collected using a combination of a 'Garmin E-trex' (2-5m accuracy) for approximate positions of survey lines and a 'Trimble R2' (1-2cm accuracy) for exact positioning of electrode locations, elevations and tracing channels of gullies shown as the solid yellow lines of Figure.

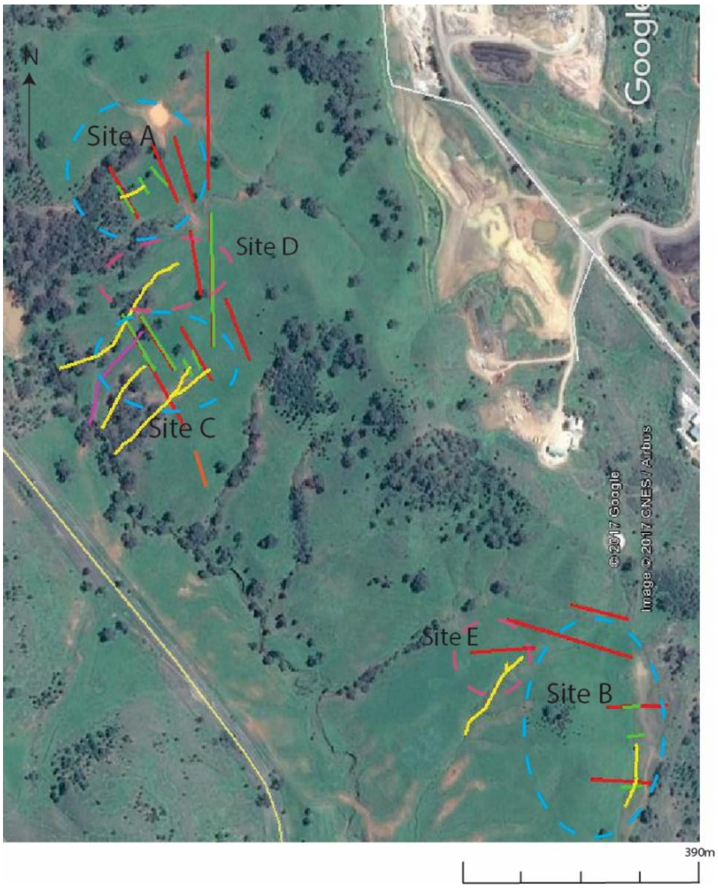

Figure 2. Image depicting the positions of all electrical resistivity (shown as solid red lines), FEM (shown as solid green lines) surveys and identified surface expressions of gullies (shown as solid yellow lines) across the site. Primary sites are represented by blue dashed circles and labelled as A, B, C. Secondary sites are depicted as pink dashed circles and labelled as D and E. Orange line depicts ERI survey conducted for background readings.

Data Processing & Filtering

Processing of resistivity data involved initial removal of data points from raw data files with a field calculated error of 10% and 5%, the percentage was determined based on the amount of data points collected. Edited data files were then imported and processed using 'Res2dinv' with a 'Robust Inversion Method' that incorporated an error change convergence limit of 0.1% and a maximum of 25 iterations. Further processing occurred after an inversion file was created in which the RMS error statistics were analysed and values over 100% were removed from the data file, data files were then re-processed with the same inversion technique to produce minimum error pseudo-sections of all resistivity lines. Additional information was included to each pseudo-section as topographic elevations for each electrode position. Acceptable error values were determined to be approximately 15-20%, this was an optimal range to preserve a significant amount of data points and achieving a minimum error. After filtering of errors has been completed profiles are then plotted with a logarithmic contour scale with a minimum value of 1-20 Ωm and a maximum value of

20,000 Ωm to produce final images. FEM processing involved generating scatter plots using excel for the HC and PC components to visualize the variations in conductivities.

RESULTS

As stated previously within this investigation there is an ever-growing necessity for predictive tools of significant environmental and production issues; not just including gullying of soils but for weather patterns, climatic conditions, crop yields and risk assessments (Stein and LaTray, 2002). Predictive models exist for a large majority of factors associated with agricultural production and urban planning, although due to the complexities with head cut migration the ability to predict the pathway of gullying is extremely limited (Poesen et al., 2003). This investigation of head-cut migration aims to produce an applicable field method to predict future pathways using electrical geophysical to trace LPP. The results given as the ERI and FEM profiles exhibit near-surface shallow conductive anomalous zones uphill from gully head-cuts with no obvious associated topographic variations.

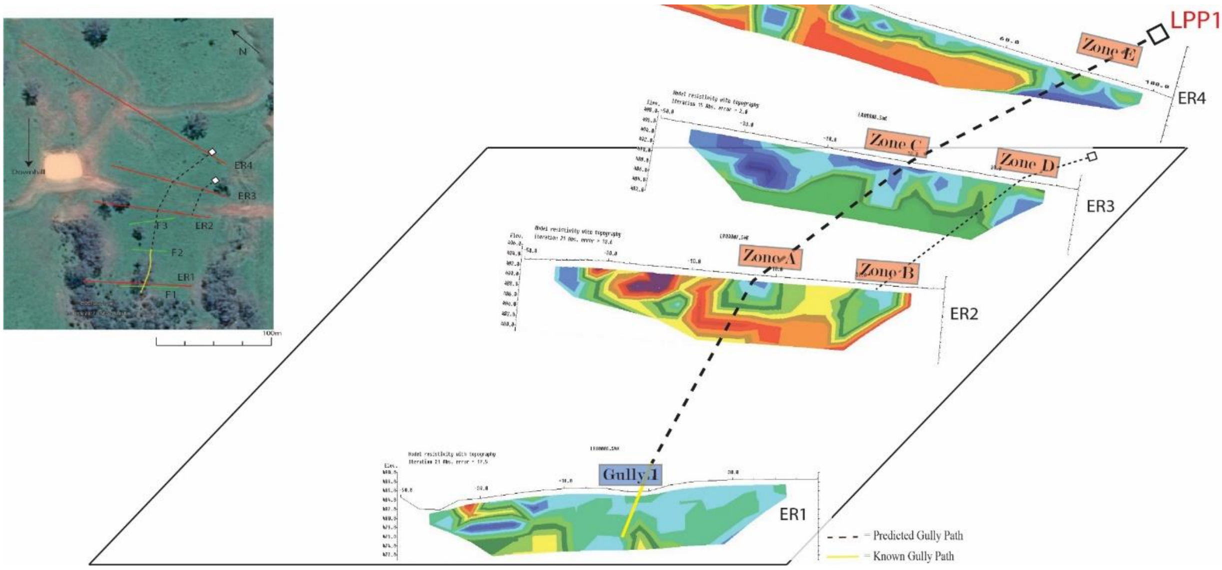

Figure 3. Integrated ERI results with an associated Google Earth image for site A; positions and orientations of each profile are relative to on ground positions shown as the small image to the top left of the figure.

Figure 3 depicts the results of the integration of the ERI surveys conducted in Site A, interpreted LPP traces are depicted as the black dashed lines illustrated through the profiles and locational image. The primary focus for this site was a moderate gully referred to as 'Gully 1' which is depicted as the yellow line and is associated to the bold dashed trace labelled as LPP1 connecting the head cut of the gully to a series of uphill anomalous conductive zones. LPP1 was traced through shallow conductors that matched the targeted electrical response outlined in the section above, the trace for LPP1 are as follows; **'Gully 1' → Zone A → Zone C → Zone E**. Majority of profiles depict singular conductive zones which are interpreted as points along an LPP, although in ER3 there are several conductors. The Northern most conductor is related to the large dam feature seen in the locational image to the North of ER3, while the smaller conductor to the south of Zone C involved less conductive values. Zone E is interpreted as the edge of detection and the conductor is considered a singular anomalous zone. Interpretation of LPP1 is given high confidence based on similarities between the predicted pathway and existing landforms erosional pathway styles, topographical conformity and correlation to targeted conductive zones.

Another thinner trace which is associated with a lower confidence is also shown in Figure which connects zones B and D as an interpreted LPP. Based on the topography and form of LPP1 it is interpreted that these features are potentially linked with Zone E but minimal confidence was given to this interpretation; it has been interpreted as a potential fork or eventual discontinuous gully.

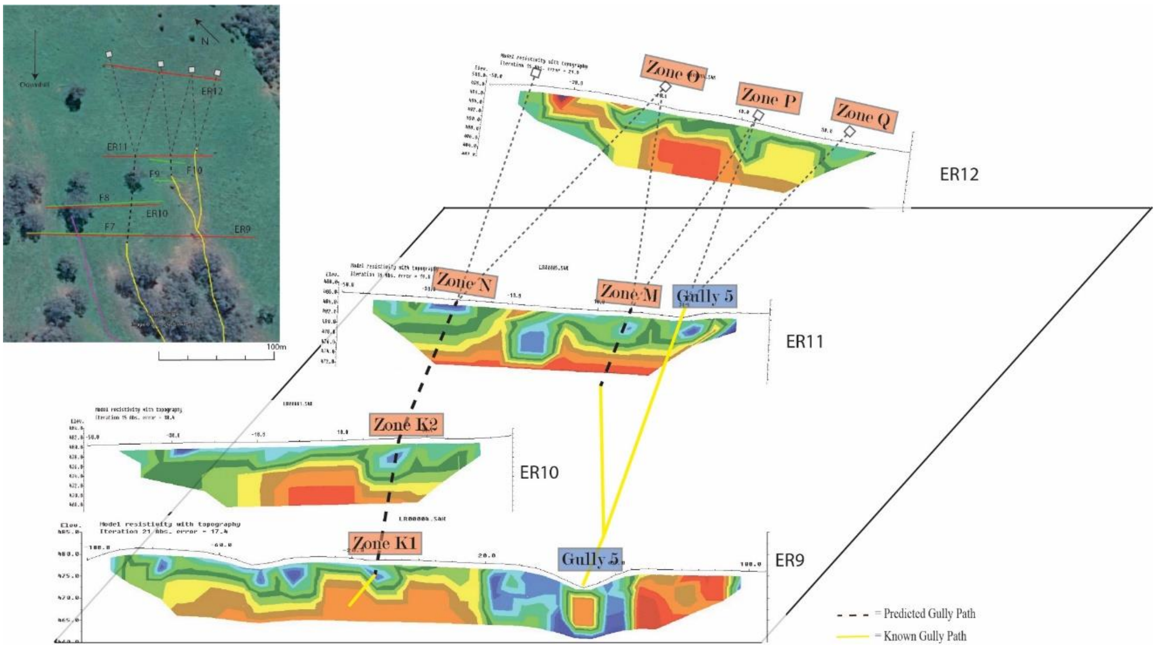

Figure 4. Integrated ERI results with an associated Google Earth image for site C; depicting the interpreted LPP shown as the black dashed line which intersects each profile through a shallow conductor.

Site C is considered the most complicated area within the investigation due to the presence of multiple gullies represented as solid yellow lines which are then associated to multiple LPP traces shown as dashed black lines; all this is depicted in the integration of ERI data for site C as Figure. Interpretations for LPP traces vary between the two gullies, the primary focus for site C was the identified central gully while the secondary focus was 'Gully 5' seen as the easterly landform.

The primary gully outlined in the center of site C was located using GPS/field observations and then included into the dataset as the solid yellow line. In terms of the associated interpretations the gully is linked with numerous uphill anomalous conductors which is represented through a bold dashed line is traced through and labelled as LPP2. The trace for LPP2 is as follows: **Gully 5 → Zone K1 → Zone K2 → Zone N → *Inconclusive***. Associated zones K1, K2 and N all fall within the targetable range for conductive anomalies representative of points along a LPP. Zone K1 is considered significant due to its relatively high conductivity and proximity to the gully head cut. Links to Zone K2 and N as a continuation of LPP2 are based on the high conductivity values and the conformity of the LPP to the terrain/slope. Past Zone N to ER12 the confidence in the predictive model is minimal due to lack of data; numerous interpretations can be made and so it is suggested that for solid interpretations of LPP2 further ERI surveys are necessary. Links associated between conductive zones K-N as LPP2 are interpreted with high confidence, as is suggested by the bolded trace. It conforms to the topography of the site as a slope to the South-West and reflects similar aspects to well-developed gullies within proximity.

'Gully 5' incorporates two distinct forks represented in Figure as a western and eastern fork. For the western fork the head cut occurs downhill of the eastern fork and is associated with a confident interpretation of an LPP. This link is interpreted between the identified head cut and Zone M; this is based on the anomalous conductor occurring within the targetable range and the conformity to the south-westerly downhill curvature of the site. Past this point interpretations are inconclusive due to multiple potential pathways represented as the two thin dashed lines branching from Zone M. The channel of the Eastern fork of the secondary gully is detected through ER11 and is shown on Figure. Links between the head cut of this channel to uphill locations cannot be confidently traced due to the lack of data mentioned earlier, this has resulted in numerous potential pathways being interpreted.

FEM data for site C is shown as **Error! Reference source not found.** in the results section as profiles F7-F10. It was found in this data set that only obvious topographic landforms that would normally be associated with changes in conductivity could be confidently identified. This is outlined as profiles F7 and F9 which depict conductive peaks that occur within the gully channel; as for

F8 and F10 which were uphill of gullies distinctive peaks could not be delineated from the background conductivity. Anomalous zones outlined could not be confidently interpreted as representative of an LPP conductor.

CONCLUSIONS

Based on the literature current predictive models for GHR are ineffective or developed with minimal confidence which leads inappropriate management strategies (Valentin et al., 2005). This lack of predictive tools for head cut retreat is due to the fact these models are based purely on visual assessments through time or measurements of select surface parameters. Currently the focus is direct remediation of visible features through physical alteration of the channel or construction of concrete check dams; preventative measures are reliant on prediction models which as stated earlier are currently ineffective (Le Roux and Sumner, 2012, Nyssen et al., 2004). There is an ever-growing necessity for prevention rather than remediation which leads to the fact that effective predictive models are required (Clothier et al., 2007). This study has proposed a method of GHR prediction through the detection of shallow conductors which are representative as a Lateral Preferential Pathway a proxy for the pathway of uphill gully retreat. Based on the findings and aims of this investigation the following conclusions have been made:

(1) Electrical Resistivity Imaging was successful at proving and detecting the existence of shallow conductors uphill of gully head cuts representative as the proposed LPP concept for continuous gullies. It is then plausible for geophysical investigations to be implemented as a potential predictive method for GHR. Limit of accurate detection of LPP conductors uphill from head cuts is ~70m; this can be extended if spacing between surveys is reduced which leads to increased costs for minimal benefits.

(2) Inclusion of Lateral preferential pathways as a measurable and significant critical point in gully assessments along with the commonly accepted critical points such as; Head cut, Channel, Mouth of the Channel (Continuous) and the Alluvial fan (Discontinuous).

(3) Frequency Electromagnetics is unable to detect relatively subtle features such as LPP as it relies on bulk conductivity variations. In terms of LPP detection it is plausible to implement as supplementary information to assist in interpretation; although the limits of detection were determined to be 0-15m uphill from the head cut. There is scope for FEM to be implemented for detection of traditional critical points as the head cut was often outlined by conductivity peaks.

(4) It is inferred that identified conductive anomalies with associated traces through them are linked as a Lateral Preferential Pathway; it seems unlikely that these connections are merely a coincidence due to the uncanny conformity to the slope and similar style to existing gullies exhibited. Based on this these pathways can be inferred with high confidence as the pathway for GHR.

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