EXAMINATION COPY

The Implementation of UAV Multispectral Imagery for Gully Mapping, Okhombe Valley, KwaZulu-Natal Drakensberg, South Africa

by

Lyndon Paul Riddle

Submitted in fulfilment for the requirement for the degree of

Doctor of Philosophy (Environmental Science)

in the Discipline of Geography

School of Agricultural, Earth and Environmental Sciences

Pietermaritzburg Campus

University of KwaZulu-Natal

2023

Supervisor: Prof T Hill and Dr A Clulow

FRONTISPIECE

Declaration

I, LYNDON PAUL RIDDLE, declare that:

I. The research report in this dissertation, except where otherwise indicated, is my original work

II. This dissertation has not been submitted for any degree or examination at any other university

III. This dissertation does not contain other persons' data. Pictures, graphs, or information, unless specifically acknowledged as being sourced from other publishers.

IV. All authors and organisations have been fully acknowledged and can be found in the text and the reference list

V. This dissertation does not contain text, graphics or tables copied and pasted from the internet, unless specifically acknowledged and the source being detailed in the dissertation and the reference list

[redacted]

LYNDON PAUL RIDDLE

[redacted]

PROF TREVOR HILL

DATE: FEBRUARY 2023

Declaration 2

Form EX1-6

COLLEGE OF AGRICULTURE, ENGINEERING AND SCIENCE

DECLARATION 2 - PUBLICATIONS

DETAILS OF CONTRIBUTION TO PUBLICATIONS that form part and/or include research presented in this thesis (include publications in preparation, submitted, *in press* and published and give details of the contributions of each author to the experimental work and writing of each publication)

Publication 1
The Use of Photogrammetry and UAV Technology to Produce 3-Dimensional imagery of a gully system in Okhombe, Northern Drakensberg, South Africa.
In preparation to submit to South African Journal of Geomatics
Authors: Riddle, L., Hill, T. and Chulow, A.
Contribution
Riddle: PhD Student
Hill and Chulow: Co Supervisor

Publication 2
Mapping Soil Erosion with an Unmanned Aerial Vehicle with the use of Altum Multi-Spectral Sensors, Okhombe Valley, KwaZulu-Natal Drakensberg, South Africa.
In preparation to submit to South African Journal of Geomatics
Authors: Riddle, L., Hill, T. and Chulow, A.
Contribution
Riddle: PhD Student
Hill and Chulow: Co Supervisor

Publication 3
Geomorphology from 'on-high': The use of drones/UAV technology in teaching soil erosion.
Submitted, accepted, and published in 2018 to Journal of Geography Education in Africa. 3 (1). 10 – 22. See Appendix 1
Authors: Riddle, L., Hill, T. and Gijsbertsen, B.
Contribution
Riddle: PhD Student
Hill and Gijsbertsen: Co Supervisor

Signed: LYNDON PAUL RIDDLE

[redacted]

Acknowledgements

First and foremost, I would like to thank Professor Trevor Hill for all his involvement, dedication, and constant guidance throughout. His assistance was second to none and I could not thank him enough.

I would then like to thank Dr Alistair Clulow for his guidance and input during this entire time. His knowledge and use of his UAV were vital in the completion of this PhD.

Other thanks, go to the Water Research Commission (WRC) for the funding of my research through the Commission project (*Assessing the impact of erosion and sediment yield from different land uses in farming and forestry systems and their effect on water resources in selected catchments of South Africa.* K5/2402)

To the University of KwaZulu-Natal and its staff (Brice Gijsbertsen, the Higher Degrees team, and the Discipline of Geography) I would like to say thank you all for providing the tools and assistance needed and for offering me the opportunity to lecture while working on my PhD.

To the Okhombe Valley communities, a big thank you for allowing access to their land for my fellow researchers to complete the collection of data and produce information from their site. As well as offering the opportunity to work in an amazing setting and views.

Lastly, I would like to thank my dad, mom, wife, family, and friends for all the support and help over the past years to help me fulfil my dream of becoming Dr Riddle. Without them, this research project would have not been possible.

ABSTRACT

The availability, cost, and applicability of Unmanned Aerial Vehicles (UAVs) are rapidly altering the way we perceive the landscape, can access sites, and model the landscape as it unfolds through remote sensing technologies. It falls to present and future researchers to take advantage of this and use the technology to improve our understanding of our surroundings. One way that geomorphologists would be able to take advantage of the improvements in technology is to use the UAV to map soil processes, in particular erosion. The current methods and technology for mapping gully erosion do not look at the smaller features but rather the landscape as a whole. The purpose of this research was to assess the prospects of UAV technology mapping gully erosion. Specifically, the study investigates the application of the UAV imagery to other technologies or methods in mapping gully erosion activities. This was achieved by testing the multiple available modelling software, by mapping objects of known shapes and volumes to determine which software produced results comparable to that of the known shapes. Tests were conducted to determine if this software and UAV combination would have the ability to map and 3D render soil erosion, thus allowing researchers to verify if this technique could be implemented into mapping gully systems. From these tests, it was found the UAV was able to improve the resolution to that of the available methods. Obtaining a resolution of 0.03m would allow geomorphologists to map and situate the soil erosional landscapes and map the test objects. The software package *AgiSoft MetaShape* had the highest accuracy and reliability in mapping various objects making it ideal in the mapping of smaller erosional features. Multiple erosional landscapes were mapped using a UAV and the attached RGB sensor and a second UAV with a multi-spectral sensor and *AgiSoft MetaShape* software. Both sensors mapped plant health, capturing plant health with band widths related to each sensor. Ideally the multi-spectral sensors were seen to be more versatile, however the RGB sensor can be useful. The combination of both UAVs created a 3D-rendered model, and the resulting data was useful in determining the potential future areas of erosion and existing areas of high erosion risk. The multi-sensor camera allowed the user to determine micro-features that could potentially become erosional areas in the future as it identified areas with a concentration in water flow. In conclusion, the UAV is a useful spatial tool to monitor, measure and manage soil erosion and gully mapping.

Table of Contents

List of Figures

List of Tables

List of Plates

CHAPTER ONE

Introduction

1.1 Introduction

From a recreational educational device that an enthusiast builds to fly with friends, take vacation images and enjoy for the sheer pleasure of flight, to a multi-billion-dollar self-flying, self-navigating autonomous military flying machine, an Unmanned Aerial Vehicle (UAV) (also known as a drone) is developing into a sought after spatial analytical remote sensing tool (Merkert and Bushell, 2020). These UAVs have a myriad of applications of potential benefit within many field-based sciences and as the technology improves and one becomes more aware of its capabilities more applications are being considered (Fan *et al*, 2017). Scientists have taken cognisance of these benefits and seek to take advantage to incorporate UAV technology and output into the rigours of their fields of specialisation. Users utilise the UAV for its aerial imagery capability and, as yet, have not fully appreciated the possibilities of viewing a site from a different angle or understanding the possible payloads/sensors a UAV can carry (Merkert and Bushell, 2020). Implementation of the UAV in the field of gully mapping allows researchers to capture images in steep and inaccessible terrain, often in what we would consider ’the best spot’s’! With the assistance of remote sensing softwares to process images, UAV outputs in field-based environmental sciences can open the researchers to a wider range of topics that were not feasible or affordable before. The ability to create time-lapse high-definition imagery of a site can assist in the understanding of soil processes of erosion and deposition and, at an even greater level of resolution, soil sediment movement (González & Rodriguez, 2017). The amalgamation of the science of soil erosion and UAV technology seems to hold great potential, however, with a note of caution, the researcher requires clear justification and understanding of what can be achieved as opposed to using for the sake of using and becoming entwined in the vagrancies of a new spatial technology.

Initially one of the most common fields of enquiry of UAVs was to obtain aerial images of inaccessible study sites (Jordan, 2015). This afforded researchers the ability to gain an in-depth visual description of a site in real-time to visually replicate a site for computer-based analysis. This allowed the computer system to display a comparable landscape digitally (Zhang *et al*, 2023). As the fundamental goal for geomorphologists is to determine the processes of movement of the land (Toth *et al*, 2016), gaining access to high-resolution aerial images is crucial to obtaining an improved understanding of soil processes. Thus, this application has the potential to collect, manipulate, store, and analyse soil movement and processes of gully erosion. Furthermore, a collaboration of a myriad of disciplines, due to the diversity of applications, and the development of spatial analytical software means that diverse fields of interest can integrate approaches and applications. The transdisciplinary capability of the UAV's data would potentially bring together ideas and new methodologies for analysing existing theories of gully erosion (Riddle *et al*, 2018).

To understand the movement of soil, researchers study past landscape-scale changes through satellite imagery and aerial photography. UAV-derived data, in particular through repetitive high-resolution data sets, can assist in soil erosion models and predicting soil loss (Le Roux, *et al*¸ 2022). As research evolves, geomorphology may no longer be studied as a single discipline, but rather as an interdisciplinary team to obtain a better understanding of a concept, idea, or issue. (Lerah *et al*, 2007). One should no longer look at the land and determine the methodology of how the landscape or soil has been morphed to its presents landscape, but rather look at the landscape from a combination of innovative spatially explicit approaches (Chakrabortty *et al,* 2022). This may assist with agriculture or engineering, as one would look at both the positive and limiting attributes determined through UAV studies to determine the ideal location to cultivate or build (Chakrabortty *et al,* 2022). One would then have to include other disciplines such as economics, geography, politics, computer sciences, and social sciences to create a complete understanding of the direct and indirect effects of soil movement (Rahmati *et al,* 2022). This is where the UAV could be of assistance in obtaining an alternative view of a study area.

Soil erosion has both a negative and a positive effect on global landscapes, as an interaction between the pedosphere, biosphere, atmosphere, and hydrosphere (Lu *et al*, 2004). It is a complex and dynamic process. Agricultural practices or anthropogenic inputs influence and accelerate the process of natural erosion (Rahmati *et al,* 2022). However, erosion is not isolated to only the input of agricultural practises or anthropogenic interference, it can be exacerbated by the mass movement of domestic livestock and the management thereof. As erosion is a natural process one cannot prevent its occurrence, however, proactive management and control can be introduced to reduce the speed and consequential effects of erosion. In the past, this was predominately achieved through preventing or hindering the movement of water in erosional landscapes. The most applied is through the construction of a physical barrier that could be either a hard (bricks, concrete) or soft (vegetation, earth-dam)-engineered structure (Keesstra *et al*, 2016). These methods can be difficult to implement in areas of lower economic standings, as the community may not have the financial backing to initiate and manage these practises. However, the local community assist by working with researchers, by obtaining continuous data from the site, such as rain splash, for researchers to later utilise for the understanding or how rain affects the soils (Plate 1.1, a). For example, using what is available on-site, stones or rocks (stone packs) have been placed in the paths of existing erosion to prevent further erosion (Plate 1.1, b). Both these structures (hard or soft) have the same objective, to reduce or to mitigate the effect of the fluid flowing over a rock or soil and removing particles from said rock or soil. These methods reduce the kinetic energy of the fluid and its ability to detach particles from the soil body. The effects of erosion are both *in- and ex-situ* (Daba *et al*, 2003).

Sediments move downslope and can have both negative and positive effects where the sediments are deposited. Erosion (gully erosion) leaves a scar in the ground where the soils have been removed, creating an area where crops can no longer be grown and leaving the potential of livestock falling in and becoming entrapped. This could bring nutrients into the sediment and deposit them downstream, allowing for greater crop growth and yield (Le Roux & Van Der Waal, 2020). However, the same sediment has the potential of silting water courses and reducing the water storage capacity of these bodies of water, reducing the water availability in the area. Previously, this had been mapped using aerial photography to determine the movement of the soils and then moved to satellite images and 3D laser scanning (González & Rodriguez, 2017). As this was undertaken from a distance, smaller features were not captured and were often overlooked.

Scanning landscapes with 3D technology is becoming more widely applied and many research projects have been carried out with this technology, however, the technology is costly and, at present, cumbersome to use (Glendell *et al*, 2017). The use of 3D scanning technology is not a new concept and has been applied in earth-moving construction sites, pavement monitoring and highway alignment (El-Omari and Moselhi, 2008). Laser 3D scanning has been applied to scan patients where limbs have been removed to design and manufacture a perfect match for a prosthesis (Lerah *et al*, 2007), has assisted in the animation creation for films and games, and 3D scanning has become a vital tool for historians to scan buildings and artefacts to preserve the historical culture (Remondino and El-Hakim, 2006). This scanning technology was utilised by *CYARK*, where the company, in partnership with African Conversation Trust (ACT) and the University of KwaZulu Natal (UKZN), created a 3D model of the rock art created by the traditional tribe (the San People) (Cyark, 2021). This was carried out to preserve and allow for non-invasive unobtrusive research on the artwork in the future. However, at present, the computer hardware is the limiting factor in processing the data captured and producing a photo-realistic image, however, as hardware improves, this objective will become more of a reality (Remondino and El-Hakim, 2006).

1.2 Study Site

The study site is the Okhombe River Valley (28°42'28,215''S, 29°5'42,258''E,) situated in the KwaZulu-Natal Drakensberg, South Africa, approximately 60km NW of the town, Bergville (Figure 1). Located between 1 200 and 1 800m meters above sea level. The area is predominantly a rural landscape dominated by subsistence farming surrounding community homesteads, with hilltop plateaus used for livestock grazing. The area forms part of the catchment area of the Tugela Vaal Water Scheme and is a crucial source of water for South Africa's industrial regions (Birkett *et al*, 2016).

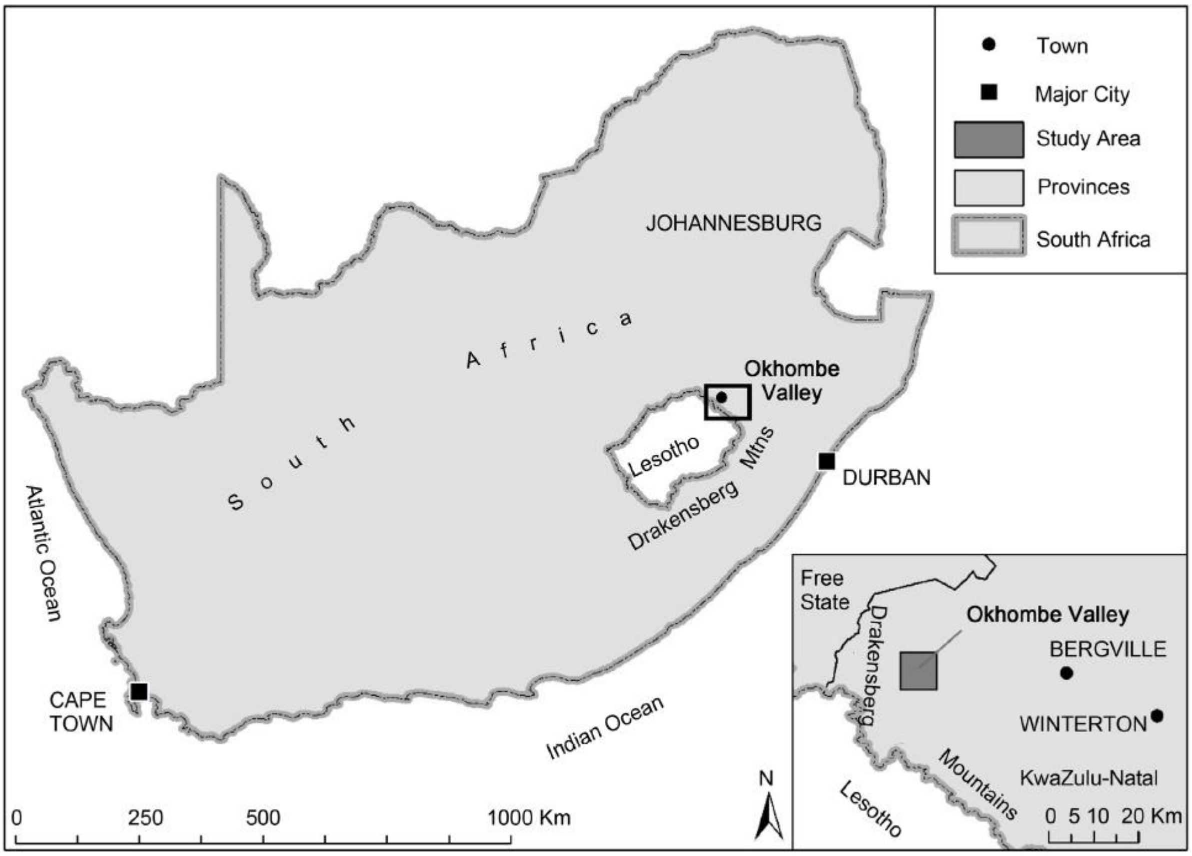


Figure 1.1: Situation of Okhombe River Valley Gully system within the KwaZulu-Natal, South Africa (adopted from Birkett *et al*, 2016)

The keeping of livestock and movement of livestock up and down the valley is the primary agricultural activity. During the 1960s, a government scheme (The Betterment Plan) was introduced into the area. (Sonneveld *et al*, 2005), The study area forms part of the Land Care

Programme, started in 1999, that focused on job creation whereby the community would assist in the implementation of erosion control measures (Everson *et al,* 2007). The Land Care Programme was deemed a successful governmental project with the single limitation of the lack of data confirming the success of the erosional control methods (Everson *et al*, 2007). This limitation formed a component of a Water Research Commission (WRC) project that set-up monitoring, management, and rehabilitation research objectives with the community (Birkett *et al,* 2016). The research objectives were achieved and the management, monitoring and rehabilitation of the erosion and management approach at this site are ongoing. This scheme implemented the involvement of the local community to combat the soil erosion issue, in which the community compile data and implements measures to mitigate the effects of erosion (Plate 1.1). The community have been invested in this scheme, due to the negative impacts that the erosion has on the local soils and the instability that it may cause. Workshops have been held on-site with numerous researchers and community members to share findings and to educate and assist the community in preventing the further progress of the gullies (Plate 1.2). The Scheme allows for expert-driven mapping in terms of monitoring and mapping while the on-the-ground monitoring and rehabilitation are completed at a community level. This dual monitoring and implementation of both expert and community allows for the transfer of information directly to the community with the assistance of technology and can be critical for the success of the rehabilitation of the gully.

Plate 1.1: Splash plate (a) installed on-site to measure the splash erosion after storm events. Results are recorded by the community and (b) the community installs stone packs to prevent further expansion of the existing gully network.

The area experiences a sub-humid climate, with a mean annual rainfall of approximately 800mm to 1 265 mm per annum, occurring predominantly during the summer months (Temme *et al*, 2009). The temperate range varies from extremely high temperatures in summer to extremely cold temperatures in the winter, with an average summer high temperature of approx. 27 to 30 °C and winter low temperatures of approximately -2 to 0 °C (Mucina and Rutherford, 2010).

Plate 1.2: A workshop with the community to discuss footpaths created by cattle and how we can prevent and reverse the effects of the footpath (a), and then completing a field workshop to physically show the mitigation methods (b)

The site has an unstructured soil texture with soil stability of 61-80% with the main vegetation biome being Southern Tall Grassveld (Mucina and Rutherford, 2010), and according to Mucina and Rutherford (2010), Drakensberg Grassland (Gd). The majority of the soil types affected by the degradation are Cambisols, Regosols and Luvisols (Schmid *et al*, 2005). The western and central areas of KwaZulu-Natal of South Africa are known to be colluvial sediments from the Masotcheni Formation (Temme *et al*, 2008). The Masotcheni Formation is a thick layer of unconsolidated deposits of colluvial sediments, comprising mudstone and soil with a pH of approximately 5.2 (Temme *et al*, 2008). This makes the susceptible to erosion and thus the potential formation of gullies. This area is said to be the least threatened area in terms of conservation of flora, however, the increase in erosion could increase the risk to the flora and migrate the status to threatened. The protection status according to National Spatial Biodiversity Assessment (NSBA), is believed to be poorly protected (Mucina and Rutherford, 2010).

Erosional features in the area are a common feature and are predominantly created by the movement of livestock upslope for improved grazing and moved downslope nightly for an encampment. This movement follows a particular daily route to reduce theft, resulting in overgrazing along the route, trampling, loss of vegetation cover, slope instability and, finally, increased surface run-off and erosion that has occurred over an extended time-period (Plate 1.3). The routes have created erosional paths onto which surface runoff has concentrated, leading to rills and finally gullies (Plate 1.4). The cattle have trampled areas of bares soils that are exposed and thus allow for the erosion of soils leading to gully initiation. From community workshops, the researchers and community have installed stone packs within the gullies to prevent the movement of soil downslope (Plate 1.5).

The Okhombe valley region has a population of approximately 4 000 people, many of whom are reliant on the land and its ability to grow and sustain crops (Sonneveld *et al*, 2005). With approximately 4 000 cattle and 2 000 smaller livestock, these areas are well-used in terms of livestock movement. The community were forcibly moved to the foot slopes of these areas as the lower regions adjacent to the river were designated for the growth of crops (Sonneveld *et al*, 2005). At the time of Sonneveld *et al*, (2005) research, there were approximately 52 erosional features located within the area. Many of these were created by the movement of cattle, up and down the slopes to offer better grazing. Aerial images have been captured of this site from 1962 at irregular intervals and a progression of the gully can be seen (Plate 1.3). With the movement of cattle on and within the erosional formations, soil cracks within the soils can be expanded or caused to fail and thus fall to expose bare soils due to the trampling. This can create an increased downslope movement of soils, compared to that of natural erosion timescale from wind and rain, increasing the erosional feature to a gully in a shorter time frame. This will, in turn, increase the size of the gully at a greater rate compared with natural processes. During the year 2000, the area experienced a drier year, which exacerbated the erosion rates, where aerial imagery proved the increase in gully formations (Plate 1.3). One can determine a definite scar in the ground in image B (plate 1.3) compared to that of image A (plate 1.3), which shows an area that is believed to be an existing footpath in image A. This footpath over time has developed into the gully system we see today.

Plate 1.3: Aerial images taken of the Okhombe River Valley site from the years 1962 (a) and 2004 (b). The landscape slopes downwards towards the NNW regions of the image

A paradox thus is created, in how would one move their cattle to better pastures, while still preventing the negative impacts of the cattle trampling the vegetation to expose bare soils, which then erode. The issue of cattle theft/ livestock theft is not isolated to the Okhombe Valley, but rather a national issue. where livestock owners follow their livestock to various pastures to prevent theft.

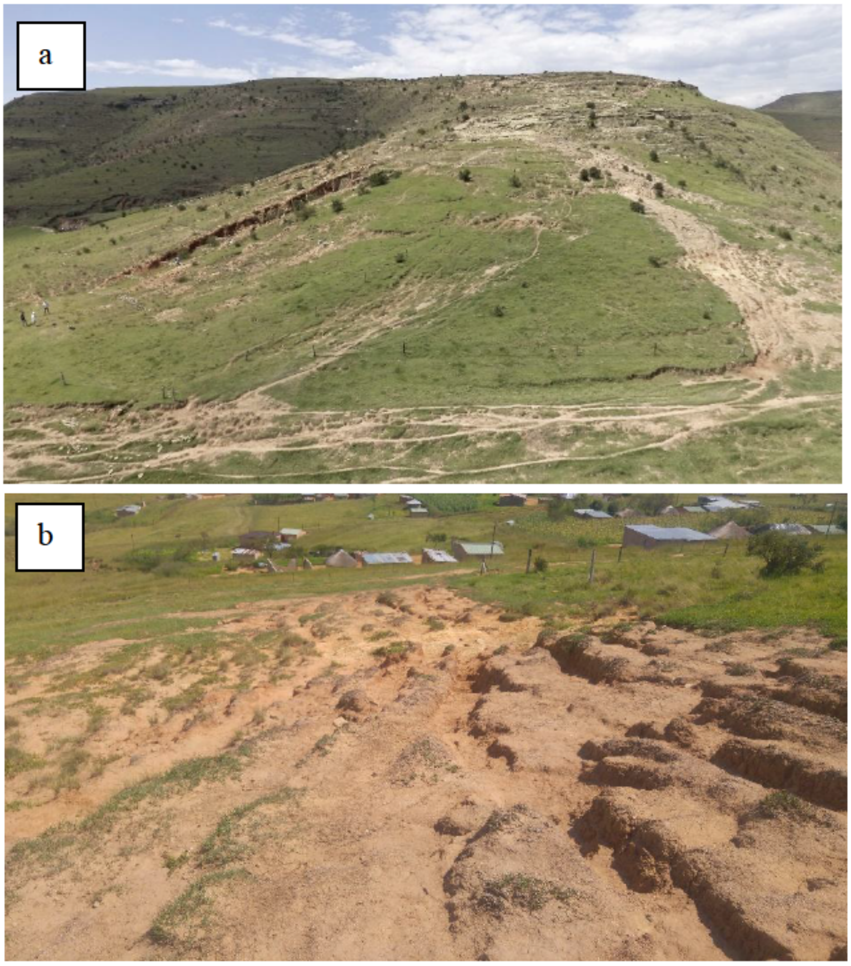


Plate 1.4: Extent of erosion at the study site. 'a' – southward view, 'b' well-entrenched footpaths created by daily movement of cattle to higher altitudes for grazing.

Of the projects that have been implemented in the Okhombe River Valley area, all have worked with the community to assist in the mitigation of erosion of the rehabilitation of areas already eroded (Everson *et al*, 2007). This is currently being completed with the use of stones packed together and revegetation with Vetiver Grass in the path of the gully. This hinders the movement of water downslope and creates an area of deposition where soils in suspension in the overland flow can settle. This has proved to be successful as soils have built-up and vegetation is growing behind the stone packs (Plate 1.5).

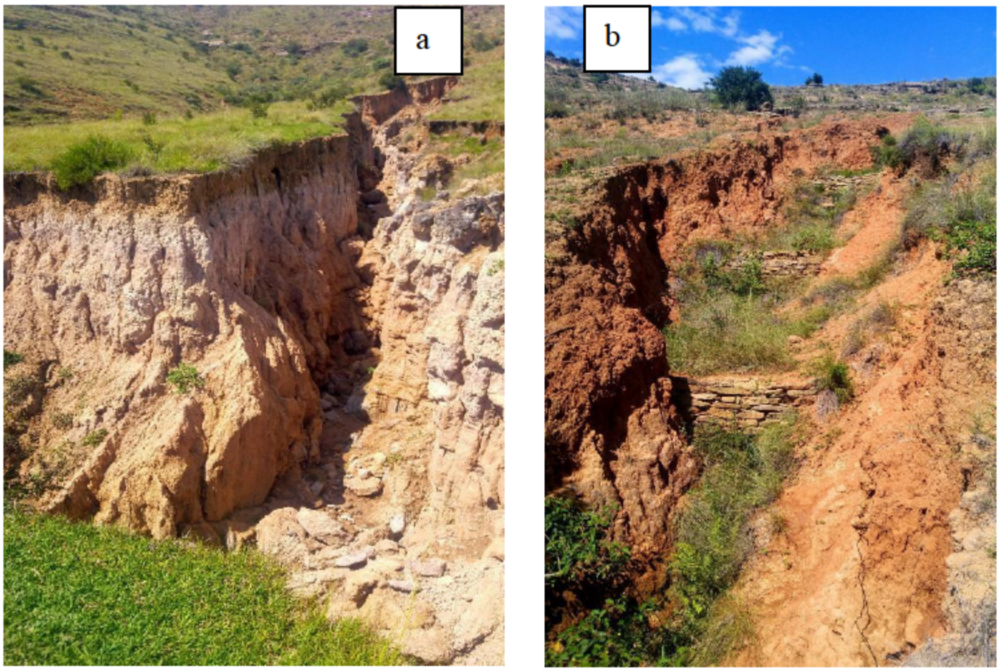


Plate 1.5: Extensive gully formation on site. Gully with no rehabilitation (a), and (b) where stone packs have been constructed to reduce erosion and surface flow.

1.3 Research aim and objectives.

To determine if a UAV, and associated software, could be applied within the field of gully mapping and assist researchers in mapping, describing, monitoring and management of gully movement to understand the landscape all with the involvement of the local community. This would assist the community in implementing appropriate agricultural practises and reduce footpaths that would, in turn, become gullies or research in determining the path a gully may erode too. The impact of this daily migration of livestock was evident (Plate 1.4 and Plate 1.5), and the erosion in this area is active and possibly irreversible. The use of the UAV may assist in the mapping and monitoring of erosion and thus assist in the mitigation of rehabilitation of the gullies. As the Okhombe area is currently in both erosional and rehabilitation phases of gully erosion, the UAV can be utilised to map and monitor both processes to determine if the rehabilitation methods are successful.

The primary aim of this research project is to investigate current methods of remotely mapping erosional landscapes (gullies) to determine if the UAV is applicable and would assist in mapping gully systems. Erosional landscapes are unique in their shapes, thus the UAV sensor and software used to capture the features would need to be accurate enough to scan both larger and smaller features within and surrounding the gully. The overarching aim of this research was carried out through a series of objectives that have been written up as separate papers that are presented here as chapters.

The first objectives are to determine if the ground resolution and pixel focus, with the use of an RGB sensor, would deteriorate with altitude and what would be the ideal height to fly above the ground for gully mapping. This was found by flying the UAV above a Pixel Density Reference Chart (PDRC) at various heights to determine if the pixel density reduces. This was replicated on multiple occasions to get an average. The aim was determined where one looked at the use of an RGB sensor and a multi-Spectral sensor to determine if the plant health imagery produced by each sensor was compared to that of what is found on the ground. This was completed by flying a UAV with each of the sensors above the study area. This information was then input into the used software and processed.

The second objective was set out to address whether the UAV and orthomosaic software can 3D map various shapes and structures and thus the mapping of gullies. At the time of this research, various software, both on- and offline, are available to allow for the 3D rending of features. The third objective was to investigate the software to determine which applies to gully mapping. This was completed by measuring the objective of known volume and shapes to determine the accuracy of each software to calculate volumes and dimensions.

The fourth objective was to determine how the combination of the UAV and orthomosaic software would replicate a gully landscape and be used to interpret soil erosion. This was completed with the use of the Altum Multi-Spectral Sensor to capture images of the research site. These images were processed through the orthomosaic software and ArcGIS software.

1.4 Summary

The UAV can be implemented in a diversity of fields, to obtain real-time information on inaccessible sites. The user demarcates an area of interest for the UAV to scan and the UAV would complete this flight and land autonomously and upload captured information. The UAV is designed for usability and user-friendliness as it is relatively easy to learn to fly and operate. At present, a UAV can be an ‘off the shelf’ purchase and be ready to fly once the batteries have been charged with little assembly required. Some UAV manufactures offer an online training program that allows the user to practise with a virtual UAV to prevent any damage to the physical UAV. Furthermore, many UAVs have sensors surrounding their body structure which assist in object detection, thus preventing the UAV from flying into a physical barrier, and thus protecting the craft. With the quad copter UAV, it is possible to release all controls and the UAV will hold its position both in relation to the ground and altitude, making the UAV safer to fly. If the connection from the remote to the UAV is lost, the UAV will return to its starting position autonomously to prevent the loss of the craft.

The Okhombe Valley, KwaZulu-Natal Drakensberg has numerous erosional landscapes and is understanding the processes of soil erosion management and livestock management to assist the community in preventing further erosion. The community assist the researcher in implementing the findings found during research by installing mitigation and rehabilitation practises in an attempt to stabilise and rehabilitate the gullies. The UAV may be a tool that is used to assist researchers in obtaining a better understanding of soil erosion and mapping the features on a higher resolution than previously possible. This could lead to understanding soil movement to prevent further issues (social, economic, or environmental). Knowledge is a vital tool to prevent negative impacts on an area. The UAV could be a tool to improve the knowledge of the area and understand not only how the soil is being eroded and why and how to prevent it. This technology can monitor existing mitigation methods and determine where and how these are successful or failing. This would be applicable for the mapping of the gully systems to assist in obtaining a better understanding of the erosional process, provide a mapping device that can be used in consultation with the participatory local community in managing and monitoring rehabilitation efforts and predict the future direction of the gully.

References

Birkett, C., Hill, T., Zuma, K., and Everson, T. (2016). Bringing Rain to the Land: Rainfall Simulation as a Participatory Teaching Aid to Understanding Erosion. *Journal of Environmental Protection*. 7(10), 1305-1316.

Chakrabortty, R., Chandra Pal, S., Santosh, M., Roy, P., and Chowdhuri, I. (2022). Gully Erosion and Climate Induced Chemical Weathering for Vulnerability Assessment in Sub-Tropical Environment. *Geomorphology,* 398, 1 – 18.

Cyark (2021). *Drakensberg Rock Art* [Online], Available at https://www.cyark.org/projects/drakensberg-rock-art/overview [Accessed 16th May 2022].

Daba, S., Rieger, W. and Strauss, P. (2003). Assessment of Gully Erosion in Eastern Ethiopia Using Photogrammetric Techniques. *Catena*, 50 (2-4), 273 – 291.

El-Omari, S. and Moselhi, O. (2008). Integrating 3D Laser Scanning and Photogrammetry for Progress Measurement of Construction Work. *Automation in Construction*. 18 (1), 1-9.

Everson, T.M., Everson, C.S. and Zuma, K.D. (2007). Community based research on the influence of rehabilitation techniques on the management of degraded catchments, *Water Research Commission.* Report No. 1316/1/07, Pretoria.

Fan, X., Kawamura, K., Xuan, T.D., Yuba, N., Lim, J., Yoshitoshi, R., Minh, T. N., Kurokawa, Y. and Obitsu, T. (2017). Low-cost visible and near-infrared camera on an unmanned aerial vehicle for assessing the herbage biomass and leaf area index in an Italian ryegrass field. *Japanese Society of Grassland Science*. 64(2), 145-150.

Glendell, M., McShane, G., Farrow, L., James, M.R., Quinton, J., Anderson, K., Evans, M., Benaud, P., Rawlins, B., Morgan, D., Jones, L., Kirkham, M., Debell, L., Quine, T.A., Lark, M., Rickson, J., and Brazier, R.E. (2017). Testing the utility of structure from motion photogrammetry reconstructions using small unmanned aerial vehicles and ground photography to estimate the extent of upland soil erosion. *Earth Surface Processes and Landforms*. 42(12), 1860 – 1871.

González, M. and Rodriguez, P. (2017). Monitoring Soil Erosion by Raster Images: From Aerial Photographs to Drone Taken Pictures. *European Journal of Geography*. 7(5), 117 – 129.

Jordan, B. (2015). A Birds Eye View of Geology: The Use of Micro Drones/UAV in Geologic Fieldwork and Education. *The Geological Society of America*. 25(7), 42 - 43.

Keesstra, S., Pereira, P., Novara, A., Brevik, E., Azorin-Molina, C., Parras-Alcántara, L., Jordán, A., and Cerdà, A. (2016). Effects of Soil Management Techniques on Soil Water Erosion in Apricot Orchards. *Science of the Total Environment*. 551 – 552(2016), 357 – 366.

Le Roux, J., Morake, L., Van Der Waal, B., Anderson, R., and Hedding D. (2022). Intra-Gully Mapping of the Largest Documented Gully Network in South Africa Using UAV Photogrammetry: Implications for Restoration Strategies. *Progress in Physical Geography: Earth and Environment,* 46(5), 772 – 789.

Le Roux, J. and Van Der Waal, B. (2020). Gully Erosion Susceptibility Modelling to Support Avoided Degradation Planning. *South African Geographical Journal*. 102 (3), 406 – 420.

Lerah, T., MacGillivrery, M. and Domina, T. (2007). 3D Laser Scanning: A Model of Multidisciplinary Research. *Journal of Texture and Apparel, Technology and Management.* 5 (4), 1 – 22.

Lu, D., Li, G., Valladares, G. and Batistella, M. (2004). Mapping Soil Erosion Risk in Rondônia, Brazilian Amazonia: Using RUSLE, Remote Sensing and GIS. *Land Degradation and Development*. 15 (5), 499 -512.

Merkert, R. and Bushell, J. (2020). Managing the Drone Revolution: A Systematic Literature Review into the Current Use of Airborne Drones and Future Strategic Directions for Their Effective Control. *Journal of Air Transport Management*. 89 (2020), 1 – 10.

Mucina, L. and Rutherford, M. (eds) (2010). The Vegetation of South Africa, Lesotho, and Swaziland. Edition 1, Impression 2. South African National Biodiversity Institute, Pretoria. *Strelitzia* 19.

Rahmati, O., Kalantari, Z., Ferreira, C., Chen, W., Soleimanpour, S., Ghajarnia, N. and Kazemabady. (2022). Contribution of Physical and Anthropogenic Factors to Gully Erosion Initiation. *Catena*. 210 (2022), 1 – 11.

Remondino, F. and El-Hakim, S. (2006). Image-Based 3D Modelling: A Review. *The Photogrammetric Record*. 21 (115), 269 – 291.

Riddle, L., Hill, T. and Gijsbertsen, B. (2018). Geomorphology from ‘on-high’: The Use of Drones/UAV Technology in Teaching Soil Erosion. *Journal of Geography Education for Southern Africa.* 3(1), 10 – 22.

Schmid, T., Koch, M., Gumuzzio, J. and Medel, I. (2005). Field and Imaging Spectroscopy to Determine Soil Degradation Stages in Semi-Arid Terrestrial Ecosystems. *Proceeding of 4 EARSEL Workshop on Imaging Spectroscopy.* New Quality in Environmental Studies, Warsaw University, Warsaw.

Sonneveld, M., Everson, T. and Veldkamp, A. (2005). Multi-Scale Analysis of Soil Erosion Dynamics in KwaZulu-Natal, South Africa. *Land Degradation and Development*, 16 (3), 287 – 301.

Temme, A., Baartman, J. and Schoorl, J. (2009). Can Uncertain Landscapes Evolution Models Discriminate Between Landscapes Responses to Stable and Changing Future Climate? A Millennial-Scale Test. *Global and Planetary Change*. 69(1 -2), 48-58.

Toth, C., Barkoczi, N., McIntosh, R. and Plasztan, Z.J. (2016). Studying the Development of Fluvial Landforms in the Berettyo-KOROS Region Using Geoinformatics Methods. *Landscape and Environment*. 10(3-4), 137 – 144.

Zhang, G., Zhao, W., Yan, T., Qin, W. and Miao, X. (2023). Estimation of Gully Growth Rate and Erosion Amount Using UAV and Worldview-3 Images in Yimeng Mountain Area, Chine. *Remote Sensing*. 15 (1), 1-17.

CHAPTER TWO

Literature Review

2. Introduction

Soil erosion is a constant process that has shaped the Earth through the progression of the breakdown and removal of rocks or soils (Valentin *et al,* 2005) and is the detachment of particles from the impact of falling/movement of water as the first stage of the movement of soils (Zambon *et al,* 2021). The falling of water (rainfall) on soils is known as splash erosion and is believed to have a greater effect on the removal of sediments than that of runoff, before the stages of rill and gully erosion (Daba *et al,* 2003). The driver behind the process is the Kinetic Energy (KE) transfer from the rain drop to the sediment (Zambon *et al,* 2021). This KE is dependent on the amount and intensity of rain falling, the size of each drop, the fall velocity, and the occurrence of external forces, such as wind. This would determine the volume of soil erosion that could potentially occur in the area of rainfall. This chapter will look at the existing knowledge that is related to gully erosion and its processes while looking at the existing knowledge on UAVs and software related to the mapping of 3D structures.

2.1 Erosional Process

The erosional process is accelerated by the presence of exposed soils as there is little to no vegetation cover to bind the soils together (Chakrabortty *et al,* 2022). Anthropogenic impacts exaggerate these processes, increasing the rate of movement of soils (Daba *et al,* 2003). Soil erosion starts with the concentration of water into a single indentation of overland flow (Kariminejad, *et al,* 2023). The indentation is then slowly eroded, creating a rill. This is not a permanent feature as it is a small erosional landform and can be altered. If the concentration of overland flow continues in this rill, a gully will eventually be formed, which is characterised as an advanced type of soil erosion in which the land is incised, with steep sides and upslope erosion at the head (Poesen *et al*, 1996). Soil erosion can negatively affect land processes by reducing arable land, making landscapes dangerous and unstable and decreasing the land suitable for agricultural practice (Temme *et al,* 2008).

Gullies and rills are distinguished by the cross-sectional area of the landscape. (Poesen *et al,* 1996). This cross-sectional area of the rill must be below 1m^2; once this area has been increased beyond 1m^2 across, a rill will be classed as a gully, whereas a gully is classed as a deeply eroded landscape that removes parent material and surface soils and cannot be removed via tillage (Roy and Saha, 2022). Farmers can recognise the differences between the two by using a pseudoscientific method where they believe if a rill cannot be ploughed through or tilled, it would be classed as a gully. Gullies are more likely to be formed in areas where there has been a decline in erosional resistance and an increase in the forces acting on the land (Bettis & Thompson, 1985). Surface runoff or sheet wash can result from either the saturation of the soil, not allowing any more water to infiltrate and thus forcing the water to flow above the ground. Alternatively, if there are large volumes of rainfall, and if the infiltration rate is low, this will cause water to flow over the ground creating sheet wash. This process erodes the face of the soil and, if an indentation is created, the sheet wash will concentrate within that region, eroding it faster. This could create a micro-rill in which the overflow of water will increase its concentration, creating a rill. This rill, if not attended to, will eventually form a gully where rehabilitation methods would need to be implemented to prevent further erosion.

This type of erosion is the concentration of water to remove soils from settled locations (Kariminejad, *et al*, 2023). The monitoring of this process is retrospective, and it is only by understanding the past that one would be able to understand the future to assist in the prevention and rehabilitation process. The rehabilitation of soil erosion is known to be difficult, at present, as there is no 'one fits all' method of rehabilitation or mitigation method for gully erosion which can lead to large areas of barren land and the removal of vital topsoil (Reubens *et al,* 2009).

Anthropogenic processes increase the rate of erosion through agricultural practices and intensification to meet the demands of human consumption (Reubens *et al*, 2009). The reduction of sustainable arable land through the removal of soil is a direct effect of soil erosion. As erosion is the removal of soil from an area, this leaves the site with unstable lands that are prone to collapse, making it unsafe to farm. The effects of soil erosion on- and off-site can be both negative and positive, for example, offsite deposition can result in land features such as alluvial fans which are known for their fertile soil and mineral resources (Grab & Deschamps, 2004). The effects of erosion can impact the siltation of water bodies downstream from the erosion site, reducing the water storage capacity of dams and lakes, and lowering the useable water. The sediment can blanket water-borne flora downstream preventing access to light. As soil erosion is the movement of soil, a mitigation method would be to determine ways to prevent the soil from being moved. Erosional landscapes such as rills and gullies can be addressed by installing barriers in the pathway of the flow direction, which can be described as hard or soft barriers. Both these methods will reduce the kinetic energy on the soil and allow for the dispersion of flow velocity and reduce the removal of sediment. A study was completed by Le Roux *et al* (2008) in South Africa, looking at water erosion prediction, to which the researchers found the soil loss rate in South Africa to be higher than that of Australia with 90% of KwaZulu-Natal (a province within South Africa) to have high potentials of erosion. While the actual erosional cover approximately 10% with the main source of erosion being overgrazing and extensive cultivation.

To combat the increasing size of gullies, local farmers fill the void with any possible obstruction such as household rubbish, wood, and rocks, this would be an example of hard barriers, as these items create a hard physical barrier (Valentin *et al*, 2005). Multiple preventative methods have been used to reduce the effects of erosion, from increasing vegetation cover by planting particular species or encouraging vegetation growth, to mechanical means of slope reduction, stone packing, and wall building (Reubens *et al*, 2009). This practice is generally completed by placing physical barriers in the path, be it stones or gabions. The lack of macro pores and crusting increase the runoff and decreases the infiltration of surface runoff, thus increasing the potential kinetic energy of the surface runoff and its ability to remove soils (Keesstra *et al*, 2016). Ideally, one would initiate the mitigation method with a hard barrier to prevent the soils from moving and then implement soft barriers to assist with the bonding of the 'saved' soils. One can install soft barriers such as crops, which are physical barriers, however, do not consist of hard physical structures and can be aesthetically more appealing to that of a hard or physical barrier, thus blending into nature. These are grown on-site and mitigate the effects of soil movement by hindering or slowing down the flow of overland flow. However, this method is reliant on the ability of crops to grow in an unstable environment such as a gully. It has been found that vegetation is one of the most critical paraments in preventing or reducing soil erosion (De Asis & Omasa, 2007). Surface roughness hinders the movement of surface runoff and can increase infiltration and reduce soil erosion. Soil with vegetation coverage, has a better soil structure, higher protection against a detachment of sediments and a reduction in vulnerability (Seutloali & Beckedahl, 2015).

The method used at the research site, Okhombe Valley, KwaZulu-Natal, is stone packing, using available rocks from the surrounding hillslopes. This in itself is not sustainable and can lead to less protection and increased surface wash on the surrounding slopes, so by no means ideal. This method of mitigation is laborious and time-consuming as the community collect and transports the stones to the site. This is a method the community has been using to attempt to hinder the erosional processes in the gullies located within the site as well as to prevent the occurrence of a gully forming by placing the stone pack in rill and footpaths.

2.2 Soil Erosion Monitoring

The monitoring of soil erosion dates back to the birth of soil science and pedology, where Vasily Dokuchaev would map soil types and plot this on a map in the late 1800s (Arrouays *et al,* 2021). Due to the demands placed on soils, the monitoring of the movement and mitigation of the movement. This said the monitoring of soils, can be completed in multiple ways, to produce the outcome one requires, such as the remote sensing of the soils, or physical testing on site of soil. The monitoring of soils is not only required, as environmental aspects, such as temperature and rainfall but it is also required to determine plant health, due to the correlation between areas of low plant health and soil erosion, as this would assist in determining potential areas of future erosion and thus allow for the implementation of mitigation methods (Rowntree, *et al*, 2004). Soil monitoring and soil erosion monitoring are vital for food security, with low soil qualities (infertile, low nutrient) and high degrees of soil erosion, the soil would not yield sufficient crops, resulting in a declining food supply (Sepuru and Dube, 2018). Soil monitoring can be conducted by three techniques, namely empirical, conceptual, and physical (Sepuru and Dube, 2018). Empirical models are based on what is observed or experimented on, while conceptual models, consider the representation of reality, producing different models with what each was based on, which can create a variant in results. Conceptual is regarded as the halfway point between empirical and physical. Physical modelling is a model of physical parameters based on the fundamental knowledge of erosional processes. These three models incorporate aerial photography, remote sensing, plot monitoring, and rainfall simulation. Where satellite remote sensing is classed as both empirical modelling and physical modelling. From these were able to determine Soil Organic Carbon.

Soil Organic Carbon (SOC) is crucial for the health and productivity of the soil (Viscarra Rossel, *et al,* 2016). SOC increases crop yield and can increase carbon emissions (Nie *et al,* 2018). The yield is increased as SOC assists the development of soil structure, improves water storage, protects, and hinders the effects of soil erosion. The sampling of SOC is conducted by obtaining soil samples and measuring in the laboratory with the use of Visible-Near infrared (VIS-NIR). According to Nie *et al* (2018), they found a correlation between SOC and the thermal reflectance of soils. VIS-NIR includes the visible (350 – 780nm) and the near-infrared (780 – 2500nm) ranges (Fang *et al*, 2018). Near-Infrared and Red bands are potentially the most important for determining vegetation index, as vegetation reflectance in the red band is low and high on the near–infrared (Phinzi & Ngetar, 2017).

There have been studies and methods used to monitor soil erosion and to determine the amount of soil loss, such as the Revised Universal Soil Loss Equation (RUSLE) (equation 1) (Alkharabsheh, *et al*, 2013).

$$A=R \times K \times LS \times C \times P \qquad (1)$$

Where A is the calculated spatial average of soil loss per unit area (t/ha/yr.), R is the rainfall-runoff factor, K is the soil erodibility factor, L is the slope length, S is slope steepness, C is vegetation cover and P is the erosional control practice. The C factor can be calculated with the use of GIS and remote sensing, which can assist researchers in calculating the soil loss. This is advantageous to researchers in understanding soil movement and can assist farmers in obtaining rapid results of what their land is experiencing at that particular time. The limitation of this method occurs when one looks at a larger area as this method uses smaller sample areas (plots) (Lu *et al*, 2004). The use of the RUSLE, GIS and remote sensing allows for an improved understanding of soil loss in a given area and assists in the conservation plans and creation of a development guide (Lu *et al*, 2004).

The monitoring of soils can be completed remotely using satellite images, GIS, aerial images, and remote sensing (Lu *et al*, 2004). These methods obtain large-scale data sets of regional to continental size maps, however, larger areas often are not accurate compared to that of smaller scale they delineate the maps for ease of drawing and viewing (Arrouays *et al*, 2021). This is where aerial photography can assist, as the images are captured closer to the ground surface and thus obtain a high-resolution image of a site (Table 2.2.).

2.3 Soil erosion mapping and Unmanned Aerial Vehicles (UAV)

The mapping of soil erosion is a complex process as no one erosional landscape is the same, varying in space and time, making it difficult to map at the fine scale required (Toth *et al*, 2016). This is due to the complex shapes and textures located within the landscapes. Small erosional features have the potential of developing into larger features and thus it is important to be able to map these smaller features.

Fine detail is required to locate and map smaller features located within these landscapes. There is a plethora of methods currently in use to assist in the mapping of soil erosional landscapes and the mapping process has become obtainable from the use of GIS, satellite imagery and remote sensing (Lu *et al,* 2004). In the past, the practice of validation of one's results of erosion mapping was to complete physical surveys and compare the results (De Asis & Omasa, 2007).

The measurements were often not completed or applied as the labour and time required outweighed the need. This leaves a gap in the research process as the manual mapping and validation of 3D landscapes are not complete (De Asis & Omasa, 2007). This is an opportunity for the application UAV with the approach that can complete the validation and possibly replace the current methods. The technology dates back to 1916 when the Sperry Gyroscope company developed a control system that controlled a Curtiss Flying bomb automatically, for the purpose of being a flying bomb (Cook, 2006). The development of cruise missiles or aerial torpedoes during the Second World War (Keane and Carr, 2013), was an unmanned aerial craft that was designed to strike from a distance. The capabilities of a UAV for aerial imagery and surveillance date to late 1959, when the USA Air Force commissioned a remote-controlled aircraft for photographic surveillance missions (Cook, 2006).

The technology was developed for use in warfare however, it has migrated to the public sector and the hobbyist community, to provide an image-capturing technology to fit into small fixed-wing crafts and single rotary air crafts. A four-propeller craft was developed to improve control, manoeuvrability, stability, and the ability to hover in a stationary position (Jordan, 2015). Today’s UAV is a device that can be controlled remotely by a pilot or can be preprogramed to conduct tasks that were previously programmed into the device and complete the tasks autonomously. They can either be fixed-winged or propeller-driven craft, with the most common are multi-rotors because they don’t require landing and take-off areas like the fixed wing. However, many of these crafts cannot hover or remain stationary and thus result in blurry aerial images. The propeller-driven quadcopter (UAV) can hover in a stationary position for long periods to obtain a clear image.

A UAV has the potential of carrying a payload within its structure. These payloads comprise cameras or sensors to remotely capture images in both the visible and near-infrared spectrum, and a sampling apparatus to obtain samples remotely. Image Spectroscopy (IS) sensors were first operated on board aircraft. Although the images were low in quality as the level of noise negatively impacted captured images, preventing the results from being useable (Ben-Dor, *et al*. 2009). Today these IS sensors are placed onto stable and smaller crafts, allowing for great clarity and more useable images. With the advancement in space travel, these IS sensors can now be mounted on satellites allowing for the first world-based mapping apparatus, mapping large areas in a relatively short period. However, this is only as accurate as the satellite sensors used or available at the time of mapping. These resulting images would be useful in strengthening our understanding of larger areas whereas smaller and more intricate landforms were lost in the image. Technologies are continuously being developed to produce a higher-resolution image for mapping landscapes (Van Lynden & Mantel, 2001).

Image Spectroscopy (IS) sensors on aircraft are increasingly accurate and produce less noise, but still lack the ability to fly close to the ground for a high-resolution image, due to the safety of both the aircraft occupants and the public on the ground (Ben-Dor, *et al*. 2009). These IS sensors were then placed onto remote control aircraft which allowed researchers to gain access to previously not possible sites. These platforms had limitations as the IS sensors were hard fixed to the aircraft and imaging errors arise when the aircraft are not flying horizontally to the ground. With the introduction of UAV, and the ability to hover at a single position and attach the IS to a gimble to reduce or remove all noise or distortion in the image. However, the use of UAVs and remote optical sensing only can analyse the surface of the soil and not the entire body (Ben-Dor, *et al*. 2009). This creates a challenge in the understanding of soils. In this regard, the surface of the soil still offers information such as salinity, degradation, organic matter, moisture, runoff, and infiltration (Ben-Dor, *et al*. 2009). Past technology allowed users to install sensors below manned aircraft to capture soil moisture with the use of multi-spectral and thermal sensors, this is now possible to install these sensors onboard a UAV, and the sensors' sizes and hence weight have been reduced.

Remote sensing from satellites is one of the few methods of monitoring the landscapes both temporally and spatially from a continental to a regional scale (Jiao *et al*, 2021). Satellite imageries can determine the movement of soils from sequential times, including the ability to map precipitation and land surface temperature (Jiao *et al*, 2021). This can assist in the understanding of soil movement as areas with low precipitation and high land surface temperature, have lower vegetation cover and thus more exposed soils, to be eroded (Jiao *et al*, 2021).

The UAV can produce aerial images of a site with higher resolution compared to that of the SPOT 5 imagery (Le Roux & Sumner, 2012). The resolution of the SPOT 5 images is 2.5 m. When one considers the size of small erosional features, then this resolution is to the course and would not map the smaller features found within an erosional landscape. This means that the processes of gully formation will not be mapped and thus be outside of the scope of the resolution when using these techniques (Mararakanye & Sumner, 2017). The technology to map features is not a new concept, but rather a concept used in alternative fields, such as engineering, where civil engineering gain 3-Dimensional (3D) models of structures (Strecha *et* *al*, 2012). The technology can be used to map land features and has been passed to map gully erosion, thus proving the possibility of mapping gullies remotely. Landsat8 is adequate for large areas and catchment scale studies. These resolutions (1:30m) would not be able to map individual gullies or rill and the movement of these erosional landforms would be lost. Spot6/7 has a high resolution and can map larger erosional landforms such as gullies. They both still cannot micro-map the features within a gully or rill. As the UAV has a 0.03m resolution, it can map rill features within gullies and could potentially adjust the way researchers understand the movement of soils (Gonzáles & Rodriguez, 2017).

Projects such as the Geographic Object-Based Image Analysis (GEOBIA) have been developed to identify and extract data regarding soil erosion using remote sensing (Mararakanye & Nethengwe, 2012). The study used SPOT 5 imagery to determine the location of soil erosion landscapes but did not map the gullies in 3D, as the imagery used had a resolution of 30 m (Mararakanye & Nethengwe, 2012). This has developed a 'miss or gap' in the knowledge of remotely identifying gullies and erosional landscapes. As these images are from a satellite, the image produced does not display smaller features or 3D scan smaller features. Satellite images and aerial photography are relevant sources of aerial imagery to study the evolution, morphology, and dynamics of the movement of land (González & Rodriguez, 2017). These methods are still practised as it is only by understanding the past movement of soils from studying past images to determine patterns, we will be able to monitor and manage land practices. Satellite images and aerial photography allow for a chronological investigation of the movement of landscapes to understand the dynamics behind the movement, showing the understanding of how the soils move, and allowing for the possible future prediction of soil movement. Satellite images and aerial photography assist in the monitoring of gullies and assisting in the monitoring of the impacts of erosion management as well as determining methods of management that work and the methods that do not work in an area.

The UAV has the potential to map soil erosion and develop 3D modelling to improves understanding of landscapes and the movement of soils, at a high level of accuracy and resolution. At present, aerial imagery from manned crafts and satellites cannot capture the erosional features. A UAV has been used to obtain aerial imagery with a resolution of 0.03m, allowing for the possibility of the mapping of smaller features located within a gully (González & Rodriguez, 2017). A study by Chidi *et al* (2021) in Nepal measured the slope angle with the use of a UAV. This research shows that a coarse resolution of 10m x 10m overlooked smaller land features found on the slop, thus minimising the complexity of the slope, and overlooking important features or details located on the slope (Chidi *et al*, 2021).

Table 2.1: List of the commercially available UAVs including average prices per craft.

Name	Price in US Dollars
APEX Air	$200-00
DJI Mini 2	$600-00
Holy Stone HS720E	$300-00
DJI Mavic 2 Enterprise	$6700-00
Elios 2	$33000-00 - $52 000-00
DJI Matrice	$6000-00 - $12 000-00
Parrot Anafi	$9500-00
DJI Phantom 4	$1200-00 - $7300-00

Many commercially available UAVs, have onboard cameras mounted to the airframe with a 3-axis gimbal, however the more features and technology placed onto the UAV, the higher the price (Table 2.1). The UAVs listed are considered the most popular or widely used, however, there are more UAVs on the market, with price per craft varying depending on the technology attached to the UAV. Camera sensors are standard RGB sensors and only process reflected light, while the majority nonspecialised commercially available cameras do not have multispectral sensors which are beneficial to the aerial mapping and photography of landscapes. These sensors are mounted onto manned aerial crafts and satellites, and these technologies are superior to that of the UAV. Thus, UAVs should not replace the technologies used, but rather assist the technologies, to create the ideal aerial imagery. UAVs are at present electronic, running off battery power. Thus, flight time is limited to no more than 30min for most UAVs, which is a relatively short flight time that could hinder the mapping of extensive areas. However, due to the quick change of batteries, it can easily be overcome, by dividing the mapping into sections and later stitching them together to create a single image.

The mapping of soil erosional features is a relatively simple task with a UAV. The aerial imagery is produced and stitched together to create a single image. With the advancements in technology, 3D programs have been developed to use the images taken from a UAV and recreate a 3D computer render of the landscapes, using a method named Structure from Motion (SfM) to recreate the landscape (Zhang *et al,* 2023). This is possible as the UAV records the GPS location, camera angle, and height that the UAV is above the ground to locate each image in relation to the next image, thus creating a 3D-rendered model. For example, mapping the movements of glaciers (Bhardwaj *et al*, 2016). Due to the remoteness of glaciers, UAVs have until recently not been viable (Bhardwaj *et al*, 2016). According to Bhardwaj *et al*, (2016), research has been conducted on the High-Altitude Long Endurance (HALE) UAV which would be solar powered to allow for long flight times and higher altitudes. Airborne LiDAR and the use of Terrestrial Laser Scanners (TLS) have improved the ability of users to create 3D images of a landscape (Wang *et al*, 2016). A case study was completed in Japan, where researchers investigated various campsites and mapped the surface topography and how campers affected the region (Wang and Watanabe, 2022). The researcher utilised the UAV and photogrammetry technique to determine the removal of soils, to which they found the rapid deterioration of vegetation cover during the few first years of opening and the removal of soils.

3D scanning of objects and landscapes has been and continues to be conducted with the use of Terrestrial Laser Scanners (TLS). This device is expensive and cumbersome to use. At present, the user would need to set up the device within the gully or erosional landscape. The device would need to be set correctly, and the user would need to remove themselves from the scanning area. The scanning processes would be conducted, and the device would scan the immediate ‘seen’ area around the device. The GPS location of the device is recorded, and the process is then repeated in another area. These data would then need to be processed and mapped in the correct location to produce a 3D map. This process can take several minutes to hours to complete, and the user would have to enter an unstable erosional landscape (Wang *et al*, 2016).

2.4 Soft- and Hardware

The UAV is an aerial vehicle that is either remotely controlled or programmed to complete a task autonomously. These aerial vehicles have been used in various applications including the military, while the concept then moved to place cameras on the UAV to gain access to the feeling of flying from the safety of the ground. Fixed-winged aircraft were the first to use this concept. However, imagery errors would occur as the camera was fixed to the craft and when the craft pitched, rolled, or vibrated, the image would be distorted. The solution was to isolate the camera from the craft using a gimbal. This improved the image quality, however as fixed-winged crafts require movement to remain in the sky, which can create a blur or irregularities in the image. As the technology evolved, so did the hobbyist crafts. A quadcopter/UAV became popular, with the ability to take off and land vertically. These crafts slowly became the craft of choice for aerial imagery. The 4-propeller craft configured in an ‘X’ formation is a relatively stable craft, with the use of a mechanical 3-axis gimbal to isolate the camera from the craft, and increased image quality (Jordan, 2015). This allows the aircraft to move in any direction while the camera itself remains stationary, allowing for stable imagery. Once the image quality was sufficient, the use of manned crafts became unnecessary. The UAV became useful for its ease of use, relatively cost-effectiveness and image quality, and allowing users to gain aerial images of locations previously not possible. The use of the UAV allowed users to fly and capture images on cloudy days, previously not possible with manned crafts. These UAV crafts can be commercially bought for the required purpose such as the DJI brand (www.DJI.com) or purpose-built from the ground up to include features that are specific to each task. This software allows civil engineers to take multiple images of structures or buildings at different angles and reproduce a 3-Dimensional model on a computer.

A diversity of software packages has been developed to assist in the mapping of landscapes and vegetation health. This software falls into two categories, namely off- and online. The categories have both positives and limitations to each and deciding on a particular product is user preference and application dependent. Off-line software packages are downloaded to a personal computer and require large amounts of computer processing abilities. This allows users to remotely capture images and commence the processing of the results in remote locations without the use of the internet, thus allowing users to be completely remote. This does have its limitations as the processing times of the images are dependent on one's computer processing abilities. Slow processing power would mean large processing times, reducing results and data generation time. This can be adjusted by adding a faster processor however, this can be costly. The second category is online, which requires internet access. This software uses the ability to have a 'slave' software that is the user interface for software stored in the cloud. Also known as Cloud computing software (Saura, *et al*, 2019), which does not require expensive computers with fast processing powers. The user uploads the images to their user's interface application and submits this to a remote computer that can process large amounts of images. Once processing is complete, the results are displayed on the user's application. This allows for the rapid processing of images and a rapid response time. The limitation of these is that it is reliant on internet strength and speed, slow to no internet means that this method would take the time or not work.

Off-line software such as *AgiSoft*, *Altizure* and *UgCS* allows users to remotely process data without internet access, although these are processing-laden software and take time to complete the processing of data. *DroneDeploy* is an online/cloud-based software that allows users the use any computer or mobile device that has access to the internet to process images and obtain results. Both the on- and off-line software can process the images captured from either an RGB camera or a multi-spectral camera to process data such as 3D landscape, plant health and diversity of vegetation (Hodgson *et al,* 2018). The RGB camera is not able to capture the reflectance of near-infrared and determines the health of plants from its reflectance. These wavebands are then processed with Visible Atmospherically Resistant Index (VARI) to estimate plant health. This is an estimate, however with the use of a multispectral camera and Normalized Difference, Vegetation Index (NDVI) one can determine plant health. Thus, a combination of the RGB and the multispectral camera provides users with the most representative images (Miller *et al*, 2020).

The software through orthomosaic, where the higher degree of overlap of each image is beneficial to the results (Küng *et al,* 2011), can produce a 3D image. This research utilises both on- and offline software to compare the applicability, speed, and digital replication of data within the field of gully mapping. As the technologies develop and become increasingly accessible and cost-effective, the imaging platforms become larger and lighter allowing for inclusion into UAVs, users can place these platforms in localities previously not possible. This opens up the opportunity of obtaining new information and improving the current knowledge of gully mapping. One of these platforms is the multi-spectral and thermal imagery systems, which allow for multiple bands and thermal reflectance to be recorded. The UAV can carry a diverse array of payloads and is dependent on the mission required, be it chemical, visual, biological, or acoustic (Pedro *et al*, 2022). The platform used in this research was the Micasense Altum Multi-Spectral and Thermal imagery device (Plate 2.1). This device measures 8.2cm x 6.7cm x 6.45cm and weighs 407 grams (Hutton, *et al,* 2020), and can capture five spectral bands (red, green, blue, red-edge and near-infrared) and a Longwave Infrared (LWIR) thermal camera. RGB cameras are useful for their high spatial resolution which makes them suitable for analysing and monitoring the degradation and movement of soils. The RGB sensor is unable to capture the reflection of vegetation and soils from the invisible light spectrum, which could result in loss of information such as water content and plant health (without software calculation) (Gonzáles & Rodriguez, 2017). However, both the RGB and Multi-sensor cameras, with the assistance of GIS or image manipulation software calculate parameters such as Normalized Difference Vegetation Index, thus allowing for further investigation with the use of GIS software and resulting images from both sensors.

Plate 2.1: The Micasense Altum Multi-Spectral and Thermal imagery device on a UAV.

Normalized Difference Vegetation Index (NDVI) has been used to determine the vegetation cover management factor (C-Factor) for the Revised Universal Soil Loss Equation (RUSLE) (Alkharabsheh *et al*, 2013 and Jiao *et al*, 2021). The NDVI is a ratio between the red bands and near-infrared bands on the spectrum (Mbatha and Xulu, 2018). The NDVI is a major parameter used to monitor vegetation, allowing for the monitoring of temporal and surface spatial changes (De Carvelho, *et al*. 2014), and assisting in determining soil and crop health. According to Saura *et al*, (2019), the NDVI can be used to estimate the development, quantity, and quality of vegetation through remote sensing. A technique of combining GIS and RUSLE has been tested and proven to accurately estimate the spatial distribution and magnitude of soil erosion (Lu *et al*, 2004). The combination of GIS and RUSLE can be manipulated to incorporate the use of a UAV to improve the accuracy and resolution of the results. The technique of combining GIS and RUSLE allows one to estimate the C-Factor on a pixel-to-pixel basis, however, the accuracy of calculating soil erosion is low due to the equation being expressed as average soil loss per year, thus limiting this technique to calculating annual averages and no single events. One of the extensively utilised imaging sources is the Landsat 8 (Phinzi & Ngetar, 2017). This has a spatial resolution of 30m for its bands 1-7 and 9 (Table 2.2), band 8 is a panchromatic band with a spatial resolution of 15m, and thermal bands (10 and 11) have a spatial resolution of 100m. The SPOT 6/7 is multispectral with a 6m spatial resolution and a panchromatic band of 1.5 spatial resolution. The LandSat 8 was seen to be successful apart from two issues: (Masek, *et al*, 2020) i) the optical design flaw and ii) an early orbit failure, that led to the requirements for LandSat 9 and 10, of which the LandSat 9 was launched in September 2021 (Masek, *et al*, 2020). The spatial resolution is identical to that of the LandSat 8. An alternative satellite imagery system, from Planet Scope, has the use of approximately 180 satellites that can produce a spatial resolution of 3m, which is greater than that of the LandSat 9 (Niroumand-Jadidi *et al*, 2022).

Table 2.2: Types of raster images and their associated spatial and spectral resolution (Gonzáles & Rodriguez, 2017).

Raster Image	**Date of Initial Use**	**Spatial Resolution / Scale**	**Spectra Resolution**
Aerial Photograph	1956	1: 25000	Panchromatic
Aerial Photograph	1961 – 1967	1: 30000	Panchromatic
Landsat 8 Images	June 2013	15m 30m	Panchromatic Blue, Green, Red, NIR, 2 SWIR
Spot 5 Images	September 2013	2.5m 10m / 20m	Panchromatic, Green, Red, NIR/1, SWIR
UAV	March 2015	0.03m	Natural Colour (R-G-B) Multispectral (G-R-NIR)

2.5 Conclusions

Soil erosion is the concentration of a medium over soils that create the detachment and movement of particles away from a site. This can be in the form of overland flow, rill erosion or the more advanced, complex, and extensive gully erosion, formed from the concentration of water during overland flow, creating, initially a rill leading to the formation of a gully. Gullies have a clear negative impact on the local environment, impacting areas of arable land and creating instability in the soils. The mapping and monitoring of these features have been undertaken in the past with the use of aerial imagery, satellite imagery, satellite laser scanning and land-based 3D scanning and experiments and monitoring directly on the soils. However, this can be expensive, time-consuming and lacks the resolution to map finer details located within an erosional landscape. This allows the incorporation of new technologies such as UAVs that can assist in obtaining 3D images of the landscape, at a lower cost, relative ease of use and a higher degree of accuracy.

The UAV can be a tool with a diverse range of applications, while still being a relatively cost-effective medium that is attainable for most researchers. The UAV started as a device used for warfare and slowly moved to the hobbyist community and then to the cinematography and research fields, and today is available from electronic stores at reasonable prices. However, the high-end UAV, with multiple sensors and specific payloads, needs to be purchased from a designated dealer as these UAVs are specialised in their applications. The UAV can be set to autonomously fly a designated route (that can be replicated) to obtain multiple images to be uploaded to orthomosaic software to create a 3D replication of the landscape. This software can be both on- and offline. The software recreates the scanned objects with a high degree of visual replication, however, the fine details, such as vegetation clumps, rills, and smaller features, are yet to be replicated digitally. As a gully landscape is an area of complexity and texture, the UAV software combination has the potential to accurately map both the larger broad-scale and the finer features within the landscape. This is the central premise of this research, asking the questions, would it be possible to map an erosional landscape using a UAV and can we manipulate this information to improve our understanding of how erosion takes place, monitor change through time and as a consequence of land use practices and erosional mitigation processes, and predict future movement, shifts or erosional direction of the soil? Are we able to monitor rehabilitation or mitigation methods to determine if they are functional, successful and the ideal method for a specific landscape? For the UAV to be successful, the implantation of transdisciplinary studies to improve the technology to thus improve the ability to map and monitor gullies is crucial. As this will allow for the targeted technology required for the mapping and monitoring of gullies to prove results that replicate the gully and the finer features within each gully.

References

Alkharabsheh, M., Alexandridis, T., Bilas, G., Misopolinos, N. and Silleos, N. (2013). Impact of Land Cover Change on Soil Erosion Hazard in Northern Jordan Using Remote Sensing and GIS. *Procedia Environmental Science*. 19, 912 – 921.

Arrouays, D., Mulder, V. and Richer-de-Forges, A. (2021). Soil Mapping, Digital Soil Mapping and Soil Monitoring Over Large Areas and The Dimensions of Soil Security - A Review. *Soil Security,* 5 (2021), 1 – 12.

Ben-Dor, E., Chabrillat, S., Demattê, J., Taylor, G., Hill, J., Whiting, M. and Sommer, S. (2009). Using Imaging Spectroscopy to Study Soil Properties. *Remote Sensing of Environment.* 113, S38 – S55.

Bettis, E. and Thompson, D. (1985). Gully Erosion. *Rangelands*. 7(2), 70 – 72.

Bhardwaj, A., Sam, L., Akanksha., Martin-Torres, F. and Kumar, R. (2016). UAVs as Remote Sensing Platform in Glaciology Present Application and Future Prospects. *Remote Sensing of Environment*. 175, 196 – 204.

Chakrabortty, R., Chandra Pal, S., Santosh, M., Roy, P., and Chowdhuri, I. (2022). Gully Erosion and Climate Induced Chemical Weathering for Vulnerability Assessment in Sub-Tropical Environment. *Geomorphology,* 398, 1 – 18.

Chidi, C., Zhao, W., Chaudhary, S., Xiong, D. and Wu, Y. (2021). Sensitivity Assessment of Spatial Resolution Difference in DEM for Soil Erosion Estimation Based on UAV Observations: An Experiment on Agriculture Terraces in the Middle Hill of Nepal. *International Journal of Geo-Information*, 10 (28), 1-17.

Cook, K. (2006). The Silent Force Multiple: The History and Role of UAVs in Warfare. *IEEE Aerospace Conference 03 – 10 March 2007.* Big Sky, MT, USA.

Daba, S., Rieger, W. and Strauss, P. (2003). Assessment of Gully Erosion in Eastern Ethiopia Using Photogrammetric Techniques. *Catena*, 50 (2-4), 273 – 291.

De Asis, A. and Omasa, K. (2007). Estimation of Vegetation Parameter for Modelling Soil Erosion Using Linear Spectral Mixture Analysis of Landsat ETM Data. *ISPRS Journal of Photogrammetry and Remote Sensing*. 62 (4), 309 – 324.

De Carvalho, D., Durigon, V., Antunes, M., De Almedia, W. and De Oliveria, P. (2014). Predicting Soil Erosion using RUSLE and NDVI Time Series from TM Landsat 5. *Pesquisa Agropecuária Brasileira*. 49(3), 215 – 224.

Fang, Q., Hong, H., Zhao, L., Kukolich, S., Yin, K. and Wang, C (2018). Visible and Near-Infrared Reflectance Spectroscopy for Investigation Soil Mineralogy: A Review. *Journal of Spectroscopy*. Article ID 3168974, https://doi.org/10.1155/2018/3168974, 1-14.

Grab, S., and Deschamps C. (2004). Geomorphological and Geoecological Controls and Processes Following Gully Development in Alpine Mires, Lesotho. *Arctic, Antarctic, and Alpine Research*. 36 (1), 49 -58.

González, M. and Rodriguez, P. (2017). Monitoring Soil Erosion by Raster Images: From Aerial Photographs to Drone Taken Pictures. *European Journal of Geography*. 7(5), 117 – 129.

Hodgson, J., Mott, R., Baylis, S., Pham, T., Wotherspoon, S., Kilpatrick, A., Segaran, R., Reid, I., Terauds, A. and Koh, L. (2018). Drones Count Wildlife More Accurately and Precisely Than Humans. *Methods in Ecology and Evolution*. 9(5), 1-8.

Hutton, J., Lipa, G., Baustran, D., Sulik, J., and Bruce, R. (2020). High Accuracy Direct Georeferencing of the Altum Multi-Spectral UAV Camera and its Application to High Through put Plant Phenotyping. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*. XLIII (B1), 451 – 456.

Jordan, B. (2015). A Birds Eye View of Geology: The Use of Micro Drones/UAV in Geologic Fieldwork and Education. *The Geological Society of America*. 25(7), 42 - 43.

Jiao, W., Wang, L., and McCabe, M. (2021). Multi-Sensor Remote sensing for droughts Characterisation: Current Status, Opportunities and a Roadmap for the Future. *Remote Sensing of Environment*, 256, 1 – 121.

Kariminejad, N., Sepehr, A., Poesen, J. and Hassanli, A. (2023). Combining UAV Remote Sensing and Pedological Analysis to Better Understand Soil Piping Erosion. *Geoderma*. 429, 1 – 15.

Keesstra, S., Pereira, P., Novara, A., Brevik, E., Azorin-Molina, C., Parras-Alcántara, L., Jordán, A., and Cerdà, A. (2016). Effects of Soil Management Techniques on Soil Water Erosion in Apricot Orchards. *Science of the Total Environment*. 551 – 552(2016), 357 – 366.

Keane, J and Carr, S. (2013). A Brief History of Early Unmanned Aircraft. *John Hopkins APL Technical Digest*. 32(3), 558 - 571.

Küng, O., Strecha, C., Fua, P., Gurdan, D., Achtelik, M., Doths, K. and Strumpf, J. (2011). Simplified Building Models Extraction for Ultralight UAV Imagery. International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences. Volume XXXVIII-1, 217 – 222.

Le Roux, J., Morgenthal, T., Malherbe, J., Pretorius, D. and Sumner, P. (2008). Water Erosion Prediction at a National Scale for South Africa. *Water S.A*, 34(3), 305-314.

Le Roux, J. and Sumner, P. (2012). Factors Controlling Gully Development: Comparing Continuous and Discontinuous gullies. *Land Degradation and Development*, 23(5), 440-449.

Lu, D., Li, G., Valladares, G. and Batistella, M. (2004). Mapping Soil Erosion Risk in Rondônia, Brazilian Amazonia: Using RUSLE, Remote Sensing and GIS. *Land Degradation and Development*. 15 (5), 499 -512.

Mararakanye, N. and Nethengwe, N. (2012). Gully Features Extraction Using Remote Sensing Techniques. *South African Journal of Geomatics*. 1(2), 109 – 118.

Mararakanye, N. and Sumner, P. (2017). Gully Erosion: A Comparison of Contribution factors in Two Catchments in South Africa. *Geomorphology*. 288, 99 -110.

Masek, J., Wulder, M., Markham, B., McCorkel, J., Crawford, C., Storey, J., and Jenstrom, D. (2020). LandSat 9: Empowering Open Science and Applications through Continuity. *Remote Sensing of Environment*. 248, 1 - 13.

Mbatha, N. and Xulu, S. (2018). Time Series Analysis of MODIS-Derived NDVI for the Hluhluwe-Imfolozi Park, South Africa: Impact of Recent Intense Drought. *Climate*, 6 (4), 1 – 24.

Miller, I., Schieber, B., De Bey, Z., Benner, E., Ortiz, J., Girdner, J., Patel, P., Coradazzi, D., Henriquez, J. and Forsyth, J (2020). Analysing Crop Health in Vineyards Through a Multispectral Imaging and Drone System. System and Information's Engineering Design Symposium. Charlottesville, VA, USA, 24 April 2020, 1- 5.

Nie, X., Li, Z., Huang, J., Liu, L., Xiao, H., Liu, C., and Zeng, G. (2018). Thermal Stability of Organic Carbon in Soil Aggregate as Affected by Soil Erosion and Deposition. *Soil and Tillage Research*. 175 (January 2018), 82 – 90.

Niroumand-Jadid, M., Legleiter, C. and Bovolo, F. (2022). Bathymetry Retrieval from CubeSat Image Sequences with Shirt Time Lags. *International Journal of Applied Earth Observations and Geoinformations*, 112 (2022), 1 – 19.

Pedro, J., Cardoza, J., Montero, P., Ruiz-Carulla, R., Alcoñiz, J., Serra, D. and Carabassa, V. (2022). Drone Based Identification of Erosive Processes in Open-Pit Mining Restored Areas. *Land*, 11(2), 1 – 13.

Phinzi, K and Ngetar, N. (2017). Mapping Soil Erosion in a Quaternary Catchment in Eastern Cape using Geographic Information System and Remote Sensing. *South Africa Journal of Geomatics*. 6(1), 11 – 29.

Poesen, J., Vandaele, K. and Van Wesemael, B. (1996). Contribution of Gully Erosion to Sediment Production on Cultivated Lands and Rangelands. Erosion and sediment yield: Global and Regional Perspectives. Proceedings of the Exeter Symposium in July 1996. IAHS Publish No 236, 1996.

Reubens, B., Poesen, J., Nyssen, J., Leduc, Y., Abraha, A., Tewoldeberhan, S., Bauer, H., Bebrehiwot, K., Deckers, J. and Muys, B. (2009). Establishment and Management of Woody Seedling in Gullies in a Semi-Arid Environment (Tigray, Ethiopia). *Plant and Soil*. 324 (1-2), 131 – 156.

Rowntree, K., Duma, M., Kakembo, V. and Thornes, J. (2004). Debunking the Myth of Overgrazing and Soil Erosion. *Land Degradation and Development*. 15 (3), 203 – 214.

Roy, J. and Saha, S. (2022). Ensemble Hybrid Machine Learning Methods for Gully Erosion Susceptibility Mapping: K-Fold Cross Validation Approach. *Artificial Intelligence in Geosciences*. 3(2022), 28 – 45.

Saura, J., Reyes-Menedez, A., and Palos-Sanchez, P. (2019). Mapping Multispectral Digital Images Using a Cloud Computing Software: Applications from UAV Images. *Heliyons*, 5(2), 1-22.

Sepuru, T. and Dube, T. (2018). An Appraisal on the Progress of Remote Sensing Application in Soil Erosion Mapping and Monitoring. *Remote Sensing Applications: Society and Environment*. 9 (January 2018), 1-9.

Seutloali, K and Beckedahl, H. (2015). Understanding the Factors Influencing Rill Erosion on Roadcuts in the South Eastern Region of South Africa. *Solid Earth*, 6(2), 633 – 641.

Strecha, C., Kung, O. and Fua, P. (2012). Automated Mapping Ultra-Light UAV Imagery. EUROCOW 2012, Barcelona, Spain, February 8-10, 2012.

Temme, A., Baartman, J., Botha, G., Veldkamp, A., Jongmans, A. and Wallinga, J. (2008). Climate Control on Late Pleistocene Landscape Evolution of the Okhombe Valley, KwaZulu Natal, South Africa. *Geomorphology*. 99 (1-4), 280 – 295.

Toth, C., Barkoczi, N., McIntosh, R. and Plasztan, Z.J. (2016). Studying the Development of Fluvial Landforms in the Berettyo-KOROS Region Using Geoinformatics Methods. *Landscape and Environment*. 10(3-4), 137 – 144.

Valentin, C., Poesen, J. and Yong, Li. (2005). Gully Erosion: Impacts, Factors and Control. *Catena*. 63(2-3), 132 – 153.

Van Lynden, G. and Mantel, S. (2001). The Role of GIS and Remote Sensing in Land Degradation Assessment and Conservation Mapping: Some User Experiences and Expectations. *International Journal of Applied Earth Observations and Geoinformation*. 3(1), 61 -68.

Viscarra Rossel, R., Brus, D., Lobsey, C. Shi, Z. and McLachlan, G. (2016). Baseline Estimates of Soil Organic Carbon by Proximal Sensing: Comparing Design-Based, Model-Assisted and Mode-Based Inference. *Geoderma*, 265, 152 - 163.

Wang, T. and Watanabe, T. (2022). Monitoring Campsite Soil Erosion by Structure-from-Motion Photogrammetry: A Case study of Kuro-Dake Campsite in Daisetsuzan National Park, Japan. *Journal of Environmental Management*. 314(2022), 1 – 10.

Wang, R., Zhang, S., Pu, L., Yang, J., Yang, C., Chen, J., Guan, C., Wang, Q., Chen, D., Fu, B., and Sang, X. (2016). Gully Erosion Mapping and Monitoring at Multiple Scales Based on Multi-Source Remote Sensing Data of the Sancha River Catchment, Northeast China. *International Journal of Geo-Information*. 5 (11), 1 - 17.

Zambon, N., Johannsen, L., Strauss, P., Dostál, T., Zumr, D., Cochrane, T., and Klik, A. (2021). Splash Erosion Affected by Initial Soil Moisture and Surface Conditions Under Simulated Rainfall, *Catena*, 196(2021), 1 -12.

Zhang, G., Zhao, W., Yan, T., Qin, W. and Miao, X. (2023). Estimation of Gully Growth Rate and Erosion Amount Using UAV and Worldview-3 Images in Yimeng Mountain Area, Chine. *Remote Sensing*. 15 (1), 1-17.

CHAPTER THREE

A Comparison of 3-Dimensional Orthomosaic Software, gully mapping, Okhombe Valley, Kwazulu-Natal Drakensberg, South Africa.

Riddle, L [a*], Hill, T[a] and Clulow, A[a]

a. School of Agricultural, Earth and Environmental Sciences, University of KwaZulu-Natal, Private Bag X01, Scottsville, Pietermaritzburg 3209, South Africa. lyndonriddle@gmail.com

* Corresponding author

Abstract

With the advancement of Unmanned Aerial Vehicles (UAV) and associated software technology, the application and development of 3-Dimensional (3D) mapping of landscapes and landforms are growing and this suite of spatial mapping and analysis is becoming more widely applied in environmental monitoring and management. The purpose of the research was to determine if the available computer software (*DroneDeploy*, *AgiSoft MetaShape* and *Pix4D*) with the combination of a UAV can be utilised for the research of geomorphological processes. This was conducted by determining how the software and UAV work together to create a 3D image. What results are produced from the software and is the software accurate to the degree at which it will become viable to be utilised in the study of mapping of soil erosion? The software can be utilised to map geomorphological features. It is accurate to a degree to which one can get a better understanding of why landforms erode and calculate the volume and area of larger quantities. Smaller erosional features may be overlooked or unable to map correctly. Both the software used in this research have their benefits and limitations that are comparable to each other, where each has its strengths and weaknesses. The accuracy is dependent on the number of images, degree of image overlap, camera resolution and the capability of one’s PC. The technology available at the time of this research proves to be a great asset to the mapping of gully erosion and would be a critical tool for future research.

Introduction

3.1 Introduction

With the availability of lightweight, fully autonomous UAVs, the UAV is a useful tool for civil applications and is becoming an essential tool for spatial analysis and geo-referenced research. The relative ease of obtaining and operating a UAV makes it a helpful tool to possess, especially for mapping an area or study site (Küng *et al*, 2011). Updated software is continuously being released to assist the UAV operation, improve their abilities, and target specific applications, including geomorphology, soil erosion and gully mapping. The UAV allows users to map areas that were inaccessible due to the instability of those landscape. The use of UAVs allows researchers the ability to access and map erosional areas that were previously not possible. Photogrammetry and 3D mapping can assist in the development, visualisation and interpretation of landscapes and erosional features. Online computer software such as Google Earth uses orthomosaic software to stitch images together to produce a composite image, thus producing a rendered image of 3D structures (William *et al*, 2016). As users stream the 3D rendered images through the internet, the image stitching program produces the lowest number of images to a virtual representation of landforms, to minimise the processing power and data required (Küng *et al*, 2011). Using this method, Unmanned Aerial Vehicles (UAVs) and presently available software are used and manipulated to mosaic images obtained from a UAV to 3D rendered structures in greater detail and resolution, thus making it possible to map both man-made and natural features.

The software to assist in the advancements of remote sensing abilities is improving map quality and assisting in obtaining a better understanding of the soil erosion process (Glendell *et al*, 2017). UAVs can attain a detailed image compared to the aerial/satellite images, due to the short set-up time and the autonomous flight control that allows the UAV to take off, fly its designated path, capture images and land (Riddle *et al*, 2018). However as erosional landscapes are not uniform or predictable, research is required to determine how accurate the combination method of UAV and orthomosaic software is in replicating features within the erosional landscape. This article assesses the available software packages and considers how they can map features of a known size, shape, and volume. To increase the accuracy of objects or features to be a map, a high degree of image overlap is required.

Gully erosion is an advance staged erosional feature that has not been studied in detail due to difficulties in accessing, mapping, and predicting output (Valentin *et al*, 2005). Due to the complexities of gully erosion and the unique resultant landforms, one requires a high-resolution capability sensor to capture fine details. The ability to map fine details is a requirement for the software in which the images are processed, as erosional landscapes have both large and fine details, in which the fine erosional features develop into large erosional features. If the software is not able to reproduce fine details, the mapping and rendering of smaller features would blend into each other to create one single irregular shape. This would not be ideal when mapping erosional landscapes as features would then be omitted.

These areas can be unstable, and landmasses may move without warning. The UAV allows the researcher to map and monitor the landforms from a safe distance (Gonzáles & Rodriguez, 2017). With the combination of UAV and stitching software, a variety of images can be produced, and renderings can be loaded into a GIS software to manipulate mapping and spatial analysis. One can export the data from the UAV orthomosaic software and process it using GIS software to create contour maps, drainage maps and various other crucial maps to better understand the erosional process. Furthermore, through time-lapse images, the impact of management practices on the site. Mapping of erosional landscapes allows for the monitoring of rehabilitation methods to determine the success rate. The mapping may also allow researchers to view areas that have the potential for erosion, that are not possible to see on the ground. This would allow the researcher to install mitigation measures to prevent erosion from initiating or increasing.

The mapping of gully erosional landscapes can assist with the spatiotemporal modelling application due to its ability to timeously map features, hourly, daily, weekly, or yearly. The *DroneDeploy* software that is associated with UAV technology has a mobile application that is free to download on android and apple devices and allows the user to access the cloud servers to receive the processed results from projects. The software was primarily set up for the engineering, agricultural and mining sectors. However, it is considered here as an opportunity to measure gully erosion and changes in landforms over time. The *DroneDeploy* and the *AgiSoft MetaShape* software have functionalities suitable for determining the volume or area of a selected feature, making it possible to measure the area and volume of erosion, and thus the change in volume to determine the amount of soil over time.

To determine and consider if the multiple smartphone application and computer-based orthomosaic software used to map structures/buildings and produce a 3D replica, with the use of a UAV, can be adapted to map gullies. For the research to be successful, the UAV and orthomosaic software need to map the objects, in all shapes and sizes and at a scale appropriate to be measured and resolution to record the fine features within gullies. Since these structures are irregular in size, shape, and volume, it is best to test objects with known dimensions first. It is known that the resolution decrease with altitude, however, it is not known if accuracy decreases the rendered dimensions, hence this work assessed whether the dimensions measured at 25m the same as the dimensions measured at 100m of the same object. This would depict that altitude does not affect measurements.

This aim was determined by obtaining results from the following objectives.

1. To map objects of known volume and dimensions to determine if the replicated rendered digital image is a true representation.
2. As the resolution decreases with height, do the quantifiable measurements of the measured shapes decline with altitude?
3. Which of the software used has the ability to measure the shapes, both in dimension and volume, to objects of known shape and volume?
4. Considering processing time and accuracy, which software would be best suited, for mapping small features and replicating gully features?

3.2 Literature Review

3.2.1 3D mapping of landscapes

3D mapping of gullies is a critical aspect required in this research, as there are various methods currently available, the ideal methods would need to be developed to assist in the 3D mapping of gully erosion. Laser scanners for 3D landscape mapping are currently available and have been used in the past to map gullies (Glendell *et al*, 2017). However, airborne photogrammetry for image acquisition is cheaper and more efficient (Zhang *et al*, 2018). Laser scanners have been used to assist in the 3D mapping of a landscape to analyse the changes in gullies over time. However, this method is complex and was a way of previously mapping erosion. 3D models of structures are now possible with the use of UAVs and orthomosaic software. This is advantageous to geomorphological research, in particular gully mapping, as it has the potential to regularly view and record changes in landforms and features as landforms erode in specific ways (Toth *et al*, 2016). The use of a UAV and associated mosaic software can reduce flight times and recreate each image at regular time intervals to obtain a time series analysis. The UAV can fly at the same altitude and position for a time series reference as the attribute information for example height, direction, and speed of the UAV is recorded and stored for future reference (Riddle *et al*, 2018).

The use of a UAV is weather dependent, as the device is lightweight (Jordan, 2015), and this can be a limiting factor to the flight capability (Hodgson, *et al*, 2018), as erosional landscapes are irregular and can be small in size The UAV is limited by the weight of the payload, due to its lightweight and low payload capacity (Vallet *et al*, 2011), which limits the payload and thus the image sensor used on the UAV. The weight of the UAV has the possibility of adversely affecting the image quality produced by the onboard sensor, as the wind has the potential to move the UAV when the image is being captured, which can create irregularity and out-of-focus images.

The orthomosaic accuracy of the software is dependent on the image-matching capability within the software, and the image quality produced by the UAV sensor. (Wang *et al*, 2017). The greater the degree of overlap between images, the higher the quality of the resulting image and thus the better the stitching of the images the processing of which is split into 5 steps (Wang *et al*, 2017). The first step is image preparation before processing, this is achieved by removing the noise (the haze or artefacts that can be seen on images that are not originally captured from the landscapes) from the image and placing the images in the correct co-ordinations in relation to one another. The second step involves matching the images using an image-matching algorithm to locate featured points within each image to splice and stitch together. The featured points are determined by the software algorithm that is then mapped, these are features that stand out or and uniquely shaped on the image that can be matched on adjacent images. Step three is the mathematical transformation of step 2, whilst in step 4 the software unifies the co-ordinate of each image, to place each image into a mesh cloud with reference to the coordinates each image was captured. Step 5 is the reconstruction of the overlapped images to create a smooth, seamless panoramic image.

DroneDeploy, Pix4DMapper, AgiSoft MetaShape, Altizure and UgCS are examples of the more commonly applied software packages that use UAV data. *DroneDeploy* is a cloud-based stitching software that produces 3D images of buildings or structures (Chowdhry, 2017), while *Pix4DMapper, AgiSoft MetaShape, UgCS and Altizure* are downloaded to a PC or as an app on Android or Apple device. The software automates the flight path of the UAV and selects the optimum positions to capture images to facilitate post-processing (Chowdhry, 2017). All UAV software allows for manual flights in which the user can control the direction, speed, path, and locations of each image taken. This ability removes the errors that may arise from the automation and allows the researcher to monitor a number of images, flight time, obstructions, and battery life. However, one needs to take cognizance of the fact that a manual flight cannot be replicated to the exact location of each image. All the software can produce high-resolution images in 2D (orthomosaic), 3D, and digital elevation models and process images to produce plant health (term used for VARI on the *DroneDeploy* software) index for the study area. The software has been applied in precision agriculture, construction, mining, and surveying (Chowdhry, 2017).

The associated software can be utilised to measure tree heights in forests and plantations, by mapping the top of the canopies and subtracting that from the Digital terrain model (DTM) acting as an accurate Digital Surface Model (DSM) (Lim *et al*, 2015). This calculation will provide the height of trees or objects requiring vertical measurements. The use of UAV allows one to use the Ground Sampling Distance (GSD) which with the use of the camera sensor size and the known number of pixels, one can determine the desired pixels size (Frankl *et al*, 2015). The software packages used in this paper were *AgiSoft MetaShape, DroneDeploy* and *Pix4DMapper.*

3.2.2 DroneDeploy

DroneDeploy is an online-based software which uses mobile applications and online processors to capture and process images. These two systems work in tandem to capture and produce an orthomosaic image, where both mediums allow the user to determine flight area. The two systems then create a flight path and the number of images required, which are subsequently uploaded to the UAV and the UAV will autonomously complete the path and capture images and save these to the online server. The researcher can access the images and submit them to be processed online. This online software relies on the internet speed the researcher has access to, as images are uploaded to the software and processed remotely. The *DroneDeploy* software requires a minimum of 30 images to create a 3D model of the desired object. The greater the resolution and detail in each image and the number of images uploaded is the limiting factor due to the file size of each image. Once the images have been uploaded, they are processed remotely with no interaction with the user. The user has limited abilities, such as selecting between parameters such as imperial measurement or metric, and what to label the folder. Once the images have been stitched together, the user is able to download the DEM, plant health and NDVI. These results are then available to view and manipulate the images online and can be exported as JPEG, GeoTiff, Shapefiles, PDF, and point clouds. As this system is online, computer processing power is not a limiting factor allowing users with a relatively low-end computer or low processing capabilities to have access to 3D modelling capabilities.

3.2.3 AgiSoft MetaShape

AgiSoft MetaShape is an offline software that is downloadable to a user’s computer. This software does not require access to the internet to complete processing requirements, however, it does require the processing abilities of the computer's Central Processing Unit (CPU) and Graphics Processing Unit (GPU). The software allows the user to input each parameter required, such as to process images at a low degree of stitching accuracy which decreases the processing time of each step. Users can upload images or videos to recreate the 3D rendered image, as the software will allow for a series of single images or a video, where the software processes each frame (image) of the video. It is beneficial to process the images at a lower accuracy for a quick processing time to produce an initial summary of a site, thereafter this can be processed at a higher accuracy to produce the final images required for processing, these processes through the same series of images and refines the information to complete higher accuracy in the stitching process and thus a higher resolution in the final image.

3.2.4 Pix4DMapper

Pix4DMapper is a downloadable software. Once the images have been imported into the package *Pix4DMapper* is complete, the software imports the flight data and utilises this information to align and stitch images together. Latitude, longitude, altitude (m), accuracy horizontal (m), and accuracy vertical (m), are parameters transferred from the UAV to the software to create the object.

Each of the above software packages requests the UAV to fly above a study site and capture a series of images. The resultant images can be saved on the *DroneDeploy, UgCS,* and *Pix4dMapper* applications and later repeated to the exact specifications set out on the first flight. This allows for software and time comparison of resulting images (2D/3D), plant health change and elevation change to determine how the landscape has altered, how the plant health has changed, how land features have changed through time as a result of land practices and land management and determine if there are comparisons. It would assist in the determination of volume change, over time which would equate to an erosional occurrence. This is ideal for chronological studies of an area, to determine changes or patterns over time.

AgiSoft MetaShape requires high computer processing power and graphics cards, to process and display images, which increases the cost of the research whereas *Drone Deploy* is online and most PCs are able to create necessary imagery. Each software has its advantages and limitations, however, the decision to use one is dependent on the requirements of the user and the hardware to which the user has access too.

3.3 Methods

To reduce the effect of error or interference from the ground, a uniform and level sports field was selected at the local university campus. The study size was a controlled environment, and testing was conducted, with the use of GPS software to determine when the sun was directly overhead the study site to produce the lowest shadows possible. Objects of known size were placed within the study area to determine the accuracy of the software and its ability to map these known objects. The objects were selected for their variations in size, shape, width, and materials. Once the study site was laid out, the UAV mobile application was opened and flight height, camera angle relative to the UAV and the percentage of image overlap were set (the higher the image overlaps the better the software can process the stitching together of each image and thus the better the final resolution). The UAV mobile application then determines the ideal flight path with the number of images needed to obtain the highest 3D results, which are determined by the size of the area, the height flown above the ground and the level of image overlap required. The user accepts this, and the UAV autonomously lifts off the ground and follows the designated path, taking images at the desired locations set out by the application. Once this is complete, the UAV returns to the starting point. The images are then uploaded to the *DroneDeploy* Computer Software program. A metric measurement system was selected, and the project was accepted and processed. Once the images were processed, the software allows for the production of four final images that were exported and manipulated by the researcher. The process was completed with all the software being used to determine which software was able to volumetric and replicate the known objects in terms of size, shape, and volume.

3.3.1 Software Processing.

The process undertaken within each software package varied. The following is a step-by-step process of how each software produced the output mosaic (Figure 3.1). The input parameters were set to be consistent before the commencement of processing the images, however, each software processes the images in their proprietary way to create the same type of image output.

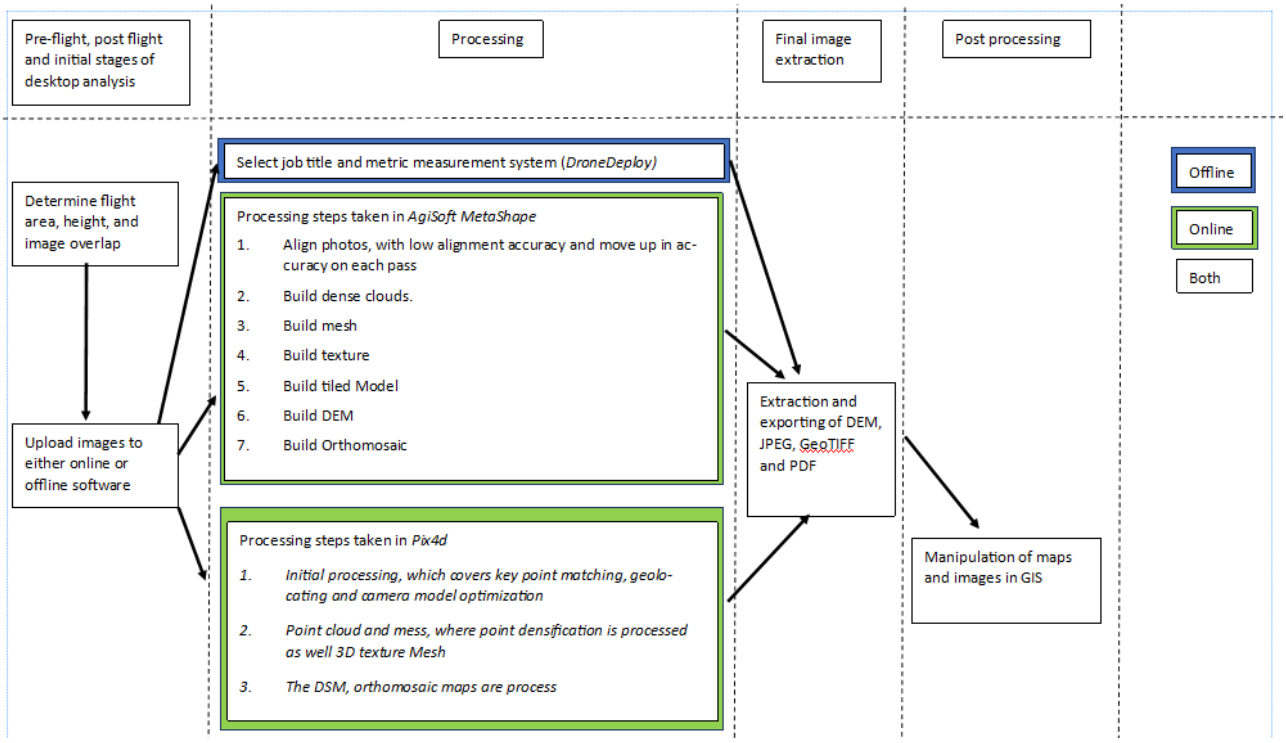


Figure 3.1: Flow chart of each online and offline software used and the path one takes from the image capturing to image manipulation.

3.3.2 Pix4DMapper

The series of images captured with the UAV of the site was loaded into the software, default parameters are left, and 3D models are selected. This software is a 3-step process, and all three steps must be selected (Initial Processing, Point cloud and Mesh, DSM, Orthomosaic and Index). This process will display an image of ‘tie points’, which are points set by the researcher with the use of known GPS coordinates on each image or by the software of unique shape features that are matched between images. Volumetric measurements cannot be taken while the image is displayed in this format, and further steps are required to determine this measurement, however, this step is critical in creating the 3D map. The user must select the image to be displayed as ’point clouds, which will reproduce a 3D model. Once the 3D model is displayed, the volume tool can be selected. The user delineates the area for which the volumetric data are required, and the software calculates the volume of the designated area. This will produce Name, Terrain 3D Area (m^2), Fill Volume (m^3), Fill Volume Error (m^3), Cut Volume (m^3), Cut Volume Error (m^3), Total Volume (m^3) and Total Volume Error (m^3).

3.3.3 AgiSoft MetaShape

The images are loaded onto the offline software, and the images are aligned, using the alignment tool that aligns the images with one another. Once the images are aligned, the user is able to commence with the ’Dense Cloud’, which creates common features within the image and plots them on a resulting image, this is a series of points created by the software to produce a 3D image of what the images were capturing. Once the cloud has been created, the process of creating a ’Build Mesh’ was started. The ’Surface Type’ of the processing could be either Arbitrary (3D or Height Field 2.5D). Arbitrary was used for this research as it displays 3D features. ‘Face count’ can be selected prior to the processing of the ‘Build Mesh’, which is the number of flat surfaces created between each point from the dense cloud, the more face counts the better the rendered image. The higher the number of faces, the greater the degree of replications of a captured feature. Once this step has been completed, the user is able to create the texture (the shapes on contours on the image) of the resulting image. Once the texture has been processed, a tiled model can be created and subsequently the DEM and Orthomosaic images can be processed and exported. The user is able to determine the volume of a selected feature and measure the dimensions of the mapped objects. This is critical as it provides an ability to map gullies and determine the volumes and dimensions of each gully and features within

3.3.4 DroneDeploy

The processing of images captured from the field started with the uploading of images onto the software site. The metric measurement system was selected (default was non-metric), as this is the standard measurement system and the system used in the other software, and the images were then processed. The *DroneDeploy* software automatically processes the images through their proprietary path to create the resulting images. When the images have been completed, the processing to create the orthomosaic, 3D images and plant health data, the software sends an email to notify the user. The user then logs onto the software homepage and selects the images to export, such as NDVI, DEM, GeoTiff, JPEG and PDF. Both the upload process and export process require a connection to the internet.

3.3.5 Validation of Measurements

The objects that were placed on a field (within a uniform landscape) to assist in determining volumes were measured within the software packages and compared to the volume of the actual object. A difference between the volumes was calculated to determine if the software reading is a representation of the actual volume of the objects. This was achieved by determining the volume of the known object and comparing that of the volumes measured using the measurement tools from each of the software packages. A percentage was calculated to numerically determine the more accurate data in terms of the volume of the object.

3.4 Results

Two hundred and fifty images were taken of a study site, which represented an intense sampling strategy. The test site, where objects of known shape and size were mapped in great detail, and then processed, with a high degree of overlap (95%). The resulting 3D-rendered image displayed errors in the mapping of the object as a representative of the shape of the object. This could be due to the materials, shape, or size of each object. It was found that the time of the day and shadows affected the mapping of objects. As the side of the objects that were facing towards the sun measured most closely to the represented true value, whereas the shaded sides were not able to measure close to the true value. The images were captured at various heights (5m, 5m oblique, 10m, and 15m). This was to determine if the UAV and software were able to 3D map and measure the objects dimensionally. All the images from each height were processed through all the software at each height and then all images from all heights were processed (Table 3.3).

The processing time of the *DroneDeploy* software was the shortest, while the *AgiSoft MetaShape* took the longest (Table 3.1).

Table 3.1: Processing time and time spent on each software.

Software Name	**Processing time**
Pix4dMapper (Offline)	1-2 hours
DroneDeploy (Online)	0.1-3 hours
AgiSoft MetaShape (Offline)	12- 72 hours

Table 3.2: 'Real' measurements of the three objects measured.

Name	**Dimensions**	**Volume (m^3)**
Box 1	310mm x 470mm x 810mm	0.00765
Box 2	200mm x 150mm x 255mm	0.118017
Box 3	895mm x 1505mm x 780mm	1.05064

Table 3.3: Measurements determined at different UAV flying heights.

Software	**Height flown above ground**	**Object size**	**Volume (m^3)**	**Difference In**	**Overread or under reading**	**percentage off (%)**
Actual measurements		Box 1	0.0076	0	Same	0
		Box 2	0,1180	0	Same	0
		Box 3	1.0506	0	Same	0
Pix4dMapper	5m	Box 1	Did not replicate the object	N/A	-	-
		Box 2	Did not replicate the object	N/A	-	-
		Box 3	1.0800	-0.0294	Over	-2.79
	5m Oblique	Box 1	0,0121	-0,0044	Over	-57,92
		Box 2	0,1227	-0,0047	Over	-3,95
		Box 3	1.3700	-0.3200	Over	-30.46
	10m	Box 1	Did not replicate the object	N/A	-	-
		Box 2	Did not replicate the object	N/A	-	-
		Box 3	0.1900	0.8600	Under	81.85
	15m	Box 1	0,0067	0,0009	Under	12,40
		Box 2	0,1232	-0,0051	Over	-4,36
		Box 3	1.2000	0.1494	Over	-14.22
	All	Box 1	0,0097	-0,0020	Over	-26,67
		Box 2	0,1536	-0,0356	Over	-30,14
		Box 3	1.1000	-0.0494	Over	-4.7
DroneDeploy	5m	Box 1	An object smaller than 0,1 cubic meter	N/A	-	-
		Box 2	0,2000	-0,0820	Over	-69,47
		Box 3	1.2000	0.1494	Over	-14.22
	5m Oblique	Box 1	An object smaller than 0,1 cubic meter	N/A	-	-
		Box 2	0,2000	-0,0820	Over	-69,47
		Box 3	Did not replicate the object	N/A	-	-
	10m	Box 1	An object smaller than 0,1 cubic meter	N/A	-	-
		Box 2	An object smaller than 0,1 cubic meter	N/A	-	-
		Box 3	1.1000	-0.0495	Over	-4.70

	15m	Box 1	An object smaller than 0,1 cubic meter	N/A	-	-
		Box 2	An object smaller than 0,1 cubic meter	N/A	-	-
		Box 3	1.1000	-0.0495	Over	-4.70
	All	Box 1	An object smaller than 0,1 cubic meter		-	-
		Box 2	0,2000	-0,0820	Over	-69,47
		Box 3	1.2000	-0.1494	Over	-14.22
AgiSoft MetaShape	5m	Box 1	0,0068	0,0008	Under	11,03
		Box 2	0,0988	0,0193	Under	16,31
		Box 3	1.0640	-0.0134	Over	-1.27
	5m Oblique	Box 1	0,0087	-0,0010	Over	-13,63
		Box 2	0,1049	0,0131	Under	11,13
		Box 3	1.1600	-0.1094	Over	-10.41
	10m	Box 1	0.0001	0.0008	Under	9.91
		Box 2	0.0002	0.1178	Under	99.84
		Box 3	0.2163	0.8344	Under	79.41
	15m	Box 1	0,0052	0,0025	Under	32,38
		Box 2	0,0389	0,0791	Under	67,02
		Box 3	1.1930	-0.1424	Over	-13.55
	All	Box 1	0,0088	-0,0011	Over	-14,37
		Box 2	0,1162	0,0018	Under	1,53
		Box 3	1.0810	-0.0304	Over	-2.89

The three boxes were of different sizes, however, there were of the same shape, this allowed for the comparison of the mapping ability of the combination of UAV and software in mapping a feature with respect to the volume of an object. This assisted in the comparability of each box for mapping and measuring in dimensions and volumes, which would then allow for the transfer of this application to the mapping of erosional landscapes with unique shapes and sizes. *Pix4DMapper* software was unable to measure accurately boxes one and two at 5 and 10 meters above the ground with regards to volume or dimension and was not able to map these two features using the combination of UAV and mapping software. This would mean that any object smaller than 0.12m^3 would not be measured, which is not ideal for the mapping of gullies and the smaller features found within a gully system (rills).

DroneDeploy was unable to measure objects less than 0.1 cubic meters, as the orthomosaic software was not able to map objects smaller, which for research purposes may have adverse effects on the results as this hinders the researcher from mapping smaller features found in erosional landscapes. *AgiSoft MetaShape* mapped Box 1, 2 and 3 at all heights (Table 3.3). The volumetric accuracy of each object mapped, declined from 5 meters to 10 meters however it increased at 15 meters, as the resolution decreased.

When all images were placed together from the different heights in each software (5m, 5m oblique, 10m, 15m), each software had their highest accuracy of measurement, this is due to the higher degree of image overlap and thus a high final image resolution. As *DroneDeploy* is an online-based software, the processing time was the least, as the images were uploaded to the online software and then the software would process. *AgiSoft MetaShape* had the longest processing time of up to 72 hours depending on the number of images processed and the degree of accuracy required, and it was the only software able to map and measure a volume for all objects thus we would conclude that *AgiSoft MetaShape* was the most appropriate and would be used for a test flight over the study area where an erosional landscape is located.

3.5 Discussion

The 3D mapping of landscapes requires a large number of aerial images, which are stitched together with the use of key features found within each image, to produce a single high-resolution 3D image. Results of rendered images rely on the height at which the UAV flies above the study site, the percentage overlap between each image, the angle of the onboard camera, the flight speed of the UAV, the number of images taken during the flight time, the camera quality and sensor size, weather conditions and stitching software. Time available due to the battery life of the UAV to capture and process images is the limiting factor on which the above-mentioned variables are determined, for example, an increase in images will increase processing time offset by a higher resolution (Zhang *et al*, 2018).

The mapped 3D area is dependent on the stitching algorithms within the software (Wang *et al*, 2017). The software identifies key features on each image and uses these as feature points to stitch the images together. This is completed using a five-step process; first, the image is processed by removing the imperfection from each of the images and the initiation of a matching template is formed (Wang *et al*, 2017). Secondly, a matching algorithm is used for determining key common features between images to match these images together, thirdly, the image is transformed for the reference image to be developed. In the four-step, the coordinate system is developed, geolocated points are produced within the image, and finally, the images are mosaiced together to recreate one seamless high-resolution image (Wang *et al*, 2017).

With the help of the *DroneDeploy* mobile application, the user inputs the study area on the world map provided in the mobile application, by demarcating the perimeter, and then observing the flight path and area to ensure no obstacles will interfere with the set flight path. The application calculates the best positions at which each image is to be captured, which is determined by the degree of image overlap and height the UAV is flown above the ground. The UAV will autonomously take off, fly the designated path, and capture images at the selected points. Once complete, the UAV will return to the take-off point. The users upload these images to the *DroneDeploy* online software for processing. The DJI UAV saves the telemetry for each image, which the stitching software can utilise, to determine the location of each image relative to one another and the height at which each image was captured. The advancements in georeferencing GPS sensors and ultrasonic sensors have allowed for the higher resolution of 3d images and 3d mapping (Vallet *et al*, 2011). The *DroneDeploy* software has the ability to allow the researcher to request a higher quality of 3d replication of landscape images or faster processing speed, as the processing is completed by a remote computer with high degrees of processing power. By selecting a faster processing speed, the output images will replicate the landscape with lower accuracy. There is a similar process for the *Pix4D* and *AgiSoft MetaShape* software where the UAV flight path is previously selected, as well as flight height and degree of image overlap. The initial process for both the offline and online software is the same, the difference is the processing time and resolution of the final image produced. The *AgiSoft MetaShape* software was found to have the longest processing time (of which this can be decreased with a computer with higher processing capability) however, it mapped the larger and smaller features and thus is best suited for the mapping of gullies.

The entry-level *DroneDeploy* package produces four images, 2D, plant health, Elevation, and 3D in the format of GeoTiff, pdf and JPEG. The 2D is a mosaic of all the images captured during the field study to produce one high-resolution image of the study area (Strecha & Draeyer, 2014). This resolution is dependent on the height at which the UAV is flown and the clarity of the atmosphere between the camera and the study object (Riddle *et al*, 2018). The resulting plant health image uses a Visible Atmospherically Resistant Index (VARI) from the Red, Green, and Blue onboard camera to determine the health of the vegetation. VARI is a measurement of how green a pixel or image is, thus does not determine the plant's health but rather the colour of the plant. However, an NDVI (Altum Multi-Sensor Camera) camera can be mounted onto a UAV.

3D images can be viewed via all stitching software, or an online site designed for 3D models (*Online 3D Viewer*, 2018). This allows the user to move around the study site, focusing on points of interest from a desktop computer. *DroneDeploy* processing time is quick and is conducted online with a remote server. Once the user has uploaded the images and commenced the processing of said images, it is processed remotely and takes several hours. *AgiSoft MetaShape*, the offline software, can be downloaded and used without the internet. However, for rapid processing time, a PC with a high-quality processor is required. This software is more complex, and several steps are needed to obtain the final 3D image. The multi-step process can take between 2 – 48 hours to complete depending on the quality of the resulting images.

The volumetric accuracy was determined by flying a UAV above known-sized objects. From this, images were taken and processed through the processing software to determine how accurate (in dimension and volume) the resulting orthomosaic image was to the actual objects being measured. It was found that the offline software *AgiSoft MetaShape*, would lower the processing time if the user would initially process the images with a low degree of stitching accuracy and thus a lower resolution of the final orthomosaic image. Once this was done the user could increase the stitching accuracy for the same step to the final point of ’Ultra High’ degrees of stitching accuracy rather than processing at ‘Ultra High’ from the start. The final orthomosaic image is not only affected by the processing but by the site condition when the images are taken.

The accuracy of 3D mapping is dependent on the weather and the position of the sun (Küng *et al*, 2011). Clouds and shadows create errors in the image that the processing software is not able to compute and manipulate into the 3D image (Zhang *et al*, 2018). The ideal image for processing is an image with no noise, which allows the processing software to correctly analyse and determine what features or details would match the mosaicking of images. The texture, colour and morphology of the structures being mapped determine the results of the mapped 3D area (Küng *et al*, 2011). Uniform textures, repetitive textures and bright colours create errors that hinder the results in the 3D mapping of landscapes, and this assists in the mapping of gullies as uniformities in nature are not common. Vertical errors arise from steep slopes and tall buildings (Høhle & Høhle, 2009).

A case study was conducted to determine the accuracy of the software *Pix4DMapper* by mapping two sites, one a sand stockpile and the other an earth protection dam (Strecha & Draeyer, 2014). The *Pix4DMapper* software was used to calculate the volume of the stockpiles and 3D map the protection dam. The results of the volumetric measurements resulted in a 0.3 to 0,8% difference between the *Pix4DMapper* measurements and the actual measurements (Strecha & Draeyer, 2014). A case study conducted by Strecha *et al*, (2012) states that the accuracy varies between 0.05m and 0.2m, proving the possibility of mapping gully erosion with a low resolution of 0.05m. This was not the case with this study as *Pix4D Mapper* did not accurately map the objects during this study, which could be due to the algorithm used in the software.

All stitching software have a trial period and there after subscriptions will be required. Both applications have advantages and limitations, such that the *DroneDeploy* software application is easier to use, and the user interface is less complicated. The processing in the *DroneDeploy* software is faster and results are processed online without taking computer processing power from one's PC.

There are difficulties with the *DroneDeploy* software with regards to recreating or measuring objects smaller than 0.1 cubic meters, this would be a limitation in the mapping of gullies as all features smaller than 0.1 cubic meters would not be mapped and can affect the overall volumetric measurement of the gully. However, the software was online and allowed users with relatively low processing powered computers to create 3D models of objects at relatively fast time intervals. Another limiting factor would be access to an internet connection. Since the software is an online system, good internet speed is required. *DroneDeploy* had its highest accuracy at 4.7% off the actual volume of box 3, proving the UAV and software produced volume measurements 5% off the actual volume. This proves the potential for the system to be highly accurate and efficient, as it can optimally map the volumes of features, however as it does not map features smaller than 0.1 cubic meters, it would not be ideal for the mapping of gully erosion.

Pix4DMapper replicated all three boxes except for box one and box two at 5 meters and 10 meters. This could have been an issue with the number of images taken or due to environmental interference such as clouds (Høhle & Høhle, 2009). With the highest accuracy being 3% off the actual volume of box 3, this software proves to be more accurate than *DroneDeploy*. The accuracy decreased slightly for the measurements of box 3 with altitude. With the failed attempts of replication of boxes one and two at heights 5 and 10 meters, the software becomes less reliable for the mapping of gullies.

AgiSoft MetaShape was able to replicate and measure each box at every height. The accuracy of each box was relatively good compared to the other software, producing the highest level of accuracy (1.27% from the actual volume) at the lowest altitude measuring the most significant box (box 3). The system had an issue with the replication of the objects 10 meters above the study site. This software (Table 3.3) had the highest degree of accuracy and reliability to recreate or replicate objects on site.

All software and processes have limitations with the capturing and processing of uniform shapes and colours. The ideal situation to produce an ideal result, would be to capture an object that has a variance in colour, shape, and texture. This from the results proves to increase the accuracy. Future recommendations for both applications are that one would be able to export the resulting images with a scale to determine how large or small the object is in the mapped area. The ability to export the values into an excel spreadsheet would be useful. This then can be displayed as a surface graph in Excel and assist in determining features and patterns of erosion.

3.6 Conclusions

UAVs are becoming a successful spatial and visual analytical tool in agricultural and geomorphic applications, in particular gully erosion. The software produces images that can be used to view the changes to a landscape over some time. All stitching software can be utilised for research in gully erosion. This software allows for the mapping of landform features and will have a positive effect on gully erosion. The images produced by the software are adequate for the use of gully mapping at a superficial level. This said the degree of accuracy found from the above calculation, is not ideal for mapping micro erosional features such as runoff, sheet erosion or rill erosion.

With the current software, accurately measuring the volume of erosion may still be an estimation rather than an accurate and valid sum, as there are errors that arise in the orthomosaic image. As technology advances so will the capabilities of UAV and onboard cameras, for example installing both an RGB camera and NDVI camera to simulations capture images, as this will capture an area in all possible bands required for the stitching software to process. This would provide high-definition imagery and near-infrared imagery, to be manipulated in GIS software. The camera and processing software are limited when mapping areas with uniform colour and texture. This is needed to be taken into consideration when mapping erosion as any uniformity in the area may create errors in the final orthomosaic image. This said the degree of accuracy to understand how and why erosional paths are taken, maybe assisted with the resulting images, and thus assist in the potential predictions of where the gully may erode too and be prevented.

This research aimed to determine which of the software used is the most accurate, in calculating volumes and dimensions of objects of known shape, size and volume. This was determined to be *AgiSoft MetaShape* for this specific research paper. The objects were mapped; however, they did not replicate the shapes of the objects, thus producing errors leading to irregularities in volume. The image resolution decreases with height, while the volume measures were erratic, and showed no pattern in volumetric measurement, and one can state that there was a decreased accuracy with height measuring (from 5m to 15m). The other software showed little evidence or any relationship in the decrease of accuracy with height. *AgiSoft MetaShape* offered the closest volumetric measurement and was the only software to produce relatively accurate measurements for each box at various heights. The time of day that the study was conducted can affect the final results, as shadows can affect the final results. This is an issue for the mapping of gullies as shadows can affect the results, and direct sunlight above the gully would produce the lowest degrees of shadows and thus the higher the results. The ideal time would be to conduct the flight on an overcast day to minimise the shadows produced or when the sun is directly above the study area. Light surface colours distort images, where the UAV sensor is unable to capture variance in surface shape, and this will have a negative effect on the processing results. If the study subject is brighter in colour, the researcher must adjust the camera equipment to reduce the reflection or glare of the surfaces. The UAV proves itself to be advantageous in the mapping of objects both visually and able to measure dimensions and volumes. The UAV should be implemented and studied future to determine how the software and UAV combination would work with the mapping of soil erosional landscape features such as gullies.

References

Chowdhry, A. (2017). *The Story Behind DroneDeploy and How It Built the Largest Drone Mapping Repository*. https://www.forbes.com/sites/amitchowdhry/2017/10/16/dronedeploy/#4e19692a592d [Accessed 15th October 2018].

Frankl, A., Stal, C., Abraha, A., Nyssen, J., Rieker-Zapp, D., De Wulf, A. and Poesen, J. (2015). Detailed Recording of Gully Morphology in 3D Through Image-Based Modelling. *Catena*. 127, (April 2015), 92 – 101.

Glendell, M., McShane, G., Farrow, L., James, M.R., Quinton, J., Anderson, K., Evans, M., Benaud, P., Rawlins, B., Morgan, D., Jones, L., Kirkham, M., Debell, L., Quine, T.A., Lark, M., Rickson, J. and Brazier, R.E. (2017). Testing the utility of structure from motion photogrammetry reconstructions using small unmanned aerial vehicles and ground photography to estimate the extent of upland soil erosion. *Earth Surface Processes and Landforms*. 42(12), 1860 – 1871.

González, M. and Rodriguez, P. (2017). Monitoring Soil Erosion by Raster Images: From Aerial Photographs to Drone Taken Pictures. *European Journal of Geography*. 7(5), 117 – 129.

Hodgson, J., Mott, R., Baylis, S., Pham, T., Wotherspoon, S., Kilpatrick, A., Segaran, R., Reid, I., Terauds, A. and Koh, L. (2018). Drones Count Wildlife More Accurately and Precisely Than Humans. *Methods in Ecology and Evolution*. 9(5), 1-8.

Høhle, J. and Høhle, M. (2009). Accuracy Assessment of Digital Elevation Models by Means of Robust Statistical Methods. *Journal of Photogrammetry and Remote Sensing*. 64 (4), 398 – 406.

Jordan, B. (2015). A Birds Eye View of Geology: The Use of Micro Drones/UAV in Geologic Fieldwork and Education. *The Geological Society of America*. 25(7), 42 -43.

Küng, O., Strecha, C., Fua, P., Gurdan, D., Achtelik, M., Doths, K. and Strumpf, J. (2011). Simplified Building Models Extraction for Ultralight UAV Imagery. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences.* Volume XXXVIII-1/C22, 217 -222.

Lim, Y., La, P., Park, J., Lee, M., Pyeon, M. and Kim, J (2015). Calculations of Tree Height and Canopy Crown from Drone Images Using Segmentation. *Journal of the Korean Society of Surveying, Geodesy, Photogrammetry and Cartography*.33(6), 605 - 614.

Online 3D Viewer, (2018). www.3dviewer.net. [Accessed 1st December 2018].

Riddle, L., Hill, T. and Gijsbertsen, B. (2018). Geomorphology from 'on-high': The Use of Drones/UAV Technology in Teaching Soil Erosion. *Journal of Geography Education for Southern Africa*. 3(1), 10 – 22.

Strecha, C. and Draeyer, B. (2014). *White Paper: How Accurate are UAV Surveying Methods? Media Release*. https://s3.amazonaws.com/mics.pix4d.com/KB/documents/Pix4D+White+paper_How+accurate+are+UAV+surveying+methods.pdf. [Accessed 15th October 2018].

Strecha, C.; Kung, O. and Fua, P (2012). Automated Mapping Ultra-Light UAV Imagery. EuroCOW 2012, Barcelona, Spain, February 8-10, 2012.

Toth, C.A., Barkoczi, N., McIntosh, R.W. and Plasztan, Z.J. (2016). Studying the development of fluvial landforms in the Berettyo-KOROS region using geoinformatics methods. *Landscape and Environment*. 10(3-4), 137 – 144.

Valentin, C., Poesen, J. and Yong, Li. (2005). Gully Erosion: Impacts, Factors and Control. *Catena*. 63(2-3), 132 – 153.

Vallet, J., Panissod, F., Strecha, C. and Tracol, M. (2011). Photogrammetric Performance of an Ultra-Light Weight Swinglet "UAV". *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences XXXVIII-1/C22.* UAV-g (Unmanned Aerial Vehicles in Geomatics) Conference, Zurich Switzerland .2011.

Wang, T., Zeng, J., Liu, D. and Yang, L. (2017). Fast Stitching of DOM Based on Small UAV. *Journal of Information and Optimization Services*. 38(7), 1211 – 1219.

William, R., Tooth, S. and Gibson, M. (2016). The Sky is the Limit: Reconstructing Physical Geography from an Aerial Perspective. *Journal of Geography in Higher Education*. 41(1), 1 - 13.

Zhang, Z., Gerke, M., Vosselman, G. and Ying Yang M (2018). A Patch-Based Method for the Evaluation of Dense Image Matching Quality. *International Journal of Applied Earth Observation Geoinformation*. 70 (August 2018), 25 – 34.

CHAPTER FOUR

UAV Sensor resolution and plant health comparison for the understanding of gully erosion in Okhombe Valley, KwaZulu-Natal, South Africa.

Riddle, L [a*], Hill, T[a] and Clulow, A[a]

a. School of Agricultural, Earth and Environmental Sciences, University of KwaZulu-Natal, Private Bag X01, Scottsville, Pietermaritzburg 3209, South Africa. lyndonriddle@gmail.com

* Corresponding author

Abstract

Unmanned Aerial Vehicles (UAVs) or ‘drones’ are increasingly applied as a spatial analytical tool within the field of soil erosion mapping. With the rapid improvements in technology, in particular minimising of carrying crafts, modification, improvements in technology and software, and customisation, these systems are attracting much attention and becoming used in a diverse array of soil process applications. This paper explores if the aerial images produced from a UAV are of sufficient resolution quality and pixel density to implement this technology in erosion mapping with a particular focus on gully mapping. We pose the question, “what degree of resolution would improve the interpretation and understanding of downslope soil migration and the associated erosion processes”. Thereafter we set out to determine if the plant health classification produced from the RGB sensor on the UAV is comparable to the multi-sensor camera. The UAV was flown above a Pixel Density Reference Chart (PDRC) to gain information on the level of clarity and resolution of the onboard camera sensor. Furthermore, the UAVs were flown at various heights to determine if the resolution would decrease and if so at what height was the ideal height to fly to capture the largest area and keep a high ground pixel resolution. There was a decline in resolution with altitude, which led to the ideal flight height of approximately 50 m above the ground. The RGB sensor produces an image that is of some value to a researcher however it is not as accurate as the image resulting from multi-spectral sensors. The plant health information from RGB is produced from pixel colours whereas the multi-spectral image uses multiple colour band images and an algorithm to compile a result. The UAV has been demonstrated to be a useful applied spatial analysis tool for the interpreting, mapping, and monitoring of downslope soil movement such as gullies. Making it ideal for the mapping and monitoring of gully formations.

4. 1 Introduction

Unmanned Aerial Vehicles (UAV) or as they are commonly referred to, ‘drones’, have become more affordable, and user-friendly and, with associated software, opened up a plethora of new spatial mapping and analytical applications. The resultant top-down view of what would have previously been inhospitable or inaccessible terrain provides the researcher with a panoramic bird’s eye view of a site, changing the perspective and capturing features previously hidden from observation (Gonzáles & Rodriguez, 2017). This provides a capability to determine features and their relation to one another, to grasp and better conceptualise features and their surroundings and how they interact. With the recent rapid advancements in technology, from aerial imagery from an aircraft to satellite images and now to the potential use of UAV, remote sensing is continuously moving forward and becoming more exact and accurate (Glendell *et al*, 2017, Chidi *et al*, 2021). The replication ability has allowed for a better understanding of the movement of landscapes and how they form or erode. Unmanned Vehicles (UV) provide an opportunity to access to areas previously too dangerous or critical to enter (Gonzáles & Rodriguez, 2017). Images that are currently obtained from satellites and aerial crafts are often costly, time-consuming and of low resolution, whereas UAVs can replicate and improve on images at a reduced cost, shorter period, and higher resolution (Toth *et al*, 2016).

At present, civil engineers are able to produce 3-dimensional models of features with the use of a UAV (Strecha *et al*, 2012). This is created from the use of orthomosaic software that stitches images together to complete a single image. The software available is both on- and off-line based, namely *DroneDeploy* and *AgiSoft MetaShape*, respectively. This software allows a user to input UAV-sourced images and develop both a 3-D representation and, with the aid of various sensors record indices linked to plant health and moisture content (Hodgson *et al*, 2018). There are numerous applications that apply UAVs to ensure efficient and cost-effective data collection, partially as a consequence of the improvement of resolution from 25 000m in 1956 to 2.5m in 2013 (Gonzáles & Rodriguez, 2017). The spatial resolution from a UAV can be as low as 0.03m, which is adequate for monitoring the micro-movement of soils and mapping erosional features (Gonzáles & Rodriguez, 2017).

UAV companies have recently installed a multi-spectral image sensor, which has the ability to capture both visible light and near-infrared (Fang *et al*, 2018). These spectral bands overlap and have wavelengths from 350nm – 2500nm. The multi-spectral sensors allow users to map different features(chlorophyll) that are not possible with RGB sensors (Fang *et al*, 2018) and have the ability to ‘detect’ the chlorophyll in plants and from this, plant health can be characterised. Mapping of plant health is critical as this has a direct relationship with vegetation cover, thus depicting the exposure of bare soils, which in turn can provide us with a proxy for potential soil erosion and a precursor to rill and gully formation.

A UAV could replicate or improve the current remote sensing methods and use the RGB sensor to map soil erosion. Soil erosion is the effect of a medium (air, water and biological) interaction with the soils (Daba *et al*, 2003), that flow over the soil and removes particles transported off-site. This process can be prevented by the interference of this flow by means of vegetation or physical barriers, which slows down or retards the movement by dissipating the force. Human interferences are a known factor to increase the rates of erosion, due to the exposure of soils and removal of vegetation cover (Daba *et al*, 2003), for example, agricultural practices can accelerate soil erosion. A gully is an example of an advanced stage of soil erosion, with multiple shapes and irregularities. As a gully structure is complex, to map and shape it is complex, therefore aerial images of these features needs to be of a high resolution to map the complex shapes. This is where the UAV has the potential of inclusion in the suite of remote sensing spatial tools as the technology has the potential to be a gully system.

This paper considers a) the applicability of UAV in mapping inaccessible gully systems in a montane area of KwaZulu-Natal Drakensberg, South Africa; and b) how user-friendly the associated software technology to produce a final output is. These aims are met through the following objectives:

i. Determine the image resolution (clarity) and accuracy (or image focus) of the UAV on-board sensor and the impact of distance (altitude) on the resolution.
ii. Calculate the ideal resolution and scale of the map to monitor and observe gully features.
iii. Compare plant health outcomes from RGB and Multi-Spectral sensors for a mapped gully system.

4.2 Literature Review

4.2.1 Aerial imagery

The UAV was developed from military unmanned flight vehicles (Cook, 2006), which prograde to the hobby enthusiast by placing cameras on board to obtain a sense of flying while in the safety of the ground and negating the need for a pilot's license. The technology was first used with a fixed-winged aircraft with a camera mounted on the front, above or below the craft (Cook, 2006). The images from this were distorted as any vibrations experienced by the craft were transferred to the cameras, resulting in an image of little practical value. The resultant images were distorted by aircraft movement and the camera not being parallel to the ground and hence were of little value as spatial analytical outcomes. Images were greatly improved by the use of a quadcopter, a 4-propeller arrangement in an 'X' configuration, with electric motors at the end of each corner or arm with an individually controlled propeller. However, this is an inherently unstable configuration however, with the advancements in technology and the installations of gyroscopes, the quadcopters are now an ideal choice as they are as mobile as a fixed-wing craft, have the ability to hover, and can take off and land vertically in a confined space. The UAV that was used for this research, had a mechanical 3-axis gimbal onto which the onboard camera was attached. A gimbal isolates the movement in three axes (X, Y and Z) from the craft to the payload. Hence, the UAV is able to move in any direction, and the camera remains parallel to the ground, improving image quality. Furthermore, there is a preinstalled GPS that captures and stores the altitude, orientation, and location of the image. A high level of GPS accuracy results in the improved image metadata, which is advantageous when processed with the 3D software, as the information assists the software in stitching a final image together. The higher degree of accuracy of these functions equates to an accurate 3D depicted landscape and maps developed from these data.

There are a few limitations to consider with UAV operation, for example, due to being light they can be flown off course by moderate winds and thus one is limited by the stability of the atmosphere and resultant cloud cover. As UAVs technology develops, they are increasingly being applied in spatial mapping and analysis as data capture is less affected by local weather (Hodgson *et al*, 2018). Furthermore, UAVs have limited power due to battery size and weight and, at present, the maximum duration is in the order of minutes than hours. The primary limiting factor is legislation and the laws governing the piloting of a UAV which are country specific. Currently, the use of a UAV for commercial purposes is illegal (Matos, 2015), whilst pilots need to obtain a Remote Pilot Licences (RPL) and a Remote Operator Certificate (ROC) to use the UAV for personal gain in South Africa (Schmidt, 2016).

4.2.2 Soil erosion

Soil erosion is the movement of soil particles by water, air, or biological interference (Daba *et al*, 2003), concentrated into a signal flow path that can result in erosion (Poesen *et al*, 1996). Erosion starts as sheet flow; the landscape creates the concentration of flow and thus rills can be initiated that can lead to galleys or time and space. A gully is a steep-sided channel, with an actively eroding head and steeply sloping side, created from the intermittent flow of heavy rains (Poesen *et al*, 1996). A gully is an advanced level of erosion and has, in the past, eroded to bedrock has resulted in the irreversible loss of soil and can have a negative impact on- and off-site (Boardman *et al*, 2003. Reubens *et al*, 2009). The on-site issues are the reduction in physical land space and removal of fertile soils, whilst off-site impacts can be both negative and positive. Negative is the siltation of lower water courses and smothering of downstream vegetation (Sidorchuk *et al*, 2003), whilst the positive is the new inflow of fertile soils and nutrients downstream. At present, the process of mapping gullies has been completed by satellite imagery and aerial imagery. The use of Terrestrial Laser Scanning (TLS) and Airborne Laser Scanning (ALS) have been used to 3D map land features; however, these are costly and high-skill dependent which can place the use beyond the reach of researchers, hence the increase in UAV applications which is able to overcome some of these limitations (Glendell *et al*, 2017).

Legislation has been implemented on the use of a UAV, predominantly to protect aircraft and prevent people from using UAVs for illegal activities (Smith, 2015). The general public’s perception of the UAV has been positive; however, this can turn to concern as hobbyists and UAV enthusiasts could use them to spy on others and encroach on peoples’ personal space.

4.2.3 UAV Software

Various software packages are available for processing UAV images to mosaic the multiple images into a single usable image. The software packages can be obtained either on- or offline, and the use of each is dependent on the requirements of the researcher and their computer processing abilities. The off-line software allows the researcher to complete the task away from the internet allowing the research to be completed remotely. Whereas online software requires a connection to the internet. The computer processing power required for the offline software is greater than that of the online versions (Saura *et al*, 2019). Both the on- and off-line software have the ability to process the images into 3D renders, can calculate volume, dimensions, plant health, DTMs, point cloud maps, 3D maps and elevation models.

One feature that the available software has, is the ability to map plant health, which is one of the key aspects of this paper. An area with healthy plant cover has less chance of erosion occurrence. This can be carried out with a standard RGB camera or with a multispectral camera with the determination of a Normalized Difference Vegetation Index (NDVI), which is a proxy of vegetation health. The multispectral camera can capture the reflection of near infrared from the chlorophyll in plants. This reflection can be used to calculate the NDVI. This is undertaken by measuring levels of chlorophyll as the less chlorophyll in the plant, the less reflectance is generated. There is a value calculated for each pixel in each image and these values are then put back together to create an overall image of the plant health of the study area. The software package *DroneDeploy* uses a scale of -1 to 1 where between -1 and -0.66 is classed as healthier plants, between -0.66 and -0.33 are classed as healthy plants and between -0.33 and 0 are unhealthy plants. Anything above 0 is classed as dead material, buildings, roads, or inanimate objects. NDVI has in the past been generated using IKONOS imaging, however, pixels sizes are large, and this is used to generate an understanding of plant health at a large scale (Tedesco *et al*, 2016). This process would not be advisable in areas where one is working with micro erosional landscapes and the monitoring of such features. In some areas near infrared is not possible and a different algorithm is required. Such as the Intensity Based Contrast Index (IBCI) where the algorithm is calculated by the red reflectance subtracted by the intensity all divided by red reflectance adding intensity (Tedesco *et al*, 2016). This algorithm is not presently available in the UAV suite of software packages.

The RGB camera does not have this ability and has to determine plant health by the colour of the vegetation using a Visible Atmospherically Resistant Index (VARI). This is considered a less accurate measurement of plant health, as the VARI algorithm does not use the reflectance from the chlorophyll, but rather the reflectance of colour (Miller *et al*, 2020). It detects how green a surface is, and from this, the algorithm determines how healthy the vegetation is. This method was not developed to substitute for NDVI but rather to assist when Near Infrared sensors are not in operation (Keesstra *et al*, 2016).

A case study has been conducted studying sand stockpiles with the use of the offline 3D software *Pix4DMapper* (Strecha & Draeyer,2014). It was determined that the software was within 0.3 to 0.8% of the total volume of the stockpiles. The 3D mapping of features or structures has been available in the past, however, the technology available is large and expensive (Zhang *et al*, 2018). This said as technology advances, the 3D mapping of features is becoming smaller and less expensive. According to Høhle and Høhle (2009), the two main 3D ground mapping techniques are Airborne Photogrammetry and Airborne Laser Scanning (ALS). Airborne photogrammetry is the cheaper process of the two; however, differentiation between the ground surface and vegetation cover is not easy. This is because the image or wavelengths of the sensors do not penetrate the vegetation but rather capture the light being reflected off the vegetation or land. This decreases the accuracy of the airborne photogrammetry in areas that are densely vegetated. The combination of ultra-lightweight UAV imagery and their automation process has increased the accuracy results and are comparable if not superior to those of traditional photogrammetric mechanisms mounted to manned air crafts (Strecha *et al*, 2012). Strecha *et al*, (2012), constructed an experiment to determine the accuracy of this method which resulted in an accuracy of 0.05 m – 0.2m. However, this accuracy was not met throughout the reconstructed image, due to lens distortion, lack of image overlaps and discontinuities in vertical depth or smaller features. The technology of overlapping is vital for the accuracy of image matching and stitching for both UAV photogrammetry and manned aircraft photogrammetry (Wang *et al*, 2017).

4.3 Methods

A DJI Phantom 4 UAV was used to carry out this component of the research, with a 4K resolution camera and a flight time of 30. The weight of the UAV is approximately 1 380g with a maximum ceiling height of 6 000m and a flight time of 28 minutes. The onboard camera was designed to capture images in the visible light spectrum. From this, the images were stitched together to create a single uniform image. This is achieved through software packages that match unique points on the image to allow for the overlaying of multiple images. Once the final image has been created, coordinates are created in 3D based on the GPS measurements and automated recorded data (Strecha, *et al*, 2012). A method of determining the size of pixel size on the ground is by the use of Ground Sampling Distance (Frankl *et al*, 2015). This technique uses the known size of the camera sensor and the number of pixels to determine the area each pixel covers. This method is advantageous as it can determine the accuracy of an image at different altitudes. A mathematical method of calculating pixel size is by the Pixel size = Pixel dimensions (altitude/ known focal length) (Strecha & Draeyer, 2014, Frankl *et al*, 2015). To complete the first objective (to determine the image resolution (Clarity) and accuracy (or image focus) of the sensor and the effects of distance (altitude) on the resolution), the UAV was flown above the test site with the flight telemetry displayed on the DJI screen. This was undertaken by the pilot to have control over the UAV and obtain exact measurements, height, and orientation of the UAV and attached sensor. The UAV was flown at different heights to determine how distance above the ground or altitude may affect the clarity and resolution of the image (Table 3.1). This means the amount of area on the ground found within each pixel becomes larger with height, thus reducing the clarity and accuracy. This lowers the resolution and smaller features start being lost in each pixel. This is not ideal for the micro mapping of erosional land features such as rill erosion. A Pixel Density Reference Chart (PDRC) was placed on a large sheet of white plastic to assist in the identification and orientation of the PDRC and the UAV. The UAV was then flown above the PDRC, and images were captured. The PDRC was a board 210 x 297mm that has been divided into six quadrants with alternating black and white colouration (Figure 4.1). Within one of the six squares is a checked pattern of 20mm-by-20mm squares. These checks were used to assist in determining the number of pixels within each section. The number of pixels was determined for each checked block. This assisted in the calculation of resolution, the more pixels in the checked box the higher the resolution. This then would assist in determining the ground resolution per pixel.

The DJI had an onboard camera, with an RGB sensor with 12 MP (4000 x 3000 pixels). As we can determine the number of pixels in each image, one is able to measure the distance covered by a pixel by determining the number of pixels within each of the squares. With an image of 4000 x 3000 pixels, a 10cm x 10cm check box could have 25 pixels (5 on the x and y axis), this would mean each pixel is 2cm by 2cm. This is then calculated to cover an area of 8000cm x 6000cm (0.08km x 0.06km)

Plate 4.1: The UAV used to autonomously fly above the gully site (Okhombe Valley, KwaZulu-Natal Drakensberg) to capture images to determine plant health and map erosion, image taken with UAV at 5m height above the ground.

The captured images were used to determine the second objective (to determine the optimal height to fly above the ground to obtain the ideal level of accuracy and the largest ground covered per image). The size of each pixel was determined by the use of the PDRC which has a known block size. The PDRC had two size boxes used to determine the ground resolution, the bigger boxes are measured at 10cm cx 10cm and the smaller boxes at 2cm by 2cm. This was done by determining the dimension of each pixel covered at different altitudes, termed the Ground Sampling Distance, these were captured at 25m, 50m, 75m and 100m above the ground surface to determine if there is a degradation of image quality with altitude. From these images, the ground sampling distance, and the total area that each image covered, can be determined. One was then able to determine the ideal height to fly and still keep a high degree of resolution. This was conducted by determining the height at which the UAV could be flown to capture the whole site while still being able to capture finer details within the gully formation. This ratio is determined by allowing for the mapping of smaller erosional features such as rills while still allowing a large enough area to map the larger extent of the gully feature.

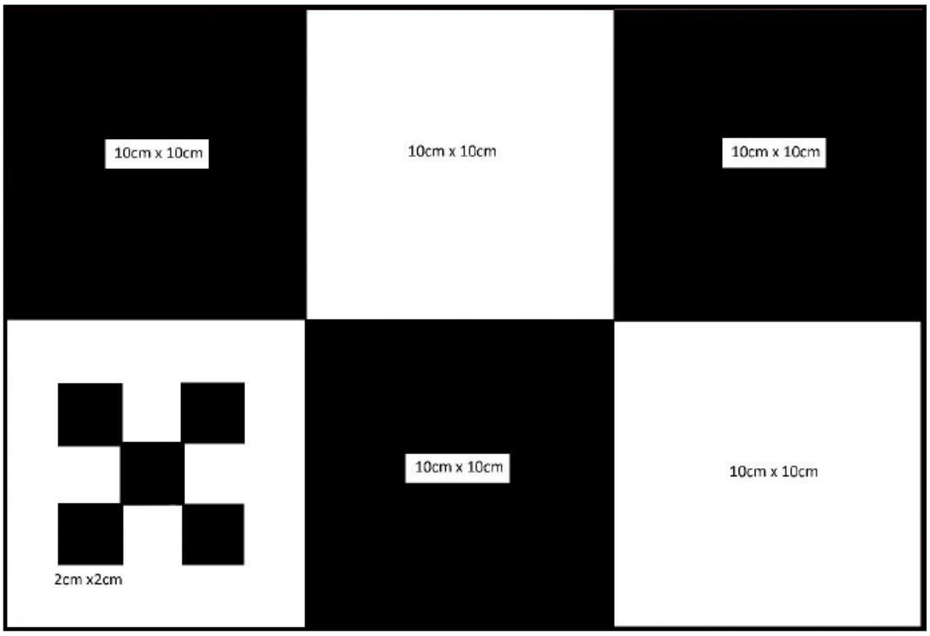


Figure 4.1: Pixel Density Reference Chart (PDRC), with three larger black blocks and two larger white blocks (10cm x 10cm) and a third larger white block with five smaller black blocks and 4 smaller white blocks (2cm by 2cm).

The third objective (to compare plant health images from an RGB and a multi-spectral sensor) was completed by flying the two separate UAVs with two separate image sensors, the RGB and a multi-spectral sensor, over the study site. The UAV followed the same flight parameters which included sensor orientation, and flight height above the ground to capture images. These series of images were processed with the same software, *DroneDeploy*, onto which the images were uploaded and processed on the online site. As the software is online, the processing is not completed by the user. Once the processing is completed, the user logs into the site and exports the images required, in this instance the images relevant to plant health.

A second offline software was used, namely *AgiSoft MetaShape,* to compare on- versus offline software packages. Once they had been uploaded, the images are aligned with each other using the 'Photo Alignment' tool. Processing time varied depending on the resolution of each image and the number of images processed, and it was more efficient to initially process at the lowest level of accuracy (a term used on the UAV software, to determine processing depth). Once this was complete, the process was repeated at a higher level of accuracy (the term used in the software). Once the alignment was completed, a 'dense cloud' was created of the site, this was a single resulting stitch image with all captured images overlapped and placed side by side allowing for the software to locate matching features within each image. This assisted the software in stitching the images together to create a 3D image. This followed the method of conducting the process in increments, slowly increasing the accuracy parameter on the software with each pass. A 'Mesh' was then generated to create a 3D model of the site. Texture, Tiled Model, DEM and Orthomosaic were the next steps to produce the required images to complete objective 3 (to compare plant health images from an RGB and a multi-spectral sensor). The 'Raster Calculator' was applied to determine plant health (RGB sensor) or NDVI (multi-spectral sensor). When the raster calculator was opened, the input bands are automatically populated, for the multi-sensors camera, this would be Blue (B), Green (G), Red (R), Red Edge (RE), Near Infrared (NIR) and Thermal (IR). With the raster calculator, one is able to select the bands required, input them into a calculation and produce a final image. This was the method used to create an NDVI image with the use of equation 1.

$NDVI= (NIR-R) / (NIR+R)$ Eqn 1

The calculation is processed, and the palette is converted to a user-defined palette. The two images (the resulting NDVI image from the multi-spectral sensor and the plant health image from the RGB sensor) were displayed side-by-side and compared with each other and then compared to the aerial images. This was undertaken to compare the resulting plant health images to the actual vegetation cover, and how the RGB and multi-spectral sensors compare to each other. A transect layer (10 x 15 segments) was placed over each image to subdivide the images to determine a percentage of comparison (between images and ground validation).

4.4 Results and Discussion

The UAV used in this research has a resolution of 4 000 pixels by 3 000 pixels, the total area covered was determined by multiplying the resolution by the pixel size. The area being covered increases with an increase in altitude, for example at 50 meters above the ground, each pixel covers an area of approximately $3cm^2$, while the total image covers an area of approximately $4\ 000m^2$ (half the size of an average football field). This area and pixel resolution allow a user to capture large areas while still being able to visualise small features (rills) within the landscape. The images from flight test 1 and flight test 2 were found to have a decrease in resolution with the increase in height. The decrease in resolution can be either natural or technological where the lens of the sensor could have been contaminated or the surrounding air had a lower visual clarity over increasing distances (Jordan, 2015). High winds can pick up loose sediment and create interference in the image quality, which links back to the idea that the Pixel Density Reference Chart (PDRC) assisted in confirming the resolution determined by

Strecha *et al*, (2012), proving the resolution found by other case studies, which was found to be 0.03m on the ground per pixel.

As many erosional landscapes are irregular in shape and size the optimum flight height would be that at which one can capture a large area whilst still being able to capture and display smaller features found within the erosional landscape. Thus, the ideal height flown for gully mapping would be approximately 50m above the ground, as this provides a ground pixel size of 2.78cm^2 while still covering around 4000m^2 of land making it possible to capture a larger extent of a study site and the smaller features located within a gully in a single image. This was determined as many erosional features, such as rills, are measured in the millimetres, thus the UAV would need to be able to map these features, which was found possible at a height of 50m. This is possible as the UAV has both barometric sensors and GPS which enable it to fly at a pre-determined height above the ground, capturing a uniform image at different locations.

Table 4.1: The size of each pixel in relation to the actual area on the ground from different altitudes and the total area covered by a single image at each altitude.

Altitude (m)	Area a single pixel covered on the ground - test 1 (cm^2)	The total area covered by the complete image - test 1 (m^2)	Area a single pixel covered on the ground - test 2 (cm^2)	The total area covered by the complete image - test 2 (m^2)
25	0.83	996	1	1200
50	2.78	3336	4	4800
75	6.25	7500	6.25	7500
100	11.11	13332	16.66	19992

One hundred images were uploaded to the online software *DroneDeploy*. One hundred images were used as this created a high degree of image overlap (95-98% overlap) of the study area, as was suggested by the software. As this is an online-based system, internet speed is a limiting factor, in this run it took approximately 24 hours. The resulting images are processed with no input from the users. Once the processing is completed, the users download the resulting stitched images, as either a JPG or a 3D file, depending on requirements. The images were then uploaded onto the offline system *AgiSoft MetaShape* to determine a contrast between the online and offline software to determine the ideal software to be used for this research. This was done by looking at the time taken to process the same number of images, and the ability to replicate the objects being captured. The uploading of the images took approximately 2 – 4 hours depending on the accuracy parameter set on the software. The image was then processed through the offline software to produce a jpg image and a 3D image. This process took 12 – 14 hours.

At present UAV technology is not a complete solution. There are still limitations with regard to atmospheric quality and transparency for best-quality images. Any obstacles in the air, such as moisture or dust, affect the final image adversely. This is more of an issue for larger manned crafts; however, the UAV can reduce this limitation due to the low-altitude flights that can, in theory, often fly below the cloud and reduce the thickness of the air column between objects and image-taking equipment. Furthermore, there is a delicate balance between the height flown and the resolution needs of the research objectives. Weather plays a vital role in obtaining the highest quality image.

Earlier studies have proven the applicability and the increasing use of UAVs in field research (Fan *et al,* 2017), in part, as a consequence of the high levels of precision, accuracy, and cost-effectiveness of the technology. The UAV now have the ability to carry RGB and multispectral sensors which are able to calculate an index of plant health. As an RGB sensor only has the ability to capture reflectance from the visible light spectra, the manipulation of said images in terms of plant health should not be accurate. The *DroneDeploy* software uses the colour of a pixel to determine a plant health index, whereas the Altum Multispectral sensors have the ability to capture information from outside of the visible light spectrum. This allows users to manipulate the images and data to create an NDVI image (Figure 4.2). Both the plant health produced from an RGB sensor and the NDVI from an Altum multispectral sensor produced health cover coverage images (Figure 4.2), where the area percentage of healthy plant health coverage for the RGB sensor is 44.7% while the Altum Multispectral sensor has a healthy plant coverage of 53.2%. The RGB plant health depicts healthy plants and displays the resulting images as green (healthy), cream and red (Unhealthy), while the Altum Multi-Sensor camera resulting image displays healthy plants as green and unhealthy plants as blue and red. The percentage area covered by live plants from the RGB sensor, and the multi-spectral sensor compared to the aerial image is 62.8% showing a 62.8% accuracy to what was on the aerial images. The plant health percentage from the aerial images was calculated by determining the degree of vegetation coverage in each image scene. This was irrelevant to plant colour which both the RGB sensor and the Multi-Spectral Sensor utilise to produce a plant health image and NDVI image respectively. The percentages are different for each of the two sensors, as this may be due to the different methods of creating the plant health image, however, the percentages are not comparable. This shows the plant health resulting image produced by the RGB and Multi-spectral sensor and the software to be of a lower accuracy compared to what is found on site. This, however, is still usual and gives a synopsis of what is occurring on-site, more work needs to be conducted within the software in order to increase the software's ability to map plant health. An issue found with the software was that the plant health resulting image did not export with a scale, which would assist in interpreting a map and should be a feature added to the software in the future.

The plant health images can be applied to determining areas of potential erosion as lower plant health depicts areas of low or no vegetation cover. This would mean the potential exposure of bare soils and thus the potential contact between soils and erosional forces, thus increasing the chance of the soil being eroded. If these images are obtained, a time sequence may allow for the later prediction of plant health and this could be overlayed with various other data, such as temperature and rainfall to determine the future movement of plant health. This then has the potential to predict areas of erosion in the future, where areas of low plant health would have little to no vegetation cover thus making it more prone to erosion.

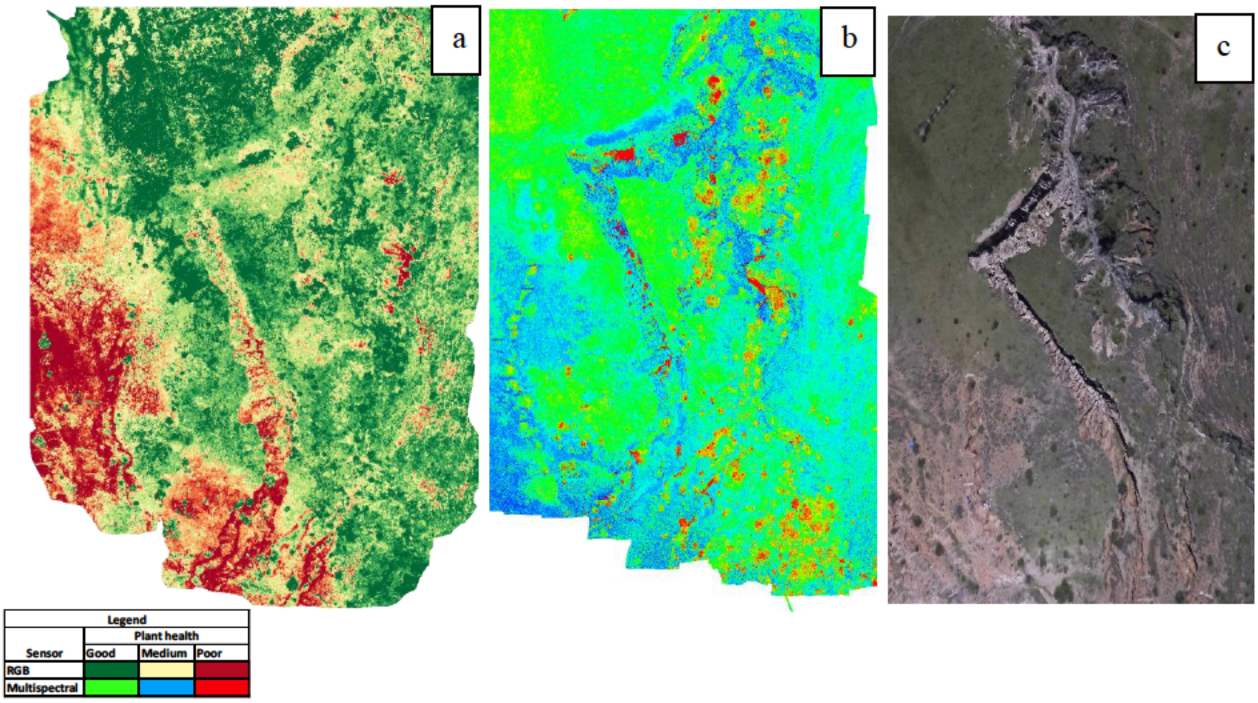


Figure 4.2: A visual comparison of resulting plant health images from an RGB sensor creating plant health image (a) from colours reflectance, an Altum Multispectral Sensor creating plant health image using NDVI algorithms (b), and (c) an aerial photographic image of the site. Width of image 140m.

4.5 Conclusion

UAVs are becoming an essential craft for multiple spatial applications, for example in wildlife conservation, vegetation monitoring, 3D modelling of buildings and structures, and Earth Sciences which require a high resolution of topographical data.

The first object of the article was to determine the resolution of the onboard camera. The ideal height to fly the UAV to obtain accurate coverage is 50m, where the resulting images capture finer details (rills) within a gully and still be able to capture the larger extent of the gully in a single image. Making it the ideal height for mapping and monitoring gullies. At this height, it is possible to map the beginning stages of rill erosion to then assist in determining areas of future potential erosion. The online-based software is suitable, providing one has access to the internet as the online software (*DroneDeploy)* processes the data at a remote server and thus processing power of the computer is not a limiting factor. *AgiSoft MetaShape* is an offline equivalent software that requires a large amount of computer hardware, however, as much research is done in the field away from technology, offline-based software could be acceptable.

With this software and the ability to rapidly obtain temporal data of a site, it allows researchers to reconstruct images quicker than previously possible. The processed plant health image from the RGB sensor depicts plant health that is 20% different compared to the aerial image, as both these images are produced from an RGB sensor where one is processed through the orthomosaic software to produce a plant health image and the other is not. However, this could be less as the percentage calculation in the aerial image is of vegetation coverage and not plant health. The multi-sensor camera has a higher degree of accuracy in reference to the actual landscape, compared to the plant health produced by the RGB sensor with the use of aerial images. One is able to visually identify the grassed areas and the bare soil area on the aerial images. These then suggest that the UAV should be implemented in the research and would and should, in fact, become a critical tool for research, to assist in monitoring, mapping and potentially predicting erosional patterns as a result of a reduction in vegetation cover. Due to its versatility and accuracy, the UAV is a critical and vital technology and should not be underestimated but rather, taken full advantage of.

References

Bhardwaj, A., Sam, L., Akanksha., Martin-Torres, F. and Kumar, R. (2016). UAVs as Remote Sensing Platform in Glaciology Present Application and Future Prospects. *Remote Sensing of Environment*, 175, 169 – 204.

Boardman, J., Parsons, A., Holland, R., Holmes, P. and Washington, R. (2003). Development of Badlands and Gullies in the Sneeuberg, Great Karoo, South Africa. *Catena*, 50 (2), 165 – 184.

Chidi, C., Zhao, W., Chaudhary, S., Xiong, D. and Wu, Y. (2021). Sensitivity Assessment of Spatial Resolution Difference in DEM for Soil Erosion Estimation Based on UAV Observations: An Experiment on Agriculture Terraces in the Middle Hill of Nepal. *International Journal of Geo-Information*, 10 (28), 1-17.

Cook, K. (2006). The Silent Force Multiple: The History and Role of UAVs in Warfare. *IEEE Aerospace Conference 03 – 10 March 2007*. Big Sky, MT, USA.

Daba, S., Rieger, W. and Strauss, P. (2003). Assessment of Gully Erosion in Eastern Ethiopia Using Photogrammetric Techniques. *Catena*, 50 (2-4), 273 – 291.

Fan, X., Kawamura, K., Xuan, T., Yuba, N., Lim, J., Yoshimoto, R., Minh, T., Kurosawa, Y. and Obitsu, T. (2017). Low-cost visible and near-infrared camera on an unmanned aerial vehicle for assessing the herbage biomass and leaf area index in an Italian ryegrass field. *Japanese Society of Grassland Science*. 64(2), 145-150.

Fang, Q., Hong, H., Zhao, L., Kukolich, S., Yin, K. and Wang, C (2018). Visible and Near-Infrared Reflectance Spectroscopy for Investigation Soil Mineralogy: A Review. *Journal of Spectroscopy*. Article ID 3168974, https://doi.org/10.1155/2018/3168974, 1-14.

Frankl, A., Stal, C., Abraha, A., Nyssen, J., Rieker-Zapp, D., De Wulf, A. and Poesen, J. (2015). Detailed Recording of Gully Morphology in 3D Through Image-Based Modelling. *Catena*. 127, 92 – 101.

Glendell, M., McShane, G., Farrow, L., James, M.R., Quinton, J., Anderson, K., Evans, M., Benaud, P., Rawlins, B., Morgan, D., Jones, L., Kirkham, M., Debell, L., Quine, T., Lark, M., Rickson, J. and Brazier, R. (2017). Testing the utility of structure from motion photogrammetry reconstructions using small unmanned aerial vehicles and ground photography to estimate the extent of upland soil erosion. *Earth Surface Processes and Landforms*. 42(12), 1860 – 1871.

González, M. and Rodriguez, P. (2017). Monitoring Soil Erosion by Raster Images: From Aerial Photographs to Drone Taken Pictures. *European Journal of Geography*. 7(5), 117 – 129.

Hodgson, J., Mott, R., Baylis, S., Pham, T., Wotherspoon, S., Kilpatrick, A., Segaran, R., Reid, I., Terauds, A. and Koh, L. (2018). Drones Count Wildlife More Accurately and Precisely Than Humans. *Methods in Ecology and Evolution*. 9(5), 1-8.

Høhle, J. and Høhle, M. (2009). Accuracy Assessment of Digital Elevation Models by Means of Robust Statistical Methods. *Journal of Photogrammetry and Remote Sensing*. 64(4), 398 – 406.

Jordan, B. (2015). A Birds Eye View of Geology: The Use of Micro Drones/UAV in Geologic Fieldwork and Education. *The Geological Society of America*. 25(7), 50 -52.

Keesstra, S., Pereira, P., Novara, A., Brevik, E., Azorin-Molina, C., Parras-Alcántara, L., Jordán, A., and Cerdà, A. (2016). Effects of Soil Management Techniques on Soil Water Erosion in Apricot Orchards. *Science of the Total Environment*. 551 – 552(2016), 357 – 366.

Matos, C. (2015). *How to get a drone licence in South Africa.* [Online] Available at: http://www.htxt.co.za/2015/11/26/how-to-get-a-drone-licence-in-south-africa/ [Accessed 7 May 2017].

Miller, I., Schieber, B., De Bey, Z., Benner, E., Ortiz, J., Girdner, J., Patel, P., Coradazzi, D., Henriquez, J. and Forsyth, J. (2020). Analysing Crop Health in Vineyards Through a Multispectral Imaging and Drone System. *Conference: System and Information's Engineering Design Symposium (SIEDS)*. Charlottesville, VA, USA, 24 April 2020, 1- 5.

Poesen, J., Vandaele, K. and Van Wesemael, B. (1996). Contribution of Gully Erosion to Sediment Production on Cultivated Lands and Rangelands. *Erosion and sediment yield: Global and Regional Perspectives.* Proceedings of the Exeter Symposium in July 1996.

Reubens, B., Poesen, J., Nyssen, J., Leduc, Y., Abraha, A., Tewoldeberhan, S., Bauer, H., Bebrehiwot, K., Deckers, J. and Muys, B. (2009). Establishment and Management of Woody Seedling in Gullies in a Semi-Arid Environment (Tigray, Ethiopia). *Plant and Soil*. 324 (1-2), 131 – 156.

Saura, J., Reyes-Menedez, A., and Palos-Sanchez, P. (2019). Mapping Multispectral Digital Images Using a Cloud Computing Software: Applications from UAV Images. *Heliyons*, 5(2), 1-22.

Schmidt, M. (2016). *Costly, clunky aviation rules clip our wings say drone operators.* [Online] Available at: https://www.businesslive.co.za/bd/companies/transport-and-tourism/2016-11-23-costly-clunky-aviation-rules-clip-our-wings-say-drone-operators/
[Accessed 7 May 2017].

Sidorchuk, A., Märker, M., Moretti, S. and Rodolfi, G. (2003). Gully erosion modelling and landscape response in the Mbuluzi River catchment of Swaziland. *Catena*, 50(2-4), 507-525.

Smith, K. (2015). Drone technology: Benefits, risks, and legal considerations. *Seattle Journal of Environmental Law*. 5(1), 291 – 302.

Strecha, C. and Draeyer, B. (2014) *White Paper: How Accurate are UAV Surveying Methods. Media Release*. https://s3.amazonaws.com/mics.pix4d.com/KB/documents/Pix4D+White+paper_How+accurate+are+UAV+surveying+methods.pdf. [Accessed 15th October 2018].

Strecha, C., Küng, O. and Fua, P. (2012). Automated Mapping Ultra-Light UAV Imagery Conference: EuroCOW 2012, Barcelona, Spain, February 8-10, 2012.

Tedesco, A., Antunes, A, and Ribeiro, S. (2016). Gully Erosion Mapping with High Resolution Imagery and ALS data by Using True Decision Hierarchical Classification and Obia. Conference: GEOBIA 2016: Solutions and Synergies, University of Twente, Netherlands, September 14-16, 2016.

Toth, C.A., Barkoczi, N., McIntosh, R. and Plasztan, Z. (2016). Studying the development of fluvial landforms in the Berettyo-KOROS region using geoinformatics methods. *Landscape and Environment*. 10(3-4), 137 – 144.

Wang, T., Zeng, J., Liu, D. and Yang, L. (2017). Fast Stitching of DOM Based on Small UAV. *Journal of Information and Optimization Services*. 38(7), 1211 – 1219.

Zhang, Z., Gerke, M., Vosselman, G. and Ying Yang, M. (2018). A Patch-Based Method for the Evaluation of Dense Image Matching Quality. *International Journal of Applied Earth Observation and Geoinformation*. 70, 25 – 34.

CHAPTER FIVE

The Use of Photogrammetry and UAV Technology to Produce 3-Dimensional imagery of a gully system in Okhombe, Northern Drakensberg, South Africa

Riddle, L [a*], Hill, T[a] and Clulow, A[a]

a. School of Agricultural, Earth and Environmental Sciences, University of KwaZulu-Natal, Private Bag X01, Scottsville, Pietermaritzburg 3209, South Africa. lyndonriddle@gmail.com

* Corresponding author

Abstract

Utilising a UAV in a wide range of applications, from recreational flying, scanning engineering infrastructure, or observing from on-high, the applications can be endless and are up to the user to determine where and how they can be used. The aim of this research was to determine if a UAV and associated 3D modelling software can be applied to mapping a gully system with advanced stages of erosion and determine if it is possible to obtain volumetric data. To replicate or create a 3D map, of multiple images of a single site are required, however, with a large volume of images, the processing power of a computer could become a limiting factor. This section investigates if there is an effect on the accuracy of the replicated 3D map with the number of images. Findings showed that the more images are acquired and used, the better the final quality. The methods of capturing images of a gully with the use of a UAV, proved the possibility of mapping gully erosion, within a relatively short period of time. The images of the site were captured to replicate the landscape digitally, while still obtaining detail to view the smaller features within the gully formation. This research proves that the 3D modelling of landscapes is possible with the use of a UAV and 3D modelling software. The volumetric data for a single section on the gully over the 3-year period increased from site visit 1 to 2 (2389 m^3 to 4265 m^3), decreased from site visit 2 to 3 (4265 m^3 to 2580 m^3) and increase from visit 3 to 4 (2580 m^3 to 3261 m^3). The volumetric accuracy is still not ideal, as the measurement is not consistent in terms of volume, however, with the increasing technology, this accuracy is likely to improve. The UAV was able to depict an expansion in the width of the gully over time and the side walls becoming steeper. The use of a UAV in erosion mapping research should be a standard tool for all researchers, to assist in mapping, monitoring, and assisting in rehabilitation methods and success.

5.1 Introduction

Unmanned Aerial Vehicles (UAVs) are becoming a critical spatial tool in day-to-day work and research, due to their being user-friendly and having relatively rapid response time to capture data. With appropriate software developers, the application of the devices in various fields is endless. UAVs are currently being used to monitor landforms, structures, and wildlife and have the potential of being multidisciplinary, not only being used to map landscape features (González and Rodriquez, 2017). This technology can be utilised to 3D map gully erosion and may assist in a better understanding of gully erosion to allow for intervention prior to the gully being developed, or to monitor the success of a rehabilitation process and hence help as a management tool.

Recently orthomosaic software has been released that allows civil engineers to 3D map and digitally replicate buildings and structures. This software allows the user to quantify the volume displaced by the structure and determine length, depth, and width on the computer-based software. This, with the improvement of UAV and sensor technology, allows for a high-resolution 3D map. The 3D mapping and aerial images of gullies in the past have been completed with the use of aerial images captured from a manned aircraft or from a satellite (Zhang *et al*, 2023). These technologies can be expensive and require skilled personnel to complete them. The UAV can be an additional tool to assist in the current suite of technologies to 3D map gullies, where remote sensing technology is able to map and determine the shape and size of landforms (Knight *et al*, 2007), and map landscape features. This improvement and development of 3D software can have a positive effect and assist in the future for a better understanding of other non-civil engineering processes, such as the monitoring of soil erosional events.

Many UAVs are preinstalled with an onboard camera thus, the image quality relies on the resolution of the camera preinstalled (González and Rodriquez, 2017), and is capable of a ground spatial resolution of 0.03m. This is 300 times smaller than the resolution produced by the LandSat 8 and LandSat 9 images, which would allow researchers to micro-map features not received by currently available aerial images. This resolution is critical in 3D mapping smaller details that can create the concentration of flow over soils that can lead to erosion. As the initial stages of soil erosion and small features, often measuring less than one meter in extent, this higher resolution would be ideal in the mapping of soil movement (Poesen *et al*, 1996).

Soil erosion is a global concern with a common driving factor behind the loss of soil being a change in land use practices (Ighodaro *et al*, 2013). In South Africa, soil erosion is considered to be a socio-political-economic as well as an environmental issue that decreases the livelihoods of the local communities where the erosion is occurring (Le Roux *et al,* 2008 & Rahmati *et al,* 2022). Soil erosion (gully) increases instabilities in the landscape, making it unsafe for the movement of people or livestock in close proximity to the gully. The formation of the gully is not only an aesthetically unappealing feature on the land but can have both on- and off-site impacts (Taylor *et al*, 2018). These impacts are not always negative as found in a case study at the Tarndale Gully in New Zealand, where the gully creates the largest supply of sediment in the Waipaoa Catchment, delivering vital nutrients to downslope crops. There are however negative impacts, where the sediment can silt up downstream catchment areas and reduce the quality of the water (Carey *et al*, 2004).

This research determines if the software available linked to UAV technology is able to map soil erosion and be applied to gully mapping research.

The research questions are:

1. Does the number of images used affect the quality (final resolution) of the final orthomosaic image?
2. How does the 3D image create from the combination of UAV and stitching software compared to a manual mapping technique of mapping the same soil erosion feature?
3. Is the software able to 3D map soil erosional landscape features such as gullies and be able to capture small erosional features within these landscapes?
4. Is it possible to determine soil loss from the orthomosaic images, with the use of volumetric measurements and analysed over time?

5.2 Literature Review

This section considers the present techniques used to create a 3D map of a gully, the techniques used in this research to 3D map a gully and possible limitations and future technologies in both software and UAV to assist in the mapping of gullies.

5.2.1 Soil Erosion and Gully Mapping

The implementation of 3D scanning technology for the monitoring and mapping of gullies is an accurate method of measurement of landform morphology (Romanescu *et al,* 2012).

Soil erosion is the removal of sediment or unconsolidated surface material from a specific area due to a concentrated force (Wang *et al,* 2016), it is a natural process of removal and movement of soil by either wind or water (Korzeniowska *et al*, 2018). It can be caused by the concentrated force of a medium over soil that ultimately removes the sediment particles away from their original position. According to McHugh (1999), soil erosion can be detrimental to an environment and have adverse effects on the surrounding region. Soil erosion occurs as sheet erosion initially and develops into rills and then gully erosion. Gully erosion is often the indicator of land degradation and desertification (Karami *et al*, 2015). This is the driving mechanism behind the creation and evolution of the Earth's landscapes. This said humans had caused the acceleration of soil erosion, from the movement of livestock for grazing. As soils do not just form, but rather develop or evolve over time, it is precious and vital to be protected or prevented from being lost (Johnson, 2000). The rate of soil loss is dependent on various factors such as slope angle, vegetation cover, rainfall intensity and volume. Poor agricultural practices can exacerbate the loss of topsoil thus reducing the fertility of the grounds in the areas where the erosion occurred, where the constant moving of livestock has trampled the vegetation and created footpaths in an area of no vegetation cover, allowing for the removal of the topsoil in these footpaths.

The offsite effects of soil erosion are the sedimentation of natural watercourses or the destruction of habitats. This would be a benefit to the people living and working on these landscapes to yield the highest crop production for farmers and potentially hazardous areas for residents below or above weak points in the landscape. Thus, creating a paradox or wicked problem – good for some however harmful for others. Soil erosion is a process that has occurred naturally, the issue arises when soil is lost due to poor farming practises or due to human interaction in which the rate of soil loss is higher than natural occurrence, not allowing for the process of regeneration of soil to take place. This places the system into disequilibrium and the system will continue to erode until the system is stable or in equilibrium (Dowsett, 1944). The need for sound scientific land use practice that considers protecting the remaining soil and needs to monitor impacts on the soil is required, this is where the use of a UAV can be utilised.

5.2.2 Application of UAVs

Over the past few decades, the availability and quality of satellite images and aerial photographs have rapidly improved (William *et al*, 2016). The technology has been used with a combination of map manipulation technology, to produce 3D maps and Digital Elevation Models (DEM). 3D scanners that are used for the mapping of landforms come equipped with GPS, where the GPS is used to provide the location of the scanner, for later use in the computer software, this provides the GPS location of each point in relation to other points to assist in the accurate measurement of a landform. This is not new technology and has been used to map the internal morphology of gullies, but seldom used in erosional studies (Tedesco *et al*, 2016). The device has to be moved to multiple points in an area, and the scanning process is started again in each location, to acquire the entire study area and the process is time-consuming. An alternative method is to map an area or gully with the use of satellite laser scanners and aerial images (Airbourne Laser Scanning) (Tedesco *et al*, 2016). The use of satellite images and aerial photography has assisted in the mapping and 3D rendering of landscapes; however, these systems are known to be expensive and difficult to obtain (González & Rodriguez, 2017). These systems, with the evolution of technology, are providing a higher resolution to depict finer details on the landscape. This technology is readily available but may be difficult for researchers from developing countries to acquire due to financial constraints (Koh & Wich, 2012). Alternatively, there are low-resolution images that are freely available (Landsat and MODIS, however, these are often of a sub-standard resolution and accuracy is hindered (Koh & Wich, 2012). For large-scale mapping and processing, these methods are sufficient whereas, for small-scale mapping and obtaining highly detailed images, the resolution is not fine enough to capture the smaller feature located within an erosional landscape. Hence the call for the application of UAVs which are able to provide an alternative technology that can be implemented and used to develop fine-scale detailed images. Riddle *et al*, (2018) determined for erosional features, in a UAV at the height of 100 meters above the ground, a single pixel covered an area of 5cm by 5cm, while the total area covered by each image was 30 000m^2. This compared to the 30 meters resolution of the LandSat-8 is a vast improvement, whereas the LandSat 8 and 9 are not able to map gully formations (González & Rodriguez, 2017). The UAV resolution would be advantageous to various research with different requirements, as the pixel area covered decreases as the UAV flies closer to the ground. This then would decrease the total area covered by each image, however, would significantly increase the ground resolution and details of each image. The higher resolution from the UAV allows researchers to identify vegetation cover with greater precision than before (González & Rodriguez, 2017). This allows researchers to confirm vegetation cover from the orthomosaic image, this is critical as a lack of vegetation can initiate the erosional process. This technology can be used to micro map erosional events from sheet erosion to gully erosion and erosional phenomena may be detected. Sensors are slowly being implemented into UAVs to conduct the same processes as a satellite but at a fraction of the cost and a greater resolution (González & Rodriguez, 2017). This allows a researcher the opportunity to map the study area when required and not rely on satellites as the costs are less and more obtainable. Despite the significant advantages of using a UAV for research, the technology is seldom taught or used for research (William *et al*, 2016).

The technological development of UAVs has increased rapidly in recent years (Jordan, 2015), with a diverse array of requirements and activities. Specific UAVs have been developed, such as a quadcopter (4 propellers) arranged into an X configuration. These technological improvements have made it easier to conduct aerial surveys, map study sites and monitor areas in real-time and allow researchers to access previously inaccessible areas, the mapping of a disaster area, during and after the event has occurred, and the 3D map of geographic landforms and structures (Jordan, 2015). Due to their size, which is a benefit for transport, the UAV has a limited source of power, with most high-end UAVs lasting 30 minutes on a single flight. The UAV can program flight paths into the software, which allows for the replication of images over time, and for the user to set flight height, flight path and level of image overlap. The UAV can be of benefit under humid conditions as cloud cover becomes an issue for aerial mapping with the use of a manned aircraft, as the UAV is able to fly below the clouds to capture data and not place a pilot at risk to capture images. Furthermore, the UAV allows the researcher to monitor cloud cover and commence flight between clouds if the interval is large enough to capture the data from a site.

One of the technologies that are constantly being developed is the software used to stitch the images together. The advances in stitching technology are critical as this allows for the increase in final resolution images and allows for greater accuracy in the 3D replication of an eroded landscape.

Software systems are dependent on image quality and environmental parameters (Zhang *et al*, 2018), affecting the final image and possibly the resultant spatial analysis. Further, the flight height and angle of the onboard camera will affect the resolution of the images. As the UAV is flown at higher altitudes above the ground, the area covered by each pixel becomes greater (Riddle *et al*,2018). Furthermore, the angle of the onboard camera will affect images, and if the UAV does not fly directly over the study object and the onboard camera is at an angle, it can create a 'shadow area' in the place where the images have not been covered, lowering the final results of the mapped object. Atmospheric conditions, and the time of the day, will also play a role in the accuracy of the final product, as shadows from the sun aspect or clouds may confuse the software to think it is a physical feature (Koh & Wich, 2012), and the software can create errors when manipulating light or bright colours or uniform textures (Küng *et al*, 2011). The software performs best with irregularities in the study objects as it allows for the software to determine points easier, as the stitching locates edge features to determine potential candidates to match pixels from each image (Küng *et al*, 2011). The algorithm filters these potential candidates to determine the ideal pixel and points to utilise for stitching multiple images together resulting in an orthomosaic image from which a 3D map can be created.

5.3 Methods

The study site is a gully complex in the Okhombe Valley region of northern KwaZulu-Natal, South Africa (28°42'28,215"S, 29°5'42,258"E) (Figure 5.1). This gully is believed to have originated and been maintained as a consequence of daily cattle migration up and down the slope for grazing (Plate 5.1). The area is classed as a rural area, sparsely populated in nucleated villages with predominately subsistence farming as the main economic activity. The topography is a flat valley bottom with steep-sided mountain slopes. The region is densely covered with erosional land features on either side of the valley.

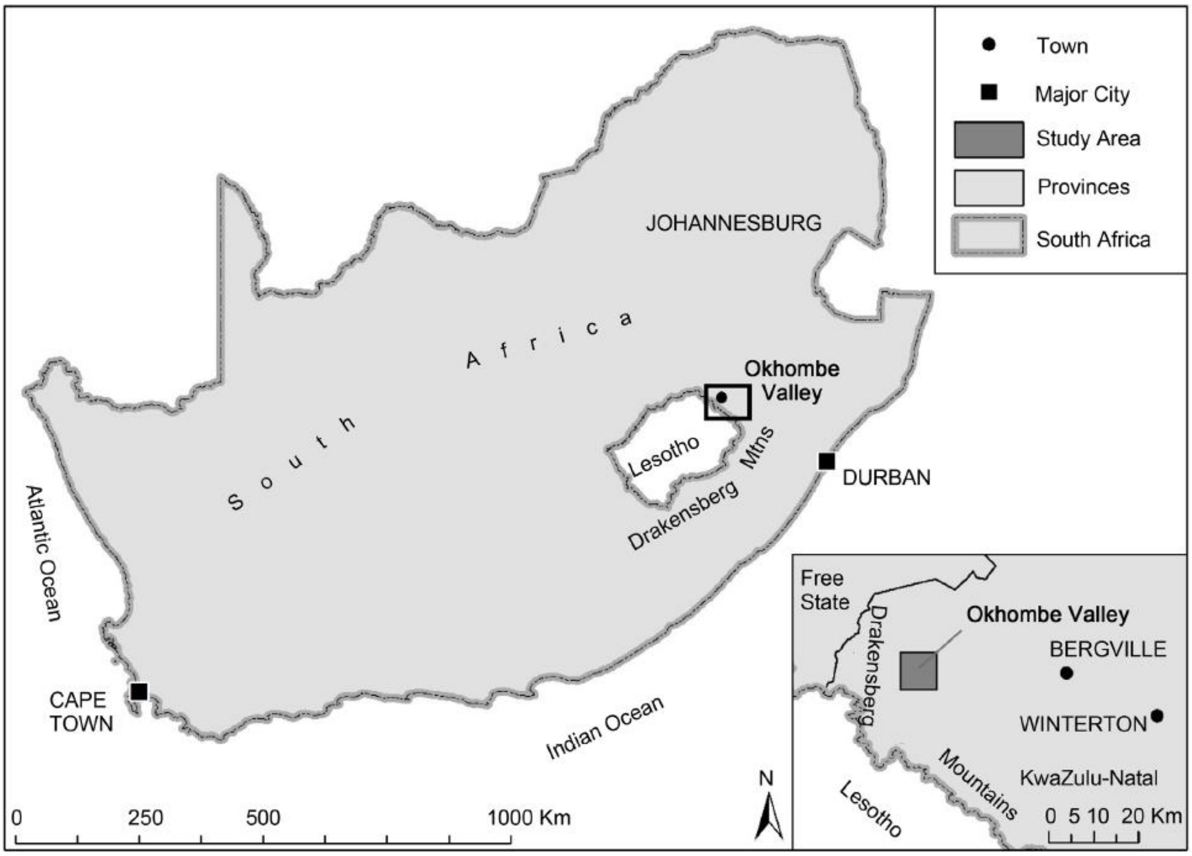


Figure 5.1: Schematic location map of Okhombe River Valley Gully system within the KwaZulu Natal, South Africa. (Adopted from Birkett *et al,* 2016)

Plate 5.1: Aerial image of Okhombe River Valley Gully system within the KwaZulu-Natal, South Africa. Note the gully on the left side of the ridge and the clear delineated cattle path to the right of the image from the daily cattle migration leading to loss of vegetation, topsoil, and surface wash.

This area was chosen due to the history of research on this site, where the implementations of the Betterment Scheme in the 1960s saw the initiation to minimise land degradation in this area, and to improve the livelihoods of the community to allow them to be self-sufficient. However, this failed to meet the intended goals and the National LandCare Programme was initialised in 1999. This was a community-based project whereby the community were trained in the benefits of crop rotation and better livestock herding practices (Everson *et al,* 2007).

The stratigraphy of this region is derived from the Beaufort group, where basalt, shale and sandstone can be found at the lower elevations, shale and mudstone on the slopes, and mudstone and sandstone on the plateau (Sonneveld *et al*, 2005). The Masotcheni Formation can be found in this region and consists of colluvial sediments (Temme *et al*, 2008). These colluvial sediments are unconsolidated deposits with a pH of 5.19 and a soil stability of 61-80%. The vegetation found on site consists of Southern Tall Grassveld and Drakensberg Grassland (Mucina & Rutherford, 2010).

The erosional features have been created by farming practices, where the daily movement of livestock from one area to the next utilises the same path. This has removed the vegetation cover from the trampling of vegetation and the exposure of bare soils. Rehabilitation efforts carried out by community members under the guise of numerous land use projects have taken place on-site to prevent or at best arrest the expansion of the gullies (Everson *et al,* 2007). This has been accomplished by using rock and boulders in the area to create rock piles within the gully itself (Plate 5.2). This method is time-consuming and labour-intensive; however, the community is driven to prevent further effects of erosion on site. The rehabilitation methods are monitored by the community and data is relayed to the researchers. Rain splash monitoring and surface runoff have been measured on-site by a collaboration between the researcher and the community, creating a bond that benefits both the researcher and the community. Thus, a true proactive community-driven rehabilitation project was being undertaken at the site.

Plate 5.2: Rock piles placed by community members to prevent erosion at the site.

This gully was chosen due to its advanced stages of erosion and was formed from the movement of cattle for grazing on top of the plateau, which has caused the trampling of vegetation and exposure of bare soils. The UAV was flown at the site on four separate occasions. This was done to obtain multiple images of the site over an extended time period to determine if soil movement is occurring.

The UAV used was a DJI Phantom 4 at the time of its release. The *AgiSoft MetaShape* software for image processing. There are minimum requirements, and higher-specification computers will process the data more quickly. The computer used for this research was the minimum requirement as the research was to determine the research questions with a budget. As multiple images were required to obtain the highest replication accuracy, a computer with fast-processing capability is required. Since erosional landscapes are not uniform and do not have regular shapes, the more images captured, the better the resulting processed image.

The UAV was set up with the flight path and height and the image overlap was set to 95%. These settings were saved, and the UAV autonomously completed the flight path capturing images in set locations, for each flight completed (2nd September 2018, 27th June 2019, 6th July 2021, and 22nd January 2022). Once the flight was complete, the images were uploaded to the *AgiSoft MetaShape* software, and images were aligned using the alignment tool. The accuracy was set low (a parameter option for the *AgiSoft MetaShape Software*) for the first run of processing and increased for each pass thereafter. This reduces the processing time of images and reduces the hardware and software's likelihood to be overwhelmed. The aligned images are then processed with the Dense Cloud Tool (tool to produce Digital Terrain Model), first with the lowest quality and then increased when the process was run. Once the Dense Cloud was created the Mesh Tool (the images are aligned, and a wire mesh was created) was used. Texture Tool (this tool fills in the wire mesh with pixels from the images captured) was used thereafter, which then allowed for the development of the Digital Elevation Model (DEM).

Once these processes had been completed, the building of the DEM and Orthomosaic was carried out. These are the two images that are the required output for the research. These were processed using the lowest accuracy at first and then increasing the accuracy for each processing of the same data, so as to lower the processing time and prevent the software from freezing and not completing the task. From this, it was possible to use the measurement tool in the *AgiSoft MetaShape* software to measure the volume of soil lost in the gully, for each site visit. The DEM files were manipulated using the orthomosaic software to determine a cross-section across the gully and compared between flight one and flight four, as these should have the greatest difference of erosional had occurred. The DEM file was manipulated with the GIS software to create contour maps of the site, to compare against the manually mapped gully and the 3D-rendered maps from *AgiSoft MetaShape.*

The research required the manual mapping of a gully, conducted by the use of an Abney level, tape measure and range stick. Intervals of 1m were used and a grid pattern was laid over the study site, this was done prior to the UAV flights and was conducted once. The purpose was to determine the angle between each section, which would assist in determining the height difference, from one point to another. As the intervals have been set to 1m, it was then possible to determine the change in height from one intersection to the next. These values were tabulated and processed to create a surface model with the use of Microsoft Excel. The surface map was then contrasted to that of the gully mapped by the UAV. The final objective was completed by mapping various types of erosion such as gully erosion, rill erosion, sheet wash and a riverbank. To determine if it was possible to map various erosional landscapes, is critical as the mapping of gullies is not the only erosional landscape, and the UAV technology would need to be versatile in its ability to map various features.

5.4 Results and Discussion

The manual mapping of gullies was found to be a long and tedious process, with features and information lost between two points of measurement. This immediately indicates the advantages provided by a UAV for infilling these gaps. Multiple flights were conducted to allow for the annual conditions and seasons, to allow the change over time to be determined. Trees and shrubs are replicated in the 3D image; however, they were distorted and difficult to map (Plate 5.3). The mapping of trees and shrubs is critical for the monitoring of rehabilitation methods implemented in gullies, as vegetation stabilizes soils and will assist in the rehabilitation of a gully. The software can map the vegetation, but only as a rudimental shape of a tree or shrub. Three sections were demarcated to subdivide the gully system into parts to determine how the volume changes throughout the network. Section one has a shallow gully system that is prograde in multiple directions, whereas the second section is a deeply incised gully. Sections 2 and 3 have similar attributes however they are 90 degrees from one another. Due to the remoteness of the site, regular trips were not possible, however, flights were taken in winter due to the absence of rain and ideal flight conditions except for the final site visit, which was conducted to capture more data prior to the completion of this research. The second site visit has a value that has been exaggerated by the software, which could be an error developed during processing, however, the first, third and fourth flights show an increase in volume in sections 2 and 3 (Table 5.1). The volume recorded in section 1 may be erratic over the four flights, as there may be anomalies in the imagery/ processing due to the smaller land features and the inability of the UAV and software to map these features. If one viewed the second flight as an outlier, then there has been a measurable loss from the first site visit to the fourth visit of approximately 1103.7 m^3 in sections two and three.

Table 5.1: The volume change from the first site visit to the fourth site visit at Okhombe valley.

Section	Site visit 1(m^3) 2nd September 2018	Site visit 2 (m^3) 27th June 2019	Site visit 3 (m^3) 6th July 2021	Site visit 4 (m^3) 22nd January 2022
1	733.4	597.7	864.4	536.7
2	2388.7	4264.6	2580.1	3261.0
3	2359.3	3807.0	2549.4	2590.7
Total	5481.4	8669.3	5993.9	6388.4

Cross sections (plate 5.3) were created of the lower and middle sections of the gully to compare and contrast the differences between the sections. The three sections were used on the bases that there are changes in morphology. Section 1 was chosen as it is the starting stage of the gully, whereas the section is a narrow deep gully, and lastly, the third section is at 90 degrees to the main body of the gully. There has been a change in the overall shape of the gully in both the middle and lower sections. The gully has become deeper and steeper, compared to the first flight. The removal of soil and topsoil is a vital resource that needs to be protected, and intense identification, monitoring, mapping, and predictive work needs to be developed to better understand the movement of soils in the future (Karami *et al*, 2015). This could be prevented by using a UAV at a lower altitude to capture images closer to the study area to increase the resolution. The mapping of micro rills would then be possible. However, the number of images would increase, thus making the need for computer processing capacity higher. The researcher could then fly at a higher altitude to obtain and lower resolution 3D of the entire site and stitch both series of images together. The combination of close-up images and broad area images would create the ideal 3D-rendered image. The movements of soils would then be possible to monitor fine detail.

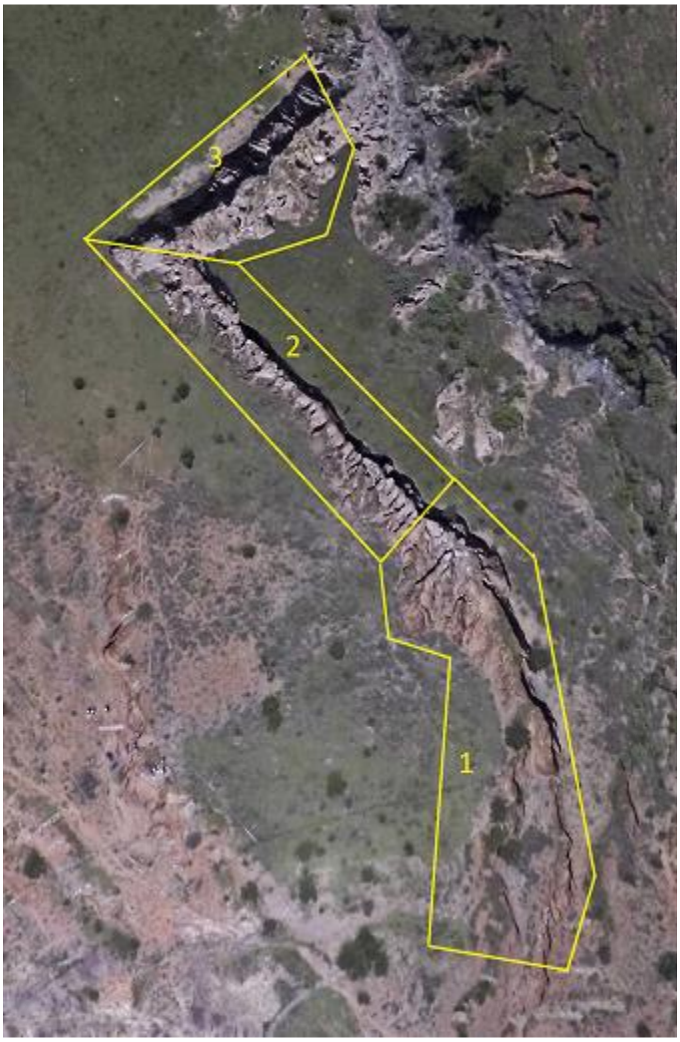


Plate 5.3: The Okhombe River Valley gully, separated into three sections.

Figure 5.2 depicts the movement of soils in a cross-sectional form, where one is able to view the change in the morphology of the gully. This cross-section shows the downward movement of the gully, however, both crossing sections from the middle (Section 2) and the lower section (Section 3), are higher in the first flight compared to the fourth. With the use of ground truth, it was determined that the surface of the surrounding land has not subsided, and this measurement error could be due to irregularities in the sensor or in the stitching software. The software does not allow the researcher to set parameters for the graphs such as starting points for the x and y axis, making it difficult to compare cross-sections. This could be a beneficial feature that should be added to the software.

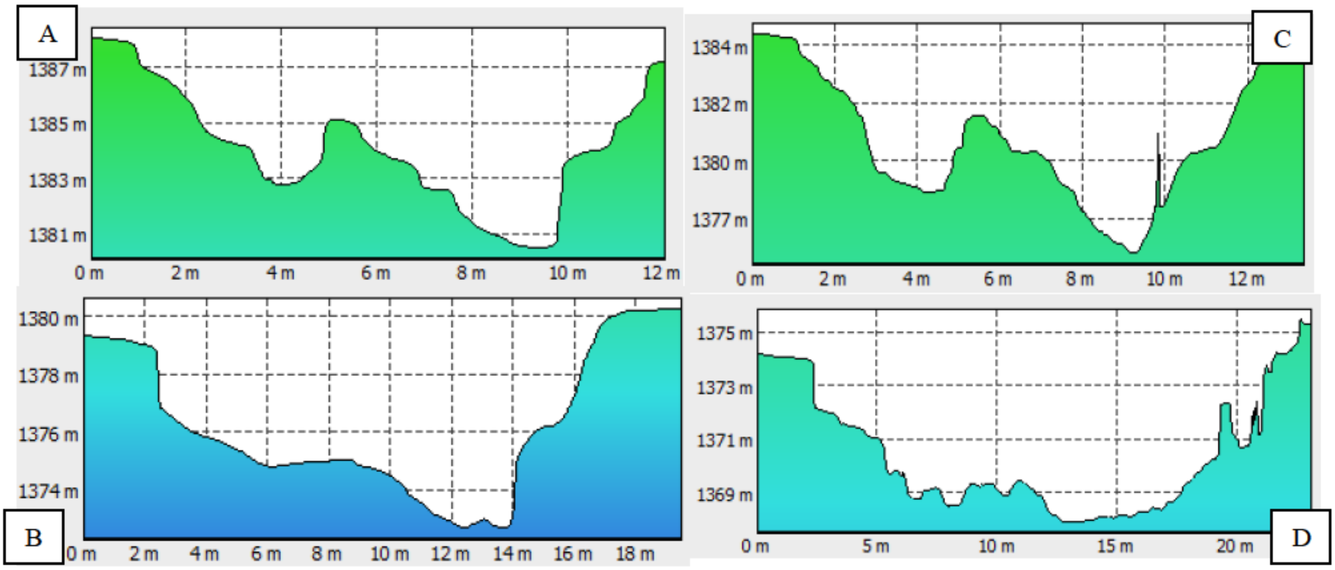


Figure 5.2: The Cross-Section at the intersection line between the middle section and Upper section (A and C) and the intersection line between the middle and lower section (B and D) of the gully from the first flight and compared to the fourth flight.

A quantifiable volume measurement to determine the ‘true’ amount of soil loss due to erosion is arguably a subjective process (Fones-Sundell, 1989), as there is no one process to map each section of a gully to include every smaller feature due to the complexities and extremely high image resolutions required to replicate a gully or erosional landscape on a 3D image or map. With the implementation of UAVs, the scanning and imaging of soil erosion can be done at a higher resolution and may assist in the calculation to determine the volume of soil being lost due to erosion, in a single gully. This is critical as the volumetric measurement would assist in determining the amount of soil lost in a gully and then determine the amount of soil lost once mitigation methods or rehabilitation methods have been implemented.

Plate 5.4: The 3D rendered image of the first site visit (2nd September 2018) of Okhombe Valley Gully, Drakensberg KwaZulu-Natal, South Africa.

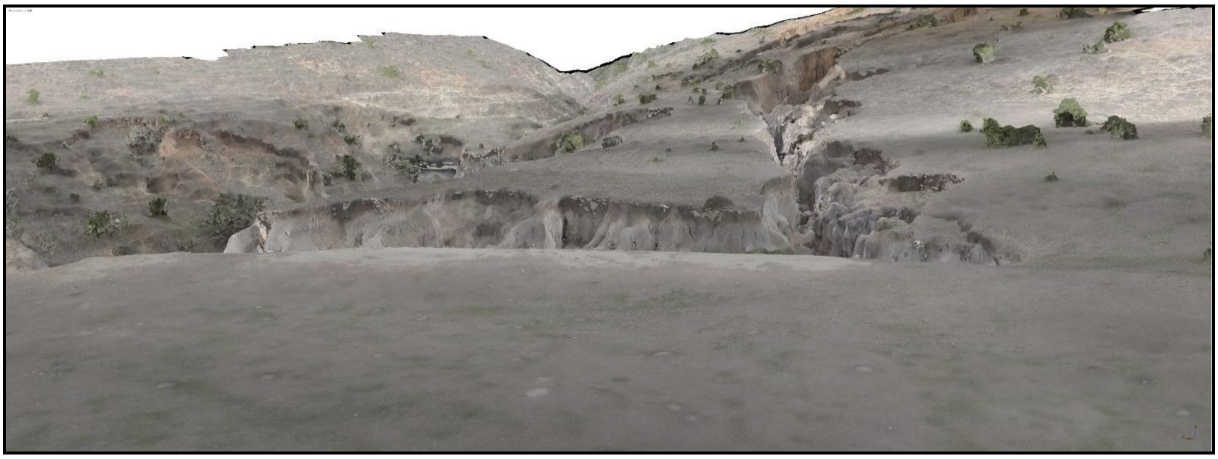


Plate 5.5: The 3D rendered image of the second site visit (27th June 2019) of Okhombe Valley Gully, Drakensberg KwaZulu-Natal, South Africa.

It is evident that the erosion has moved headward and upslope (Approximately 0.5 – 1.0m) (Plate 5.6). Image (a) has a higher accuracy than (b) due to the number of images used (Plate 5.6). What is visually evident is the rill erosion forming within the gully walls and the erosional stacks being produced. The contrast between image (a), image (b), image (c) and image (d) (Plate 5.6) proves the ability of a UAV to map the movement of soils. One is able to see head cuts expanding outwards from the first flight to the second flight, by approximately 0.1 m. Image (c) has a shadow cast over the study sight, however, the UAV was able to capture the morphology of the gully in low-light conditions. This shows the gully expanding and more soil being removed from this area. The side walls closer to the mean ground level have become steeper and will eventually erode away, thus widening the gully further.

The UAV was used to map rill erosion, gully erosion and a riverbed. This was processed and the resulting processed images are displayed. The software allows for various final images with an option being a wireframe image of the landscape. A wireframe image is produced to computer generate the surface of the land (Figure 5.4). The texture is then added to produce the images (Plates 5.7 and 5.8). The texture adds colour and ’life’ to the rendered image to provide a more realistic representation of the landscape. Furthermore, images can be displayed as an elevation model, in which a colour gradient is used to visualise changes in height (Figure 5.5). This is useful to provide a quick view of the landscape. One is able to use this colour-graded visual representation of the gully to determine the difference in heights for different sections and the steepness of the side walls of the gully (Figure 5.5).

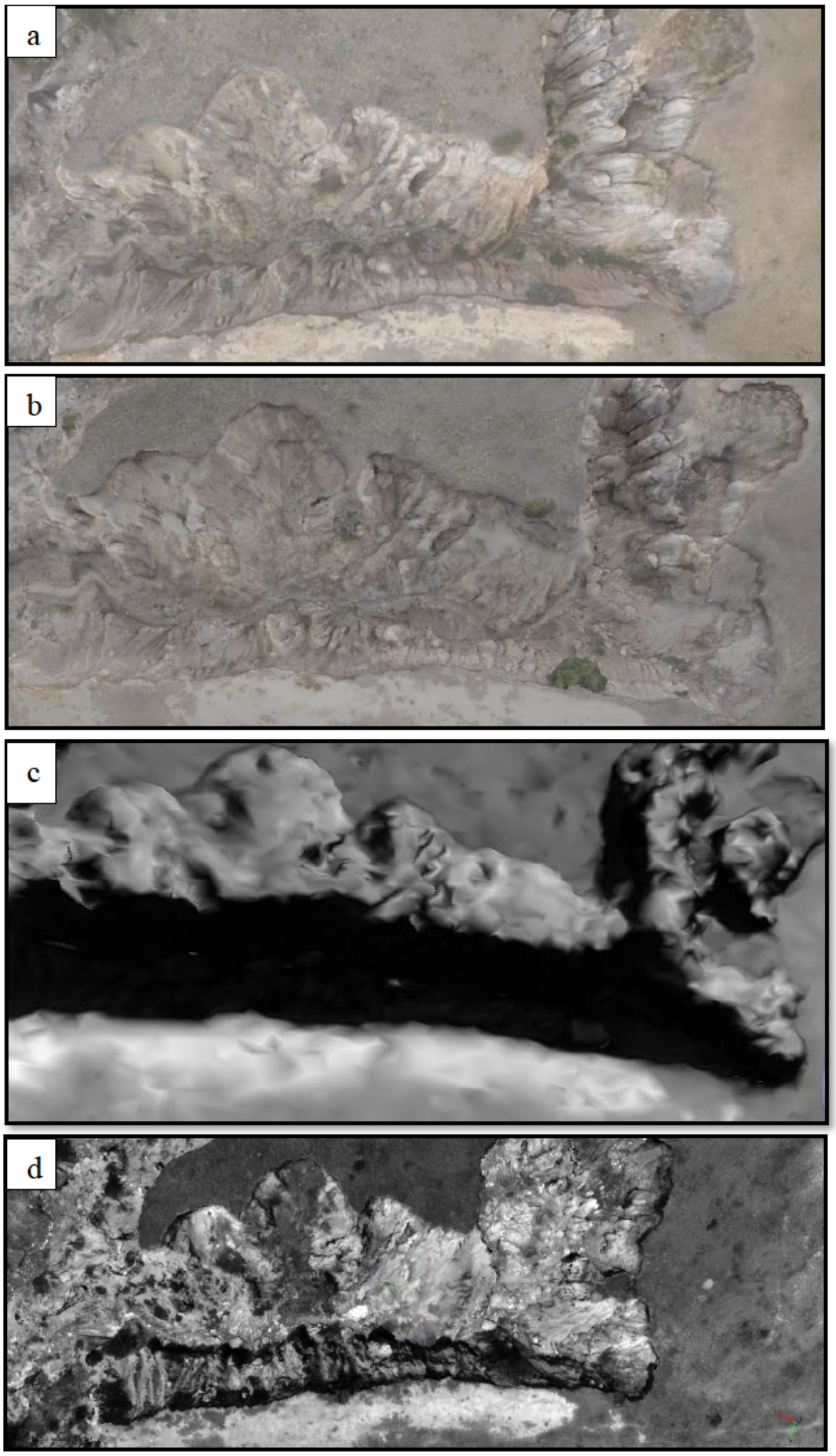


Plate 5.6: Images focus on a specific point of significate erosional change, image ‘a’ is the first site visit (2 September 2018), image ‘b’ is the second site visit (27 June 2019), image ‘c’ is the third site visit (6 July 2020), and image ‘d’ is the fourth site visit (22 January 2022).

The research applied a manually mapped method to map a gully adjacent to the main gully within this area. This was undertaken to assess the accessibility and stability of the soils. The manually mapped gully is undergoing rehabilitation using stone packs. A 1m horizontal increment was used for the mapping of this region. A difference in height was determined for each increment and graphically plotted and displayed in Excel spreadsheets as a 3D surface graph (Figure 5.1, Image A). The location of the gully was determined by the depression in the surface graph; however, the gully features are not easily seen. This would not be an ideal process to map or understand the movement of soils over time. The increment can be decreased or exaggerated; however, assessment of this process would be time-consuming. The manual mapping of this region using a 1 m increment created 306 data points and took approximately three people four hours to complete. This creates a wireframe of the site where the more points collected, the higher the resolution of the final image (Figure 5.3) If the increment has to decrease to that used to create the contour in Figure 5.4, Image C, this will create 30 600 data points, significantly increasing the time to capture.

Figure 5.4 image B is able to visualise a replicated gully using a UAV and *AgiSoft MetaShape* Software. This was completed in several minutes to capture the area and less than 2 hours to process the area with the software. Features not previously seen on the manually mapped were easily determined. The combination of the UAV, the *AgiSoft MetaShape* software and ArcGIS allowed the users to create low increment contour maps of a site (Figure 5.4, Image C). These contour maps are useful in the monitoring of soil movement. A researcher would be able to capture these images and produce a contour map with the same increment for multiple site visits to obtain a better understanding of the sources and movement of soil. This process can also be useful for monitoring the rehabilitation of a site as one would be able to determine if sediment is being captured behind a soil erosion preventative measure.

A case study conducted in Morocco, where researchers used DTM and LiDAR scans to attempt to 3D render a gully (Peter *et al*, 2014), found that the finer details as the DTM and LiDAR scanners did not obtain higher enough resolution and required manual mapping. This is no longer the case as a 3D render of a landscape can be created using a UAV and orthomosaic software (Plate 5.7 and Plate 5.8). When exporting images from the stitching software, at the time this research was conducted, the image would not export with a scale. This could be an additional feature added to the software at a later stage, or it is possible with the current process to place an object on the ground of a known scale. The UAV is able to process images for manipulation in GIS. This process is known to be less of a time constraint and more cost-effective than that of satellite imagery. The manual mapping of a gully has produced a summarised or segmented surface model (Figure 5.4). The manually mapped gully proves to provide less detail and information than the results of the gully mapped with the UAV. This does not mean that the manual mapping of gullies should not be undertaken but rather used for additional information, as this could be used as a form of ground truthing of the information provided by the software.

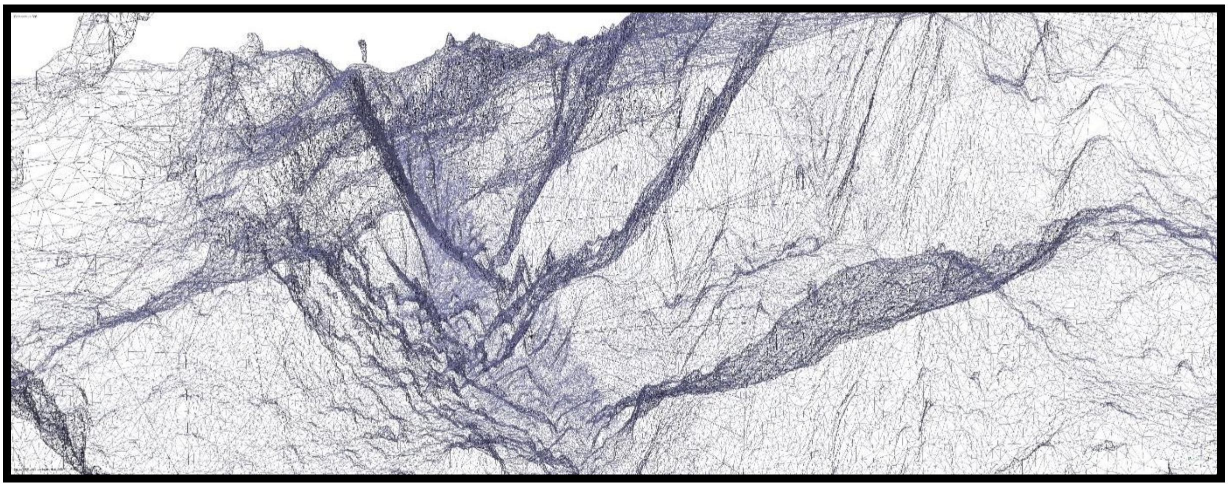


Figure 5.3: A wireframe view of an erosional landscape produced by the AgiSoft software before the texture has been added.

Table 5.2: Abney level values converted from angle to difference in heights to assist in the surface modelling.

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
0	0	-0,05	-0,1	-0,26	-0,35	-0,44	-0,52	-0,24	-0,28	-0,16	0	0	0	0,23	0,24	0,26	0,28
2	-0,2	-0,22	-0,2	-0,41	-0,62	-0,46	-0,51	-0,57	-0,76	-0,36	-0,2	-0,2	-0,2	-0,43	0,44	0,99	1,59
4	-1,08	-0,64	-0,33	-0,35	-0,66	-1	-1,18	-1,81	-1,92	-1,24	-1,43	-1,46	-1,29	-1,08	-0,35	-0,56	-0,52
6	-1,73	-1,54	-1,15	-0,85	-0,83	-1,29	-1,83	-2,34	-2,98	-2,67	-2,25	-1,35	-1,52	-1,73	-1,73	-1,21	-1,17
8	-2,45	-2,28	-2,07	-1,98	-1,82	-2,01	-2,14	-2,76	-3,29	-3,39	-2,97	-2,45	-1,4	-1,32	-2,94	-1,93	-2,17
10	-2,97	-2,85	-2,73	-2,66	-2,76	-3,23	-4,11	-4,31	-3,67	-3,6	-3,14	-2,97	-3,39	-2,52	-2,48	-2,71	-2,41
12	-3,21	-3,11	-3,04	-2,95	-2,93	-4,5	-4,56	-4,43	-4,46	-4,15	-3,73	-3,98	-3,84	-3,11	-2,97	-2,42	-2,65
14	-3,41	-3,25	-3,17	-3,88	-4,71	-4,78	-4,96	-4,87	-4,93	-4,19	-4,45	-3,99	-4,25	-3,86	-3,9	-3,25	-2,85
16	-3,69	-3,52	-3,41	-3,27	-3,28	-3,25	-4,94	-5,74	-6,03	-5,41	-5,43	-4,84	-4,32	-5,5	-5,4	-4,29	-3,69
18	-4,17	-4,01	-4	-3,86	-3,76	-3,65	-3,75	-3,8	-6,91	-7,97	-8,24	-8,82	-6,05	-4,62	-4,66	-4,69	-4,17
20	-4,59	-4,43	-4,35	-4,38	-4,45	-4,42	-4,49	-4,47	-4,31	-5,22	-5,89	-6,82	-7,7	-8,55	-9,22	-10,11	-4,59
22	-5,37	-5,27	-5,06	-4,85	-4,81	-4,85	-4,85	-4,76	-5,05	-6,47	-6,65	-6,88	-7,03	-6,11	-5,98	-5,87	-5,54
24	-6,13	-6,1	-6,13	-5,92	-5,85	-5,69	-5,72	-5,64	-5,71	-6,55	-7,37	-7,34	-6,4	-6,75	-7,06	-7,17	-7,24
26	-6,71	-6,62	-6,54	-6,4	-6,3	-6,01	-6,19	-5,98	-6,07	-7,66	-8,52	-6,67	-7,02	-7,02	-7,08	-6,96	-6,76
28	-7,16	-7,04	-7,06	-6,79	-6,6	-6,64	-6,64	-6,43	-6,69	-7,72	-7,98	-6,71	-7,04	-7,16	-7,16	-5,73	-7,06
30	-7,74	-7,74	-7,77	-7,79	-7,95	-8	-8,05	-7,86	-8,28	-8,98	-9,94	-8,28	-7,42	-7,55	-7,49	-7,58	-7,7
32	-8,19	-8,02	-7,81	-7,5	-7,15	-7,15	-6,42	-5,81	-6,63	-7,15	-7,53	-7,31	-6,16	-6,44	-6,54	-6,51	-6,28
34	-8,64	-8,64	-8,67	-8,69	-8,71	-8,64	-8,33	-8,03	-8,15	-8,91	-9,66	-10,86	-8,03	-7,61	-7,91	-7,89	-7,72
36	-9,32	-9,24	-9,15	-8,85	-8,76	-9,04	-9,94	-10,17	-10,06	-8,41	-8,24	-8,27	-8,34	-8,6	-8,76	-8,76	-8,97
38	-9,9	-9,73	-9,73	-9,59	-9,55	-9,57	-10,67	-10,67	-10,59	-9,09	-9,03	-9,06	-8,99	-9,24	-9,38	-9,55	-9,55
40	-10,38	-10,38	-10,35	-10,12	-10,24	-9,68	-11,01	-10,87	-9,54	-9,28	-9,16	-9,42	-9,33	-9,25	-9,4	-9,6	-9,26
42	-10,86	-10,74	-10,79	-10,91	-10,93	-11,3	-11,38	-10,13	-10,16	-10,08	-10,34	-10,09	-10,23	-10,18	-9,88	-9,81	-9,74
44	-11,31	-11,22	-11,1	-11,83	-11,94	-11,14	-11	-10,94	-11,17	-11	-10,96	-10,92	-10,89	-11,08	-11,07	-10,79	-10,47
46	-11,76	-11,78	-11,76	-11,55	-11,48	-11,32	-11,34	-11,52	-11,34	-11,13	-11,06	-11,18	-11,13	-10,85	-10,78	-10,98	-10,92

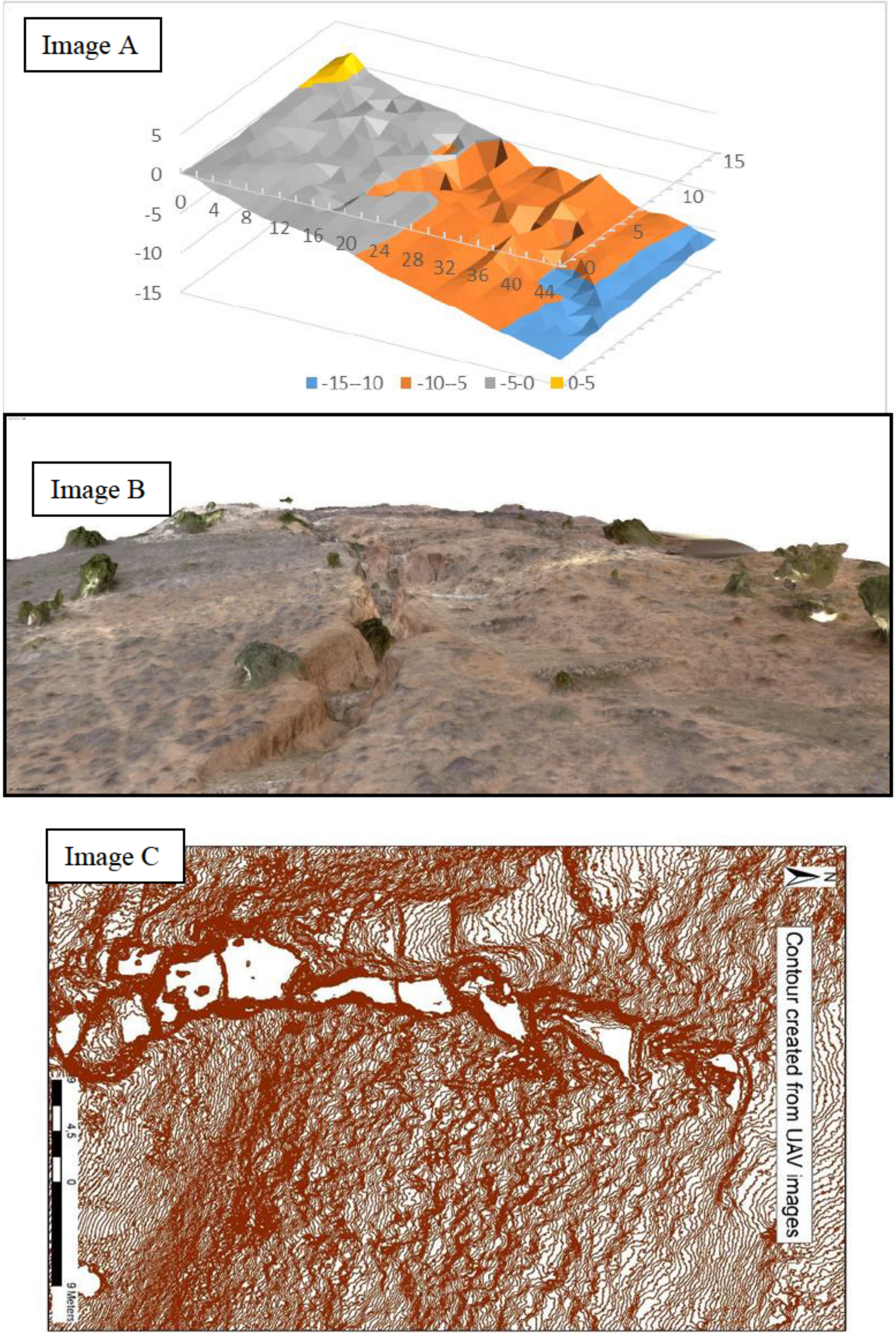


Figure 5.4: A graphical representation of a manually mapped erosional feature (Image A) compared to that of a 3D rendered image produced by *AgiSoft MetaShape* (Image B) and compared to the contour map produced by the UAV, *AgiSoft MetaShape* software and ArcGIS software at a 0.05m interval (Image C).

Plate 5.7: 3D renders of a riverbed with gully rill erosion on the riverbanks located in Mooi River, KwaZulu Natal, South Africa.

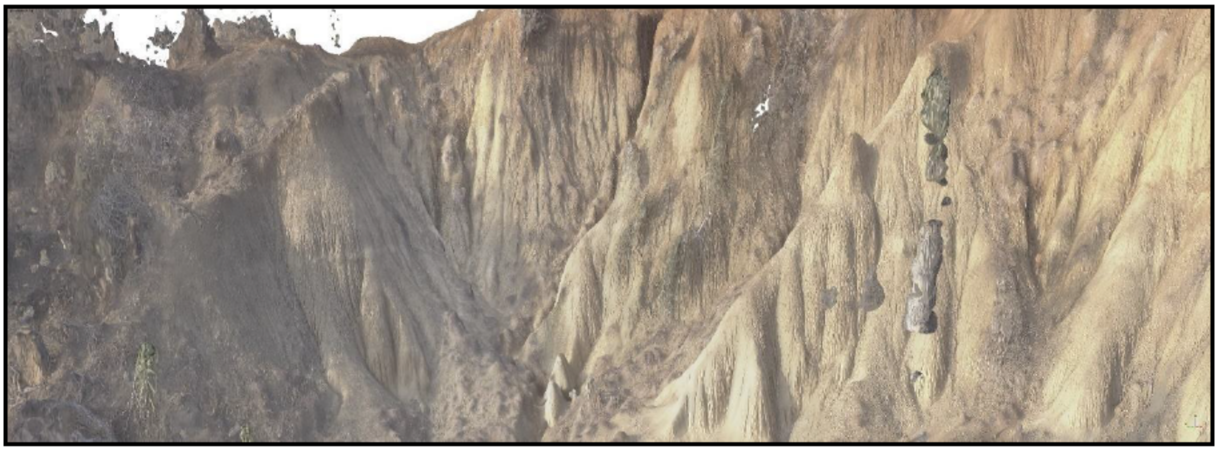
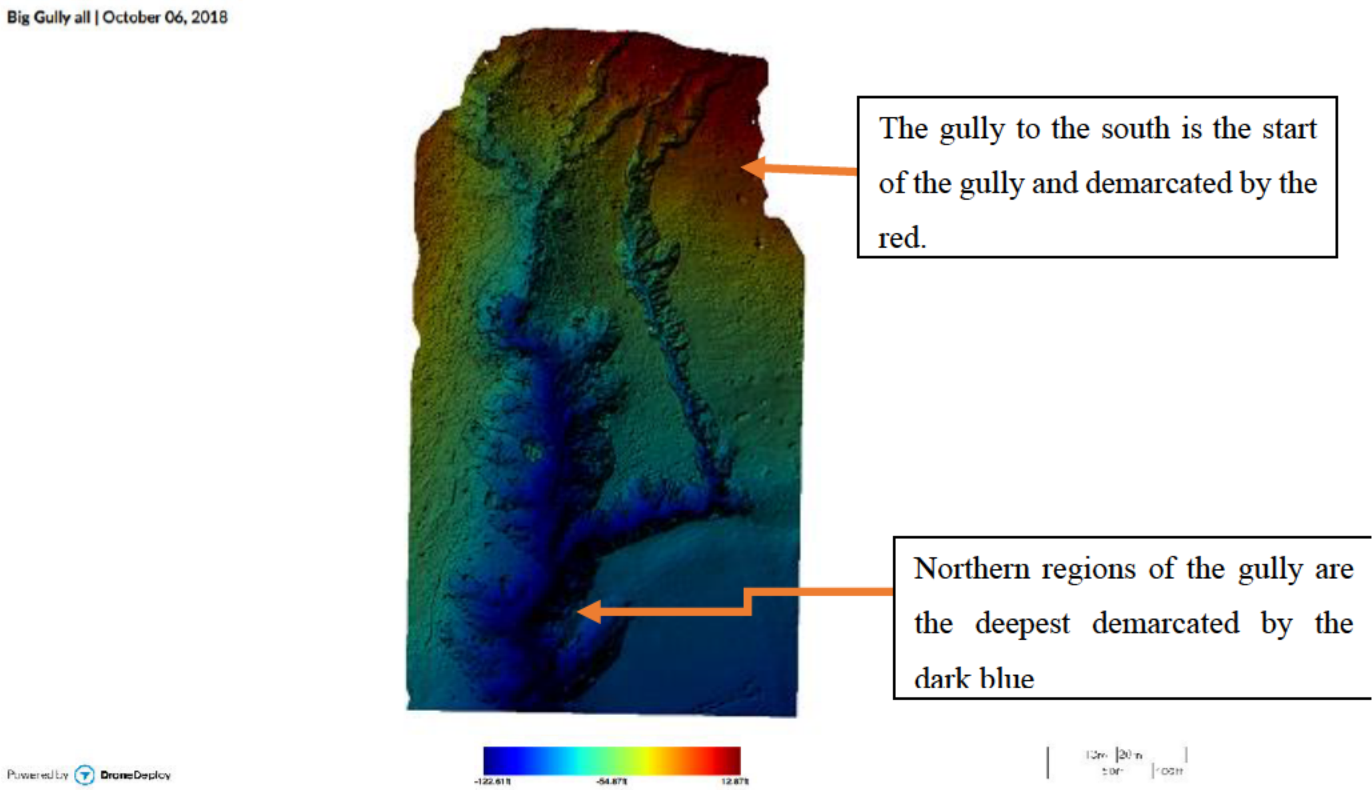


Plate 5.8: Graphic renders of the rill erosion found on walls of a riverbed, located in Mooi River, KwaZulu Natal, South Africa.



The gully to the south is the start of the gully and demarcated by the red.

Northern regions of the gully are the deepest demarcated by the dark blue

Figure 5.5: An annotated elevation model produced by *DroneDeploy* computer software. The source/top of the gully (uphill) is demarcated by the red colours and blue is the mouth/bottom and lower laying areas of the gully for the first flight.

5.5 Limitations and Recommendations

UAV technology and associated software continue to develop, and new applications are attempted. The ideal UAV would be a small, compact device with a high-resolution camera that can fly for an extended period of time than existing UAVs, as the current battery life of most UAVs is approximately 30 min in ideal conditions. The software processing time should be minimised while not affecting accuracy. The final project should be able to bond with a 3D printer to obtain a scaled model of the study.

Software processing time is a limiting factor for *AgiSoft MetaShape*, which requires high-powered computers that are expensive to purchase. The software does not yet have the ability to map vegetation in 3D, and thus the software and UAV combination is not able to successfully monitor vegetation over time despite the need to validate and measure rehabilitation projects through changes in vegetation. However, to some extent, this can be overcome by capturing the images at a lower altitude to produce finely detailed images.

For the ideal 3D image to be produced, the UAV should fly the same route over a study site at different heights and with the onboard camera angled at various orientations. This would allow the perfect mapping of a site and reduce the shadow zones.

As technology is not always reliable, it is always advisable to double-check the equipment prior to going to the site. Double-checking the battery of the UAV, the controller and the screen is required especially when travelling to remote sites. While undertaking this research, the author experienced a memory card malfunction and without a backup on hand, the flight was abandoned.

5.6 Conclusions

The research has demonstrated the ability to use orthomosaic software with the incorporation of UAVs to map physical objects with a high degree of accuracy for 3D gully mapping. In conjunction with the community-led rehabilitation project and researchers, it has proved possible for different parties to work together to mitigate erosion, rehabilitate the gully and map outcomes. The continuation of the relationship will allow for a better understanding of the requirement of the community and thus create target solutions to their day-to-day requirements. Allowing for free movement of livestock in the area is not possible as theft is a possibility, however, if this was eradicated, the fencing of a large area and allowing the free movement of animals, continued use of single footpaths from the livestock may be prevented and the chance of erosion reduced.

The aim of this research was accessing the prospects of UAV and 3D modelling in mapping of gully erosion. It was seen that with the reduction in image number, the rendered image lost resolution and clarity. The textures of the image were not as sharp as that of the image where all images were used. The manual mapping proved to be time-consuming, and the results do not reproduce the landscape accurately. The manually mapped surface model was rigid, as it missed features between 1m increments, losing the finer details that are required to map can lower the usability of the maps. The lowering of intervals would reduce the rigidity and would increase the time required. The third and fourth objectives were to determine if this combination was able to 3D map erosional land features. To which the combination of the UAV and 3D software proved itself, by mapping various gullies, rills within the gullies and a riverbed, proving the diversity of UAVs for the purpose of mapping. The last objective was to determine if the combination of image capturing with a UAV and processing these images on orthomosaic software is able to measure volume loss in soils. This could be due to the smaller land features found in the area. However, the middle and lower sections of the gully were measured, and a loss was calculated from the first to the fourth flight. Thus, the volume of soil being lost over a period of time was determined, however, the soil loss volume accuracy would need further study with ground truthing. The UAV and stitching software were able to determine an increase in width in the gully and the steeping of the gully wall. The images produced, provided, and cost and time-effective way to monitor the movement of soils. This could be created monthly to determine the movement of the soils to assist in the prediction of the movement in the future or conducted before and after an extreme storm event. The lower the flight elevation of the UAV, the higher the resolution. This would mean that with the stitching together of high-resolution images, one can create a single higher-resolution image that can be useful in terms of remote sensing or aerial photography.

Future research could be conducted where the software is implemented into other fields such as gully rehabilitation. This would be useful for developing an understanding of soil erosional events and assisting in understanding the movement of soils in the landscape. This understanding may benefit measures selected in the mitigation of erosion and could help with the prediction of soil movement in the future.

References

Birkett, C., Hill, T., Zuma, K., and Everson, T. (2016). Bringing Rain to the Land: Rainfall Simulation as a Participatory Teaching Aid to Understanding Erosion. *Journal of Environmental Protection*. 7(10), 1305-1316.

Carey, B., Leach, G. and Venz, B. (2004). Soil Erosion in Queensland Cropping Lands -An Historical Perspective and New Challenges. *Conserving Soil and Water for the Society: Sharing Solutions*. ISCO 2004 – 13th International Soil Conservation Organisation Conference – Brisbane, July 2004.

Dowsett, M. (1944). Soil Erosion. *Journal of the Royal African Society*. 43 (170), 29 – 39.

Everson, T., Everson, C. and Zuma, K. (2007). Community based research on the influence of rehabilitation techniques on the management of degraded catchments, *Water Research Commission*. Report No. 1316/1/07, Pretoria.

Fones-Sundell, M. (1989). Perspectives on Soil Erosion in Africa: Whose Problem? *International Institute of Environment and Development.* 14, 1 – 10.

González, M., and Rodriguez, P. (2017). Monitoring Soil Erosion by Raster Images: From Aerial Photographs to Drone Taken Pictures. *European Journal of Geography*. 7(5), 117 – 129.

Ighodaro, I. D., Lategan, F. S. and Yusuf, S. F. G., (2013). The Impact of soil erosion on agricultural potential and performance of Sheshegu community farmers in the Eastern Cape of South Africa. *Journal of Agricultural Science,* 5(5), 140-147.

Johnson, D. (2000). Soils and Soil-Geomorphology Theories and Models: The Macquarie Connection. *Annals of the Association of America Geographers*. 90 (4), 775 – 782.

Jordan, B. (2015). A Birds Eye View of Geology: The Use of Micro Drones/UAV in Geologic Fieldwork and Education. *The Geological Society of America*. 25(7), 42-43.

Karami, A., Khoorani, A., Noohegar, A., Shamsi, S. and Moosavi, V. (2015). Gully Erosion Mapping Using Object-Based and Pixel-Based Image Classification Methods. *Environmental and Engineering Geoscience*, 21(2), 101 – 110.

Knight, J., Spencer, J., Brooks, A., and Phinn, S. (2007). Large Area, High-Resolution Remote Sensing Based Mapping of Alluvial Gully Erosion in Australia's Tropical Rivers. *In Proceedings of the 5th Australian Stream Management Conference: Australian Rivers: Making a difference, New South Wales, Australia*, 199–204.

Koh, L. and Wich, S. (2012). Dawn of Drone Ecology: Low-Cost Autonomous Aerial Vehicles for Conservation. *Tropical Conservation Science*. 5(2), 121 – 132.

Korzeniowska, K., Pfeifer, N. and Landtwing, S. (2018). Mapping Gullies, Dunes, Lava Fields, and Landscapes via Surface Roughness. *Geomorphology*. 301, 53 – 67.

Küng, O., Strecha, C., Fua, P., Gurdan, D., Achtelik, M., Doths, K. and Strumpf, J. (2011). Simplified Building Models Extraction for Ultralight UAV Imagery. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences.* Volume XXXVIII-1, 217 – 222.

Le Roux, J., Morgenthal, T., Malherbe, J., Pretorius, D. and Sumner, P. (2008). Water Erosion Prediction at a National Scale for South Africa. *Water S.A,* 34(3), 305-314.

McHugh, M. (1999). Soil Erosion. *The Geographical Journal*. 165 (1), 113 – 114

Mucina, L. and Rutherford, M. (eds) (2010). The Vegetation of South Africa, Lesotho, and Swaziland. Edition 1, Impression 2. South African National Biodiversity Institute, Pretoria. *Strelitzia* 19

Peter, K., d'Oleire-Oltmanns, S., Ries, J., Marzolff, I. and Hssaine, A. (2014). Soil Erosion in Gully Catchments Affected by Land-Levelling Measures in the Souss Basin, Morocco, Analysed by Rainfall Simulation and UAV Remote Sensing Data. *Catena.* 113, 24–40.

Poesen, J., Vandaele, K. and Van Wesemael, B. (1996). Contribution of Gully Erosion to Sediment Production on Cultivated Lands and Rangelands. *Erosion and sediment yield: Global and Regional Perspectives.* Proceedings of the Exeter Symposium in July 1996. IAHS Publish No 236, 1996.

Rahmati, O., Kalantari, Z., Ferreira, C., Chen, W., Soleimanpour, S., Ghajarnia, N. and Kazemabady. (2022). Contribution of Physical and Anthropogenic Factors to Gully Erosion Initiation. *Catena*. 210 (2022), 1 – 11.

Riddle, L., Hill, T. and Gijsbertsen, B. (2018). Geomorphology from 'on-high': The Use of Drones/UAV Technology in Teaching Soil Erosion. *Journal of Geography Education for Southern Africa.* 3(1), 10 – 22.

Romanescu, G., Cotiuga, V., Asandulesei, A. and Stoleriu, C. (2012). Use of the 3-D Scanner in Mapping and Monitoring the Dynamic Degradation of Soil: Case Study of Cucteni-Baiceni

Gully on the Moldavian Plateau (Romania). *Hydrology and Earth System Science,* 16 (3), 953 – 966.

Sonneveld, M., Everson, T. and Veldkamp, A. (2005). Multi-Scale Analysis of Soil Erosion Dynamics in KwaZulu-Natal, South Africa. *Land Degradation and Development*, 16 (3), 287 – 301.

Taylor, R., Massey, C., Fuller, I., Marden, M., Archibald, G. and Ries, W. (2018). Quantifying sediment connectivity in an actively eroding gully complex, Waipaoa catchment, New Zealand. *Geomorphology,* 307, 24-37.

Tedesco, A., Antunes, A, and Ribeiro, S. (2016). Gully Erosion Mapping with High Resolution Imagery and ALS data by Using True Decision Hierarchical Classification and Obia. Conference: GEOBIA 2016: Solutions and Synergies, University of Twente, Netherlands, September 14-16, 2016.

Temme, A., Baartman, J., Botha, G., Veldkamp, A., Jongmans, A. and Wallinga, J. (2008). Climate Control on Late Pleistocene Landscape Evolution of the Okhombe Valley, KwaZulu Natal, South Africa. *Geomorphology*. 99 (1-4), 280 – 295.

Wang, R., Zhang, S., Pu, L., Yang, J., Yang, C., Chen, J., Guan, C., Wang, Q., Chen, D., Fu, B., and Sang, X. (2016). Gully Erosion Mapping and Monitoring at Multiple Scales Based on Multi-Source Remote Sensing Data of the Sancha River Catchment, Northeast China. *International Journal of Geo-Information*. 5 (11), 1 - 17.

William, R., Tooth, S. and Gibson, M. (2016). The Sky is the Limit: Reconstructing Physical Geography from an Aerial Perspective. *Journal of Geography in Higher Education*. 41(1), 1 - 13.

Zhang, Z., Gerke, M., Vosselman, G. and Ying Yang, M. (2018). A Patch-Based Method for the Evaluation of Dense Image Matching Quality. *International Journal of Applied Earth Observation Geoinformation*. 70, 25 – 34.

Zhang, G., Zhao, W., Yan, T., Qin, W. and Miao, X. (2023). Estimation of Gully Growth Rate and Erosion Amount Using UAV and Worldview-3 Images in Yimeng Mountain Area, Chine. *Remote Sensing*. 15 (1), 1-17.

CHAPTER SIX

The Benefits of RGB Sensor and Multi-spectral Sensor Mapping of Soil Erosion in a Degraded Landscape using an Unmanned Aerial Vehicle

Riddle, L [a*], Hill, T[a] and Clulow, A[a]

a. School of Agricultural, Earth and Environmental Sciences, University of KwaZulu-Natal, Private Bag X01, Scottsville, Pietermaritzburg 3209, South Africa. lyndonriddle@gmail.com

* Corresponding author

Abstract

Soil erosion is a common, natural occurrence exacerbated by human impact and, in particular in rural areas of southern Africa, due to livestock management. One outcome in montane fragile environs is the development of erosional gullies that litter the landscape and are considered by the community as a hazard. Determining the amount of soil loss in a gully is complex and, to date, there is no accurate method to determine the amount of soil loss. This research set out to determine the benefits of using a multi-spectral sensor in remote sensing to gain a better understanding of soil erosion. As soil erosion is classed as a process of unstable landscapes, the UAV provides access to areas that were previously inaccessible and not possible to complete regular monitoring measurements. In this research, a UAV was flown over the Okhombe River Valley, KwaZulu-Natal, South Africa; a degraded landscape exacerbated by the daily migration up the slope. Four UAV flights were completed, the first two using the RGB sensor and the second two using a multi-spectral sensor. The ideal time for capturing the images was when the sun was directly above the site or on an overcast day to prevent the effects of shadows. The series of images were then used to map the erosional landscapes in 3-dimensions. The multi-spectral sensor produced a thermal image that allowed for the cross-reference to the NDVI, NDRE, NDWI and the thermal image to locate areas which were potentially more prone to soil erosion. It was found that the multi-spectral sensor was more diverse in its ability to produce maps. As the UAV is a new innovative technology, and more applications and uses are being discovered, developed, and recognised, it is for the users to determine beneficial applications. The combination of satellite imagery and UAVs has the potential to produce high-accuracy results for mapping, predicting, and monitoring soil erosion. This, together with community engagement, has the potential to improve the monitoring and management of soil erosion in the region.

6.1 Introduction

In the past decade, the application of aerial photography and satellite imagery has increased with the technological advancement of image quality and resolution within the sub-discipline of erosional mapping (William *et al*, 2016). Platforms such as Google Earth have made it possible for all to access contemporary and historic satellite imagery and aerial imagery. This platform includes a low-resolution feature to produce 3-Dimensional (3D) renders of a specific area or landscape and allows users to view land features before entering the study areas. Platforms such as the USGS explorer site, allow researchers to download images for the use of research, however, the LandSat remotely sensed data, has a low resolution and can be expensive to acquire. With the implantation of an Unmanned Aerial Vehicle (UAV), aerial imagery is possible with a high degree of image accuracy and detail. The UAV allows researchers to obtain images of a specific site, in particular sites that are remote and/or inaccessible, while reducing operation time and costs (William *et al*, 2016). The UAV may be able to assist in hazard assessment mapping and the quick response to observing the consequence of natural disasters in isolated regions, for example, the 5.4 magnitude earthquake that struck Afghanistan on 7th November 2022 (United States Geological Services, 2022). In this case, the UAV was used to map the area to view areas of instability, including the use of thermal imagery to locate survivors or bodies.

Erosional landscapes are by nature unstable environments and deemed unsafe, and the use of a UAV from a safe distance allows researchers to obtain imagery of an erosional landscape without placing people at risk (Droeshcal *et al*, 2017). Sites are typically viewed initially using aerial images for planning purposes. This is followed by remote sensing using automatic extraction systems that have been developed that can identify gully erosion with the use of satellite images (Karami *et al*, 2015). Remote sensing technology has the ability to map, and determine the shape, size, and occurrence of the features of a gully (Knight *et al*, 2007). These remote sensing technologies map gullies on a 2D plan for researchers to locate and study. Aerial photography has been applied to monitor long-term low spatial and temporal data at a large scale. This can be useful to identify the mass movement of soil, however, the resolution lacks detail to investigate the movement of micro-erosional events, such as rill erosion or development of the side walls of gullies (Wang *et al*, 2016). However, remote sensing technologies are able to assist in the development of 3D maps of gullies. A 3D image of a gully would allow researchers to investigate the movement of sediment and the development of erosional features over time or as a monitoring tool to validate management practices. The use of 3D image software associated with a UAV and stitching software for the mapping of erosion may have a positive effect on the study of erosional processes by providing accurate measurements and possibly the prediction of erosional processes. In addition, the use of 3D image software reduces what is presently a time-consuming and costly event (Karami *et al,* 2015).

UAVs can have multi-sensor cameras installed as a payload, which are able to detect waves from the near-infrared range (780 – 2500nm), visible range (350 – 780nm) and thermal imagery (Fang, *et al,* 2018). The use of thermal imagery is becoming common practise in agricultural practises (Schönebeck *et al,* 2021), with resulting imagery assisting in the early-stage detection of plant health and deterioration. The reduction of plant health is said to be linked to water shortage (Schönebeck *et al,* 2021), which will in turn reduce the vegetation coverage on the soil, thus having the potential of increasing soil erosion. The land surface temperature can be included as a key parameter of the land's surface process, which can be measured with the use of a UAV (Frodella, *et al,* 2020). The interest in developing methodologies to identify and measure soil surface temperatures with the use of remote sensing is crucial as this will allow for a better understanding of the relationship between soil surface temperatures and soil.

This research investigates the application of orthomosaic software and UAVs to digitally replicate the erosional landscape and apply it to landscape monitoring and interpretation. This was achieved by applying a multi-spectral sensor to monitor soil loss of the landscape to assist in the prediction of soil loss, followed by a critical review of the process of using a UAV and stitching software to determine future possibilities of the application.

6.2 Literature Review.

3D scanners and imagery have, in the past, been used to monitor the dynamics of soil erosion to improve our understanding of gully mapping and the risks associated with soil erosion (Zhang *et al*, 2018). Presently Terrestrial Laser Scanners (TLS) and Airborne LiDAR devices are used to obtain precise and relatively high-resolution data for modelling purposes of erosional landscapes (Wang *et al*, 2016). The high resolution is relative, in this case, as at the time this technology was released, a resolution of 1 m was regarded as high resolution, whereas the UAV can produce an image with a resolution of sub 1m, which would be required to map a gully (William *et al*, 2016). The use of TLS and Airborne scanners is declining as TLS and Airborne LiDAR can be limited due to resolution and costly (Frankl *et al*, 2015). However, the combination of remote sensing, UAV technology and stitching software, could offer a large-scale high-resolution image. A UAV uses a technique called Ground Sampling Distance (GSD), where the pixels are used to determine ground distances (Frankl *et al*, 2015). This is achieved by determining the number of pixels a camera sensor has, the distance from the ground the image was taken, and the result is the area each pixel covers on the ground. This has been found to produce a higher resolution than that of TLS and Airborne LiDAR, often obtaining a resolution of 0.5 m to 3 m (Wang *et al*, 2016). This technique is used by capturing multiple images of a site and ortho-rectifying the images to produce a single large-scale image.

The *AgiSoft MetaShape* software has been developed for the mapping of landscapes and buildings in the civil engineering field, to assist engineers in obtaining a virtual representation of the site (Strecha *et al*, 2012). The software has the ability to create 3D maps of buildings and landscapes. The use of 3-dimensional equipment is not a new concept in the field of soil erosion, with 3D models of landscapes being created by either physically mapping an area or by using computer software (ArcGIS) to manipulate data to create Digital Terrain Models (DTM) or Digital Elevation Model (DEM) (William *et al*, 2016). These computer models are often not accurate as they are computer-generated, they run algorithms, which may develop errors. The manual modelling technique is time-consuming, cumbersome and requires multiple people to complete. The accuracy of this technique is dependent on the intervals used by the researcher for each research point, and human error is a factor in the process. In the past soil erosion has been monitored with the use of satellite and aerial imagery, which cover large spatial areas and temporal resolutions of erosional landscapes (Wang *et al*, 2016).

UAV sensors, compared to satellite sensors, have been known to have a higher spatial resolution (Niemitalo *et al*, 2021). Multispectral imaging is used to identify the different wavelengths of visible light, which is dependent on the object’s chemical composition (Miller *et al,* 2020). Multi-spectral sensors are a new addition to UAVs, with six or more bands, viewing both visible ranges (350 – 780nm) to near-infrared range (780 -2500nm) including the ability to capture thermal properties of the feature or object being viewed (Fang, *et al*, 2018). Using the multi-spectral sensor is a type of passive monitoring that has no direct impact on the vegetation, as it remotely captures images of the vegetation and does not physically or chemically affect the vegetation. The Micasense Altum that was used in this research is a multispectral sensor with five reflectance measurements in the visible wavelength bands and a sixth sensor that detects thermal reflectance. One of the five sensors is a green and red edge sensor, which detects vegetation chlorophyll, while the red sensor identifies the crop type, soil quality, plant stress and humidity (Miller *et al*, 2020). The red band assist in identifying the difference between plants and soils, whilst the near-infrared band measures and identifies soil moisture content and assists in analysing soil erosion. These will assist in identifying multiple aspects of the site to view areas of potential bare soils and thus areas of potential erosion.

As technology evolves, the costs of sensors and UAVs will decline and become more accessible. At the time of this research, the use of a standard UAV with RGB sensors was within reach of most researchers, whereas the multi-sensor camera was not. However, this is likely to change as technology advances. At present these technologies are not able to penetrate the upper layers of the soil profiles and only replicate and scan the upper layer (Ben-Dor *et al,* 2009). As soil profiles are a complex sequence of stratified unconsolidated materials, viewing the top layer provides a superficial understanding of the soil’s status. However, at present, this upper region can assist the researchers in obtaining a better understanding and a possible assumption for the subsequent layers. Ideally, one would have a multispectral sensor with onboard sensors to scan and penetrate the layers to obtain the ideal understanding and topography of the study area. This would allow researchers to obtain a visual of the subsurface processes to develop a relationship between the surface processes and subsurface processes. This may assist in the future prediction of soil erosion and prevent gully erosion from occurring.

The land eroded in rural areas of Africa is often seen as an anthropogenic construct as a consequence of the lack of knowledge of local farmers. This is highly contested in Fones-Sundell (1989) however, it is the premise taken by many governments and is reflected in their policies on land use practices. There is no one size fits all mitigation method that will reduce soil erosion. However, an improved understanding of soil movement and predictions would assist local communities and government entities to better prevent the amounts of soil being lost due to soil erosion. This would assist the local community in understanding their landscape and conducting activities in a manner that has fewer impacts on the local landscape. This can then be implemented in diverse to obtain understanding and be proactive in the monitoring and rehabilitation of soil erosion. The greatest success has been in understanding the community and the issue they face in their area and then using the UAV to develop solutions, monitoring current practises used in the community and working with communities, to provide them with more information.

A more detailed understanding of the causes and consequences of soil erosion builds knowledge that is needed for the sustainability of soil use. This is particularly the case with the impact of climate change predictions (Frankl *et al*, 2015). The use of a UAV may assist in obtaining a better understanding of soil movement and erosional events to assist in the prediction of future movement or volumetric loss. The UAV can be set up on a site to autonomously conduct scans and imagery of an erosional site at predetermined times. This system can potentially be used for monitoring and assisting in the prediction of future soil erosion.

6.3 Methods

The study site is located in Okhombe River Valley, in the northern regions of KwaZulu-Natal, South Africa (28°42'28,215"S, 29°5'42,258"E). The area was chosen as it contains gullies that are both in erosional and rehabilitation stages, that have been created from the daily migration of livestock up and down the slopes for grazing purposes and a site at which a number of rehabilitation projects, in consultation with the local communities, has taken place over an extended time period. The site has been used for research historically with the use of the Betterment Scheme (the 1960s) and the National LandCare Programme (1999) (Bangamwabo, 2009). Both these programmes have been used to assist the local community in the research and rehabilitation processes.

The UAV was flown above a gully in the area of Okhombe River Valley (Plate 6.1). This gully is in its advanced stage of erosion and has been recognised as becoming dangerous to the community and livestock. UAV images were captured on four separate occasions (2nd September 2018, 27th June 2019, 6th July 2021, and 22nd January 2022). The first two site visits were completed using a DJI phantom 4 UAV with an RGB camera sensor, whereas the last two site visits used a DJI UAV with a Multi-Spectral Sensor attached (Plate 6.1). The Multi-

Spectral sensor captured images in six separate bands. The images were uploaded to the AgiSoft MetaShape software and processed. When using the RGB sensor, single camera settings were used, whereas when using the multi-spectral sensor, multiple camera settings were used, as there are multiple sensors (cameras) onboard a multi-spectral sensor. Both these processes went through the Picture Alignment tool, commencing with the lowest tool accuracy and then moving to a higher accuracy with each subsequent pass. The Dense Cloud, Mesh, Build Texture, and Mesh Tool was used, where the dense cloud tool is the initial stage in creating a 3D model but selecting the point on maps. The mesh tool takes the points created in the dense cloud to build a polygonal model, to then add texture to the model by textures from uploaded images to make one single 3d model. This was again processed with the lowest level of accuracy at first and then increased for each pass. This reduced the processing time.

Once these tools processed the data, the DEM and Orthomosaic tool and the raster calculator were used. The raster calculation tool manipulates the processed images from the corresponding bands to produce final images. The calculated processed images were then edited to add the ideal colour palette to best represent the features. Greyscale, heat scale and Normalised Difference Vegetation Index (NDVI) colour scale were used. Normalised Difference Water Index (NDWI) is an index used for the monitoring of water content in vegetation with the use of the green bands of the spectral bands (Miller *et al,* 2020). Normalised Difference Red Edge (NDRE) index is used to determine vegetation health and vegetation density, with the use of the red band and edge of the red band on the spectral bands (Miller *et al*, 2020). The raster calculator sectioned the six bands into B1-Blue, B2-Green, B3-Red, B4-Red Edge, B5-NIR and B6-LWIR. Using the raster calculator, the output bands (exported resulting images) could be calculated, such as NDVI, where the calculation was: -

$$\text{NDVI} = (\text{NIR} - \text{Red}) / (\text{NIR} + \text{Red})$$

Or as calculated on AgiSoft MetaShape

$$\text{NDVI} = (\text{B5} - \text{B3}) / (\text{B5} + \text{B3})$$

$$\text{NDWI} = (\text{Green} - \text{NIR}) / (\text{Green} + \text{NIR})$$

$$\text{NDRE} = (\text{Red Edge} - \text{Red}) / (\text{Red Edge} + \text{Red})$$

This calculation was used to process NDVI, NDWI and NDRE.

Plate 6.1: UAV mid-flight prior to autonomously flying its designated path to capture images, Okhombe Valley, KwaZulu-Natal Drakensberg, South Africa

Once the six bands were processed, the DEM and orthomosaic data were uploaded to GIS software (ArcGIS) to create a contour map of the site and determine areas of concentrated flow. This was undertaken to determine potential areas of new erosional features, where the indentation on the ground is pronounced and could potentially concentrate the overland flow of water.

6.4 Results and Discussion

The Okhombe River Valley is degraded with gullies, rills, and rehabilitation practices (Plate 6.2). The current path where the livestock is being moved runs from the base of the plateau to the top. This area is heavily degraded with indentation of the area where the overland flow of water concentrates and causes increased erosion.

Plate 6.2: Aerial view of the study site in Okhombe River Valley, in KwaZulu-Natal, South Africa, with the three researchers standing on the left of the image for scale.

Figure 6.1 – 6.3 are images processed through the stitching software and extracted using the NDVI, NDRE and NDWI calculator tools on ArcGIS, where the images were extracted as greyscale, heat maps and colour maps both interpolated and not interpolated. This was undertaken to view different colour gradients to determine which showed a better contrast for gully mapping. The images were produced as interpolated and not interpolated, where the interpolation is how the ArcGIS software predicts points/lines between two points/lines to predict the unknown value between the points/lines. Greyscale images showed areas with vegetation covered in light grey and erosion in dark grey or black, whereas the heat map showed areas with vegetation covered as green and eroded areas as blue. The colour scale shows areas covered with vegetation as green and eroded areas as brown (Figure 6.1 to Figure 6.3). Figure 6.4 depicts a thermal image of the study site produced by the multi-spectral sensors, showing areas in blue as cool or colder areas, and areas in red and warm or hot areas, the green areas are towards the middle of the blue and red scale.

From Figure 6.1 to Figure 6.3 it is evident that the standard images in greyscale are not useable from the images that have not been interpolated, as these are dark and difficult to determine features, even when images are brightened (with the use of photo editing software) the features are still lost. From the heat scale and NDVI colour scale, it is possible to determine vegetated areas in green and bare soils in blue (Figure 6.1 to 6.3, image B). One is able to locate the areas of erosion and can determine the rock piles (Dark blue lines in parallel shown on the small gully, shown as blue and rocks do not have vegetation) being placed in the gully to rehabilitate or mitigate the effects of the erosion. This finding is comparable across the images, allowing areas of poor plant health to be identified, which represent an area of little to no vegetation, thus of exposed soils, susceptible to erosion. This could potentially be a site for future erosion as there is little to no vegetation to bond the soil particles, making it easier for the soil to be eroded.

The Micasense Altum multi-sensor camera has the ability to capture the radiated heat from an object or landform (Figure 6.4). This image replicates the thermal radiation with the red areas being areas of high heat and the blue regions colder. The colder areas are where the soil is covered with vegetation or where the area is in shadow. The warmer areas are areas where the soils are exposed, and the soils have absorbed the sun’s radiation. The Altum Multisensory sensor has the ability to amalgamate all bands to create a single image in colour (Figure 6.5)

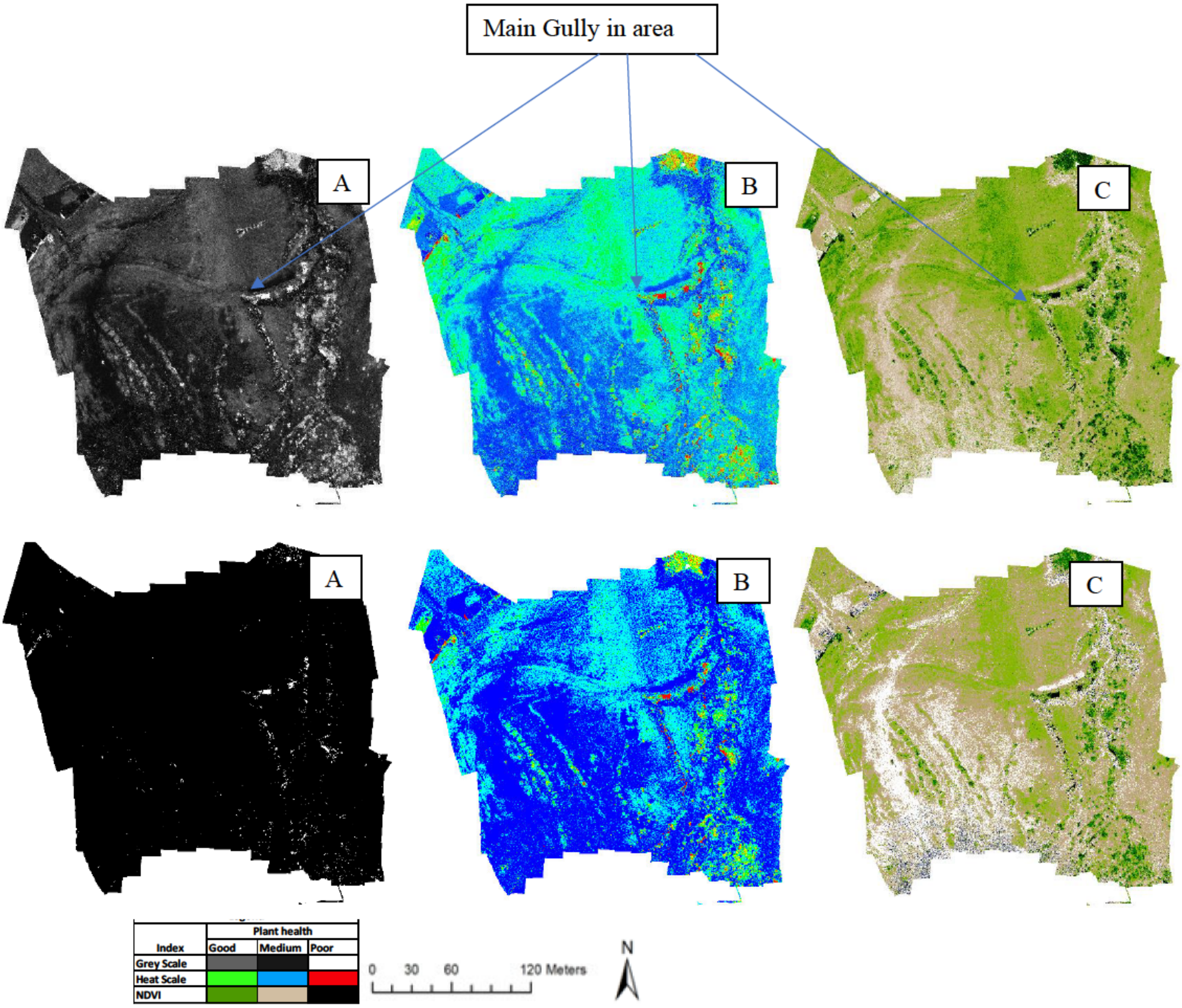
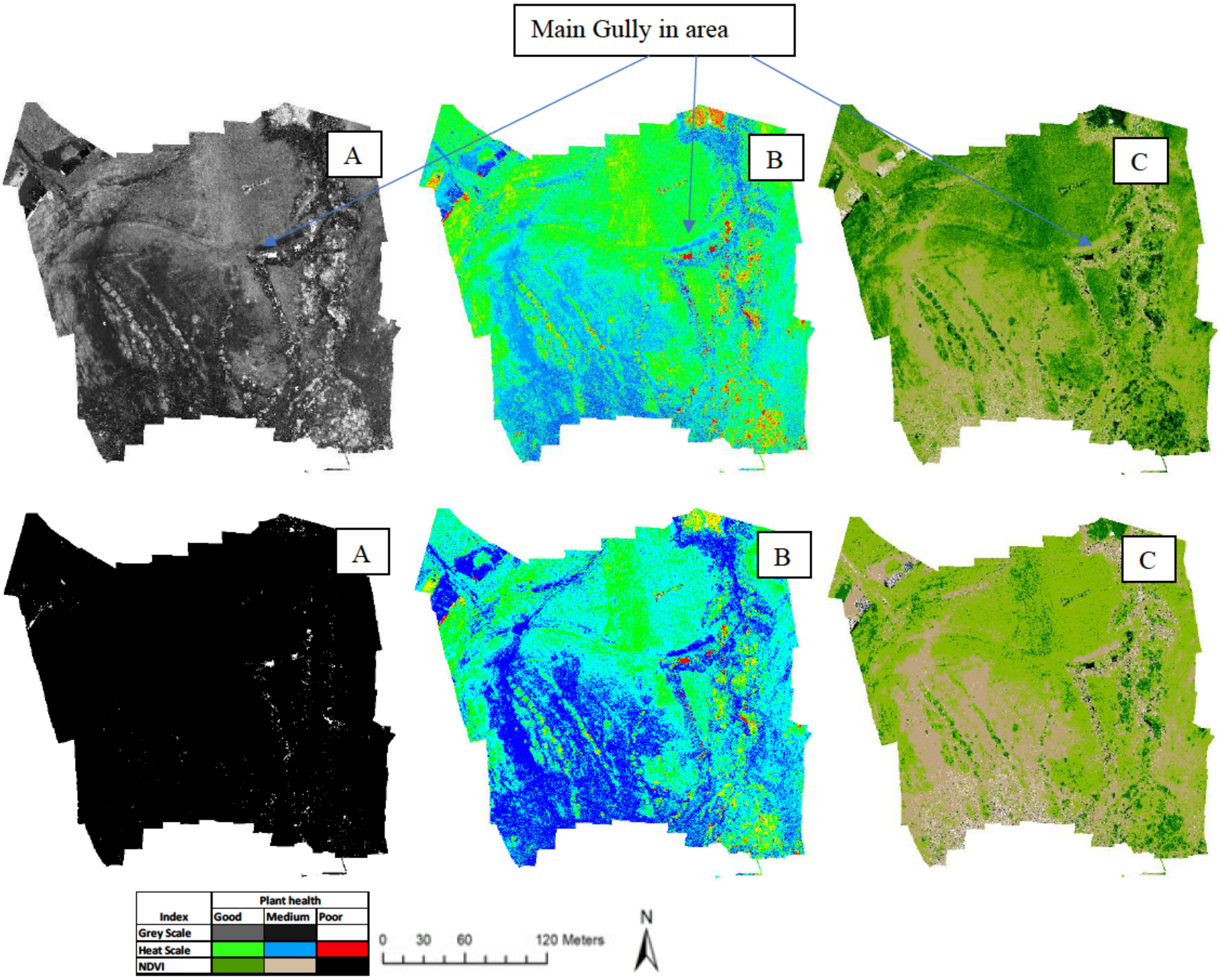


Figure 6.1: NDRE images displayed in greyscale (a), heat scale (b) and NDVI (c) colour scale of images that have been interpolated (top row) and images that were not interpolated (bottom row).



Index	Plant health		
	Good	Medium	Poor
Grey Scale	◼	⬛	⬜
Heat Scale	🟩	🟦	🟥
NDVI	🟩	🟫	⬛

Figure 6.2: NDVI images displayed in greyscale (a), heat scale (b) and NDVI (c) colour scale of images that have been interpolated (top row) and images that were not interpolated (bottom row).

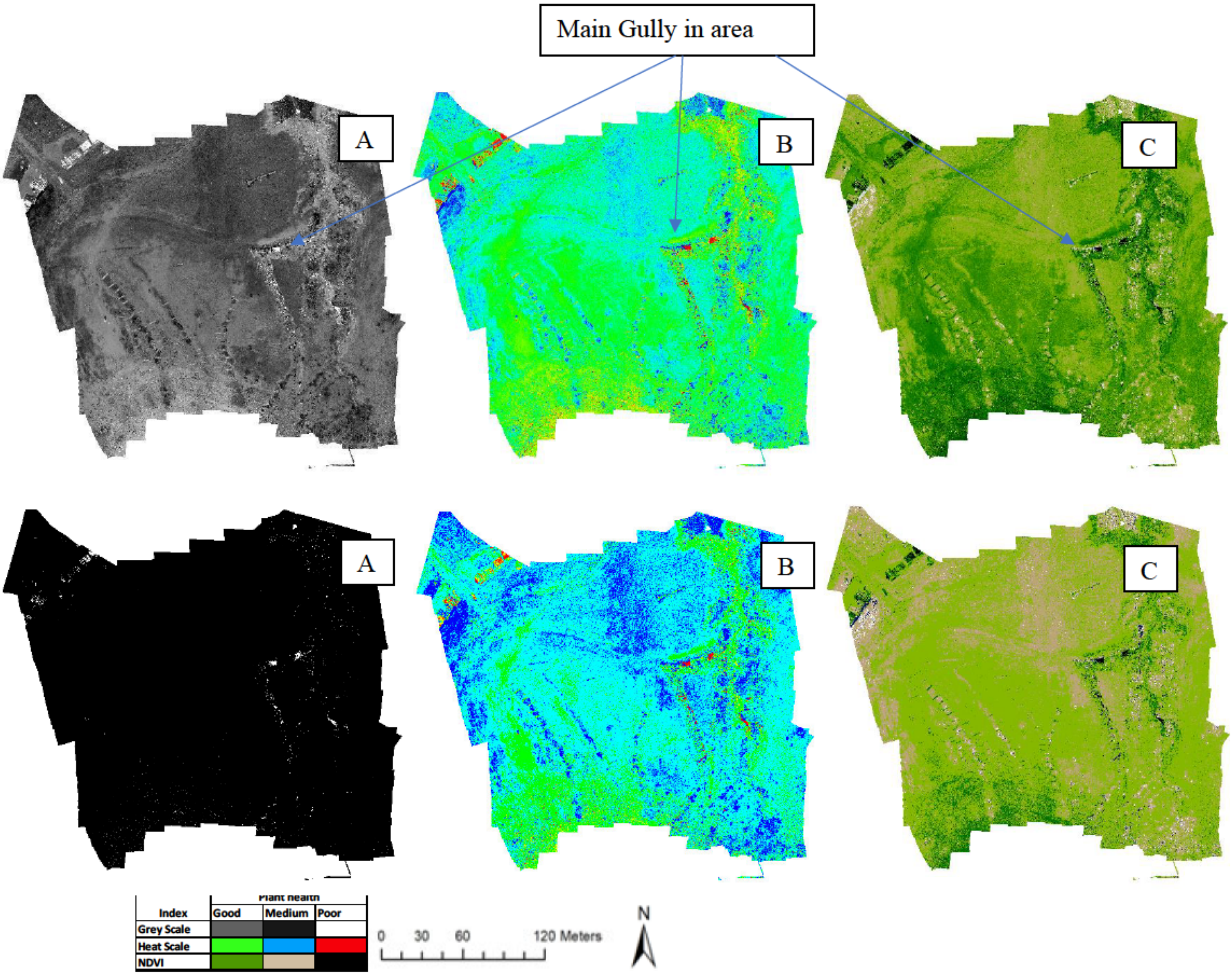


Figure 6.3: NDWI images displayed in greyscale (a), heat scale (b) and NDVI (c) colour scale of images that have been interpolated (top row) and images that were not interpolated (bottom row).

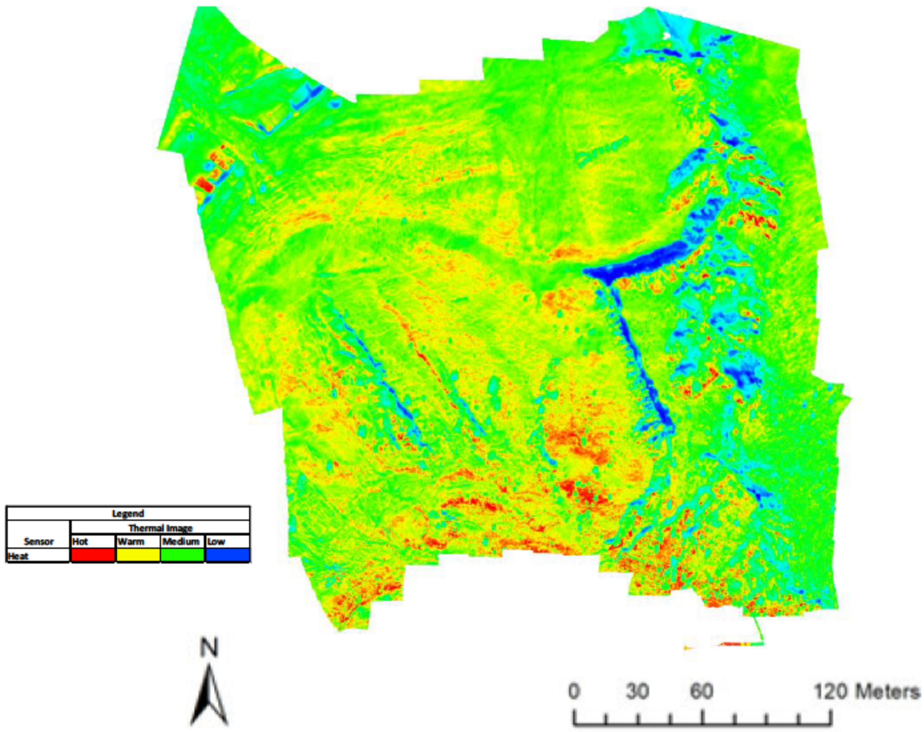


Figure 6.4: Thermal image of the study site, Okhombe gully. KwaZulu-Natal, South Africa

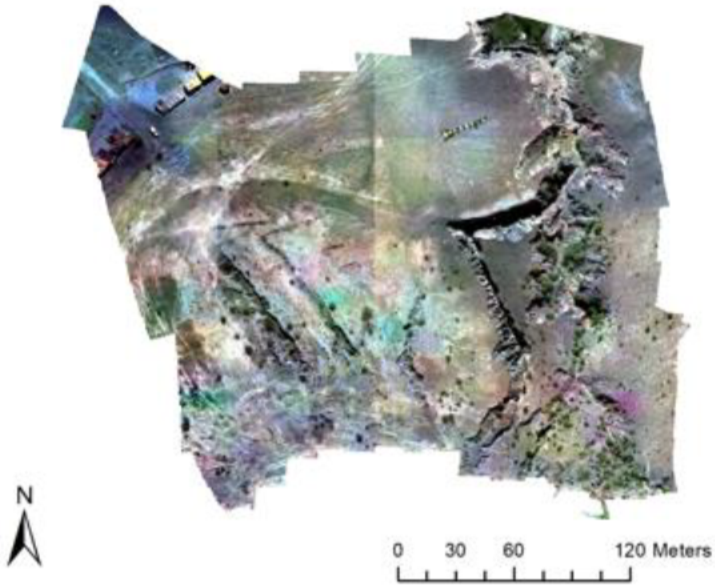


Figure 6.5: A Colour aerial image created from the amalgamation of the five bands from the multi-spectral sensor.

ArcGIS software is able to manipulate data from both the UAV and the data processed in the *AgiSoft MetaShape* software to create elevation maps, slope angle maps and potential water flow concentration maps. A slope angle image was created to depict areas with high degrees of slope angle (Figure 6.6), as these areas would be more prone to erosion and require the monitoring of erosion and rehabilitation of the site. The majority of the site is between 0 and 20 degrees, which has both vegetation and exposed soil. The gully has angles of up to 90 degrees. From this, a flow direction map was created to determine the flow of water over the ground. The image allowed the identification of areas of steep slopes that would assist in the determination of potential areas of erosion. (Figure 6.6 and Figure 6.7). The image can be used to determine the best or ideal areas to focus on management, monitoring and mitigation of soil erosion.

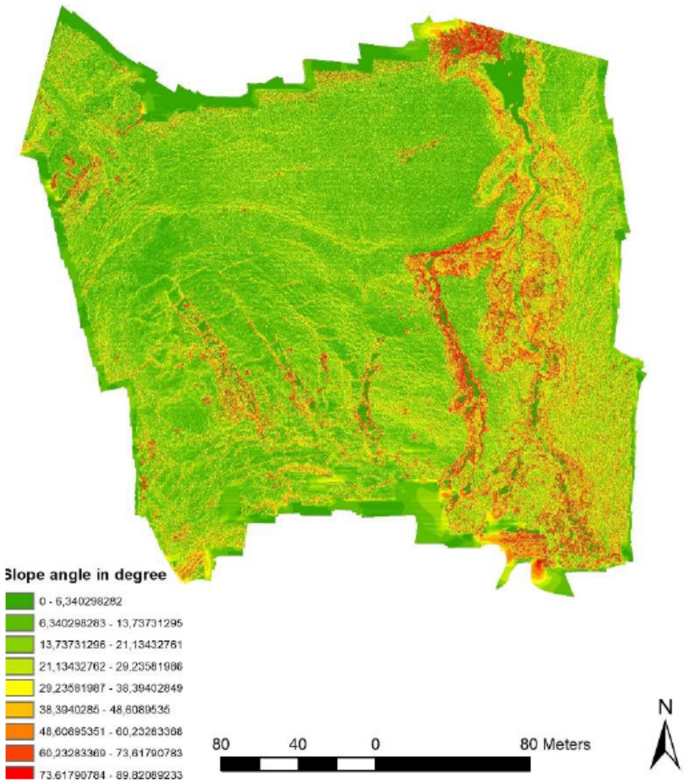


Figure 6.6: The Slope Angle Map of the Okhombe River Valley site.

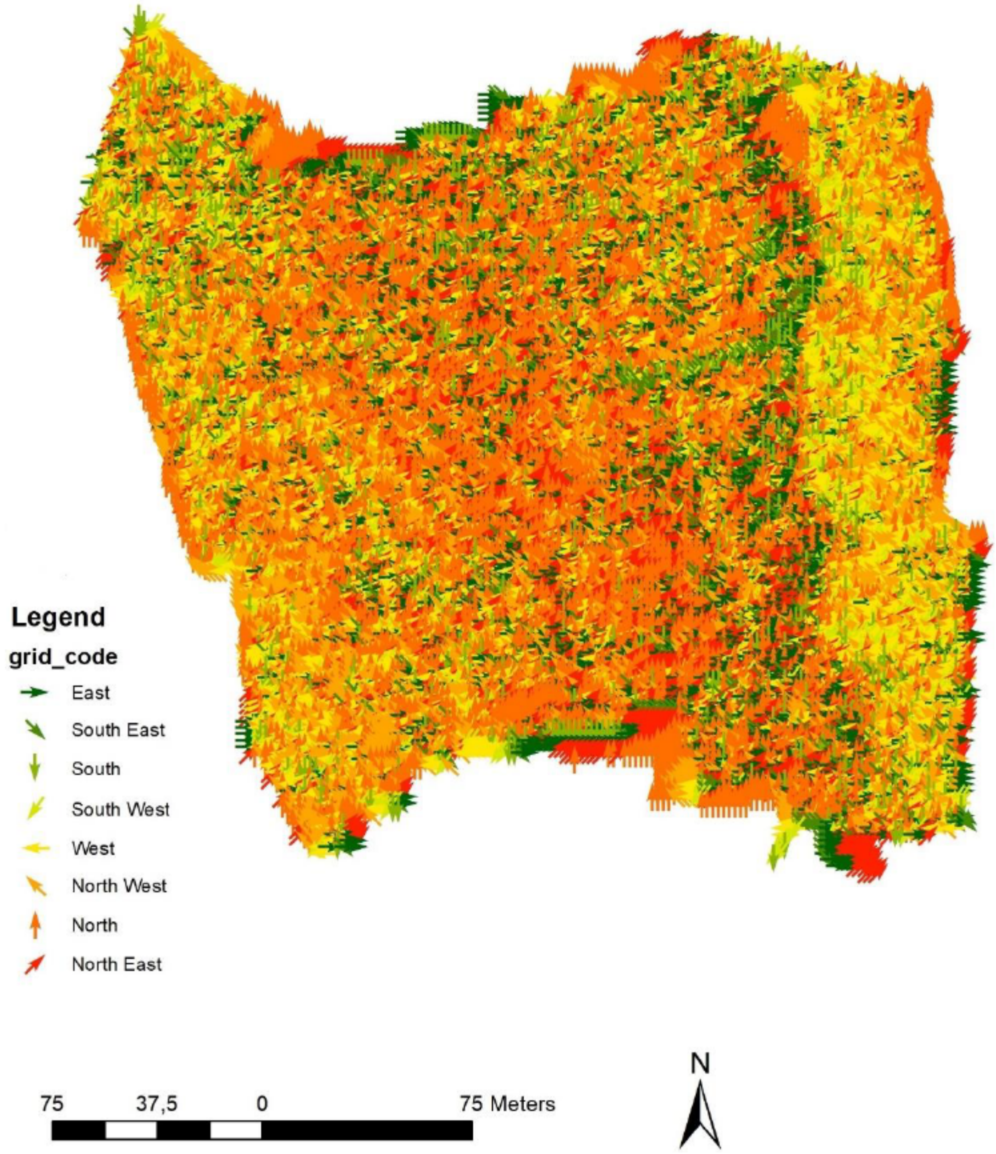


Figure 6.7: A Flow Direction Map of the Okhombe River Valley site.

Once slope angles and the flow direction have been created, this will show where the flow of water occurs, and where areas of potential erosion exist. It was possible to determine the water flow direction, where one would be able to determine the areas of concentration and thus the areas of potential erosion. This illustrates areas that are more prone to erosion. Allowing both the community and the researcher the ability to utilise the map while on site to prevent the flow of water over these areas and promote the infiltration of water into the ground. This would reduce the effects of the water on the bare soils and reduce erosional rates.

It was also possible to locate the original concentration paths from the existing gullies, however, smaller paths were noticeable in the north of the map where little to no erosion has occurred (Figure 6.8). When comparing these paths to the aerial image of the site, the flow paths in the north do not follow the existing footpaths at the head of the path. However, closer to the base of the flow path, these start to follow the existing footpaths. This ultimately will create a concentration of water over areas of bare soils and the erosion process will be accelerated. The collaboration between the researcher and community will allow for the discussion between the parties to cross-reference areas of potential erosion compared to the livestock movement. Alternative routes can be discussed between the two parties to mitigate the effects of the livestock movement and to monitor the erosion of the landscape. This method can be completed monthly and discussed with the community to determine how the new livestock movement has affected the landscape to change this route to alternative routes, to potentially mitigate erosion created by the movement of the livestock. It will allow for a chronological look at how the concentration of flow is being altered and develop a historical database that one may use to assist in the prediction of erosional partners created from the movement of livestock.

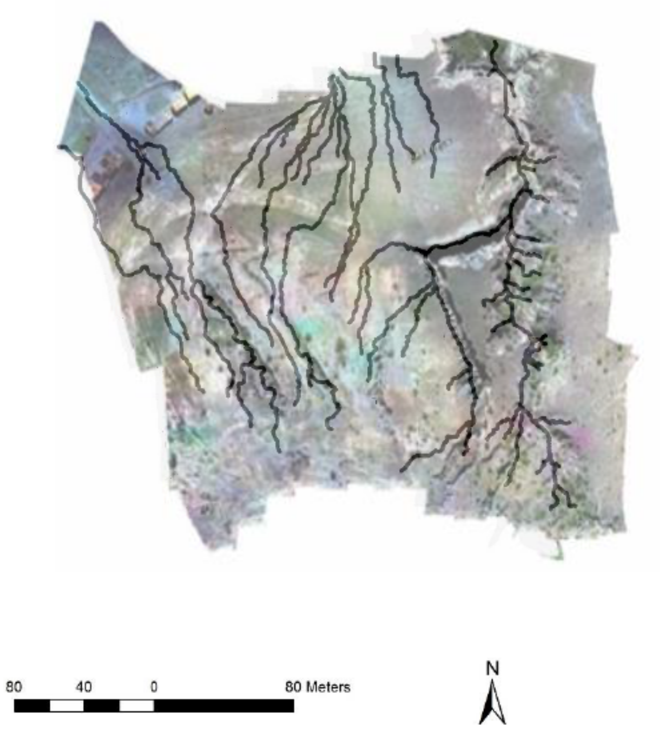


Figure 6.8: A concentration map of the flow of water over the land at Okhombe River Valley

The UAV would be a tool to be utilised for the chronological acquisition of aerial images to view processes and changes in landforms over time. The multi-spectral sensor is expensive and could be out of the range of many researchers, whilst the orthomosaic software requires a subscription, however, much software offer free trials where users are able to use some of the features of the software. The subscription can be costly, however, could be cost-effective if a school or university would pay for student access, as with GIS software. Increased technology to better the flight times and allow the UAV to fly in adverse weather conditions would allow for the improvement of the use of the UAV (Jordan, 2015). Higher-resolution infrared sensors and laser 3D scanners can be installed on the UAV and the orthomosaic software can be used with the 3D laser scanning results to obtain the highest accuracy possible. One major limitation of the UAV is the negative connotation, where people believe, it is used to spy on other people, and lack of understanding from the general public. The ideal situation would be to use a satellite to obtain a large area image of a site and then use the UAV to enforce that data by obtaining high-resolution images of the same area. This would produce a high-resolution image of a large area, allowing for the study of a larger area to gain a better understanding of the area.

As the computer used for this research was at the minimum requirements for the *AgiSoft MetaShape* software, tasks often took from a few hours to a day to complete. The computer would not allow any other software to run in conjunction with the AgiSoft software as it would slow the computer's processing time. This said the computer managed all the tasks required and completed all the processing.

High-resolution images are critical for the mapping of gullies, and one requires the ability to map small features such as rills within a gully as these are areas of flow concentration and potential erosional area (Zhang *et al*, 2023). However, as many gullies cover a large area, the mapping of these areas can become data-heavy, thus the combination between the high-resolution images produced by the UAV and the low-resolution image produced from the satellite images would be the ideal combination, where the UAV would capture only areas of erosion, or the gully areas and the satellite would capture its catchment.

The UAV is not only a spatial application to monitor soil erosion but has the potential to be deployed in a myriad of situations to assist a researcher in obtaining the task, such as aerial imagery, soil erosion monitoring, and monitoring crops or livestock (Merkert & Bushell, 2020). A farmer is able to fly a UAV over their land and obtain current information about their site. Education is an area where the UAV can be used to assist the process. An educator is able to teach a student to use a UAV, capture images and understand how each of the components works. Students can be requested to map an area with a UAV and answer questions set by the educator on the site (Jordan, 2015). As satellite images are of a relatively low resolution, the use of these for smaller feature mapping or understanding can be difficult. The UAV allows researchers and students the ability to micro-map areas and obtain resolutions previously not possible. As the UAV is a novelty technology that not many people have a sense of or used in person, it may encourage students to engage with the processes that control its flight and the data that is produced by the UAV (William *et al.*, 2016).

The UAV and stitching software can assist in mapping erosional features and is able to calculate erosional features within a gully such as dimensions, cross sections, and volume. This relationship allows researchers to determine the change of the landscape or erosional feature over time and determine the rate of change. This would assist in the monitoring of rehabilitation methods implanted to view the rates of change that have slowed down or continued at previous rates. This, with the understanding of soil type and soil properties and weathering conditions, may assist in the development of rehabilitation practises that are targeted at the reason for the initiation of the erosion process in an area.

A concept of a solar-charged UAV capable of use at high altitudes has been discussed (Bhardwaj *et al*, 2016). The future could potentially see multiple UAVs globally placed with central communication software controlling them. The user could log into the program and request a UAV to map an area autonomously without the user leaving their office. This would assist in the instant measuring of any landscape, with the UAV-developed 3D maps of landscapes with the use of GPS location, altitude, image sensors and gyroscopes. This technology can be implanted into a hand-held device such as a mobile phone and allow users to enter a region and proceed to capture images of the region. The computer-generated model could be connected to a 3D printer and a scaled model created. The 3D printing of buildings is a technology that already exists. One would be able to 3D print using sand or soil that accurately models the sand or soil found at a study site to produce an exact scaled model. This model can then be used to test various aspects of erosion in a controlled environment.

6.5 Conclusions

This research critically reviews the potential use of UAV technology with regard to gully mapping research. As UAV technology can identify erosion patterns over a time period. This can be achieved on a relatively low budget allowing many researchers the ability to conduct their aerial investigation of specific study sites. The technology still needs to be refined for use in landscape mapping. That said, the technology is useful in today's research application and may assist in obtaining a better understanding of erosion and gully erosion.

Thus, the hypothesis was proved as the software can be used to 3D map soil erosional landscapes. The UAV determined areas of low vegetation cover or bare soil, and the concentration of water flow over the ground surface. This then would ultimately create an area of erosion and would be prograde to a gully. The mapping of slope and concentration of flow of water can be produced by both the RGB sensor and the multi-spectral sensor. This would be vital to monitoring the flow of water over the land to mitigate these effects and thus reduce or prevent the erosional process from initialising, allowing for better management of the gully.

The Okhombe Valley gully land space is variable with rapid changes, where well-vegetated areas are adjacent to exposed soils and gullies, which are at times too close to be detected using satellite imagery. The Multi-Spectral imagery allows us to detect eroded areas and areas of potential erosion at a scale that allows us to take remedial action. Especially at the top end of the catchment where flow pathways develop, where the identification of these pathways allows researchers to mitigate and reduce the overland flow and subsequently the mass accumulation of water flow lower down in the catchment.

Due to the complexities in the shape of the erosional landscape, the erosional landscape proved to have errors in the replication of the landscape digitally. This can be due to the shadow areas in which the UAV camera sensor is unable to display or view. The software creators and gully mapping researchers can work together to develop the algorithm to assist the mapping of a gully to remove the potential for errors, as the creators would be able to discuss directly with gully erosion researchers to determine the requirements and understand the requirements. This would improve the ability to monitor the gully and soil erosion to be able to manage the landscape to determine rehabilitation or mitigation practices. The resolution increased with the increase in the number of images taken per site. This had an adverse effect on the processing time required. The UAV is weather dependent as it is not able to fly in rainy or windy conditions. Furthermore, the time of day affects the image quality as shadows produce errors in the images and effects the accuracy of the 3D-rendered image. It was found that the best time to fly was at midday on an overcast day to produce enough light to capture images but not enough to produce shadows.

There is an array of diverse applications for spatial analysis and in particular land scale features. This application of the UAV is ultimately down to the user’s imagination or research questions. From the use in agriculture to engineering to wildlife poaching monitoring. The future of this technology to map erosional landscapes is endless and this research is a foundation upon which the knowledge can be the basis for future research and possibilities. The foundation of the technology is sound and useful, and it is up to the researchers investigating gully erosion and gully mapping to use the information and take advantage of the technology to increase the knowledge base by looking at the limitations and determining ways to overcome them to produce better 3D maps. Interdisciplinary practices can take place where multiple disciplines work together to view issues and develop a method or technique to accurately map a gully to the ground resolution that can map fine details. Due to its low cost, relative ease of use and accuracy, this system has been proven to add quality 3D map soil erosional landscapes and be a vital tool in a researcher’s toolkit in the near future to map gullies and to assist in the monitoring of erosion and mitigations methods.

References

Bangamwabo, V. (2009). Spatial and Temporal Extent of Land Degradation in a Communal Landscape of KwaZulu Natal, South Africa. Unpublished Master of Science thesis, University of KwaZulu-Natal.

Ben-Dor, E., Chabrillat, S., Demattê, J., Taylor, G., Hill, J., Whiting, M. and Sommer, S. (2009). Using Imaging Spectroscopy to Study Soil Properties. *Remote Sensing of Environment.* 113, S38 – S55.

Bhardwaj, A., Sam, L., Akanksha., Martin-Torres, F. and Kumar, R. (2016). UAVs as Remote Sensing Platform in Glaciology Present Application and Future Prospects. *Remote Sensing of Environment*. 175, 196 – 204.

Droeshcal, D., Schwarz, M. and Behnke, S. (2017). Continuous Mapping and Localization for Autonomous Navigation in Rough Terrain Using a 3D Laser Scanner. *Robotics and Autonomous Systems*. 88, 104 – 115.

Fang, Q., Hong, H., Zhao, L., Kukolich, S., Yin, K. and Wang, C (2018). Visible and Near-Infrared Reflectance Spectroscopy for Investigation Soil Mineralogy: A Review. *Journal of Spectroscopy*. Article ID 3168974, https://doi.org/10.1155/2018/3168974, 1-14.

Fones-Sundell, M. (1989). Perspectives on Soil Erosion in Africa: Whose Problem? *International Institute of Environment and Development.* 14. 1 -10.

Frankl, A., Stal, C., Abraha, A., Nyssen, J., Rieker-Zapp, D., De Wulf, A. and Poesen, J. (2015). Detailed Recording of Gully Morphology in 3D Through Image-Based Modelling. *Catena*. 127, 92 – 101.

Frodella, W., Lazzeri, G., Moretti, S., Keizer, J. and Verheijen, F. (2020). Applying Infrared Thermography to soil Surface Temperature Monitoring: Case Study of a High-Resolution 48h Survey in a Vineyard. *Sensors*. 20 (9), 1 – 19.

Jordan, B. (2015). A Birds Eye View of Geology: The Use of Micro Drones/UAV in Geologic Fieldwork and Education. *The Geological Society of America*. 25(7). 42 - 43.

Karami, A., Khoorani, A., Noohegar, A., Shamsi, S. and Moosavi, V. (2015). Gully Erosion Mapping Using Object-Based and Pixel-Based Image Classification Methods. *Environmental and Engineering Geoscience*. 20 (2). 101 – 110.

Knight, J., Spencer, J., Brooks, A., and Phinn, S. (2007). Large Area, High-Resolution Remote Sensing Based Mapping of Alluvial Gully Erosion in Australia's Tropical Rivers. *In Proceedings of the 5th Australian Stream Management Conference: Australian Rivers: Making a difference, New South Wales, Australia*, 21 – 25 May 2007, 199–204.

Merkert, R. and Bushell, J. (2020). Managing the Drone Revolution: A Systematic Literature Review into the Current Use of Airborne Drones and Future Strategic Directions for Their Effective Control. *Journal of Air Transport Management*. 89, 1 – 10.

Miller, I., Schieber, B., De Bey, Z., Benner, E., Ortiz, J., Girdner, J., Patel, P., Coradazzi, D., Henriquez, J. and Forsyth, J (2020). Analysing Crop Health in Vineyards Through a Multispectral Imaging and Drone System. *System and Information's Engineering Design Symposium*. Charlottesville, VA, USA, 24 April 2020, 1- 5.

Niemitalo, O., Koskinen, O., Hyväluoma, J., Lientola, E., Lindberg, H., Koskela, O. and Kunttu, I. (2021). A Year Acquiring and Publishing Drone Aerial Images in Research on Agriculture, Forestry and Private Urban Gardens. *Technology Innovations Management Review*. 11 (2), 5 – 16.

Schönebeck, J., Paul, M., Lojek, O., Schröder, B., Visscher, J., and Schlurmann, T. (2021). Measuring Soil Erosion Resistance on Coastal Dikes Linking Hyperspectral UAV-Data, Plant Traits and Soil Information. *The 23rd EGU General Assembly,* Held on the 19-30 April 2021, EGU21-7116.

Strecha, C., Küng, O. and Fua, P (2012). Automated Mapping Ultra-Light UAV Imagery Conference: EuroCOW 2012, Barcelona, Spain, February 8-10, 2012.

United States Geological Services. (2022). *M5.4 – 32KM ENE of Jurm, Afghanistan* Date {Https://earthquake.usgs.gov/earthquakes/eventpage/us7000imzu/executive.} Accessed [10 November 2022].

Wang, R., Zhang, S., Pu, L., Yang, J., Yang, C., Chen, J., Guan, C., Wang, Q., Chen, D., Fu, B., and Sang, X. (2016). Gully Erosion Mapping and Monitoring at Multiple Scales Based on Multi-Source Remote Sensing Data of the Sancha River Catchment, Northeast China. *International Journal of Geo-Information*. 5 (11), 1 - 17.

William, R., Tooth, S. and Gibson, M. (2016). The Sky is the Limit: Reconstructing Physical Geography from an Aerial Perspective. *Journal of Geography in Higher Education*. 41(1), 1 - 13.

Zhang, Z., Gerke, M., Vosselman, G. and Ying Yang M (2018). A Patch-Based Method for the Evaluation of Dense Image Matching Quality. *International Journal of Applied Earth Observation and Geoinformation*. 70, 25 – 34.

Zhang, G., Zhao, W., Yan, T., Qin, W. and Miao, X. (2023). Estimation of Gully Growth Rate and Erosion Amount Using UAV and Worldview-3 Images in Yimeng Mountain Area, Chine. *Remote Sensing*. 15 (1), 1-17.

CHAPTER SEVEN

Synthesis

7.1 Introduction

Unmanned Aerial Vehicles (UAV) originated as a military application shifting to a hobbyist toy and are now becoming more widely used in a myriad of applications as a spatial analytical tool (Merkert and Bushell, 2020). The UAV is a versatile technology that allows a user to obtain data that are in areas that are inaccessible to humans and digitally capture images for the mapping and monitoring of these areas. One UAV has the ability to attach a sensor or camera to capture images of an area that can later be used for monitoring (González & Rodriguez, 2017). As gully erosion is known to create an unstable landscape, entering, and conducting research can be dangerous, however, the UAV is able to map this area in 3D while the operator remains at a safe distance (Jordan, 2015). This research investigated the use of UAVs in gully mapping, monitoring and management. This chapter covers all previous chapters of the thesis and highlights the main aspects of each chapter. The first is completed by looking at how the resolution is affected by distance and comparing RGB sensors and multi-spectral sensors when observing plant health. The research assessed whether UAVs acquired data is capable of mapping objects of known shape and size and processing the data through stitching software to determine if the measuring tools are able to replicate the volumes and dimensions of the objects. The research then considered mapping gully systems and measuring the sediment lost over time. The section discusses each paper and the objectives and research aim, responding to the overall research aim of whether a UAV can effectively be used map gully systems.

7.2 A Summary of the Literature Review.

Soil erosion is a part of the processes that have shaped the surface of the Earth to produce the present landscapes, from the breakdown and removal of parent rocks and soils (Valentin *et al,* 2005). The erosional process is initiated with the overland flow of water during a rainfall event, that is concentrated into a depression in the surface of and land, that erodes away to create a rill, this rill, with erosion over time, becomes a gully (Kariminejad, *et al*, 2023). The mapping of gullies has been conducted using satellite imagery and other remote sensing techniques. However, this can be costly as some resolutions mask out critical features within the gully (Lu *et al*, 2004). Thus, allowing for the implementation of the UAV into this area to potentially assist in the mapping of gullies or erosional landscapes at a higher resolution. According to

Gonzáles and Rodriguez (2007), the UAV has the potential ground resolution of 0,03m per pixel width and height, allowing for the mapping of smaller features found within a gully network. This may allow for the potential of predicting where the gully may erode in the future with the use of 3D mapping.

Software packages currently available for the 3D mapping, are categorised and either online or offline, both have their limitation and positives. However, both categories allow for the orthomosaic of multiple images to create a single final image for the use in 3D mapping. The software available allows for the exportation of GeoTiff, JPEG, Shapefiles and PDF files, that are then able to be manipulated on GIS software, where one is able to determine flow directions of water over the land and areas of potential overland flow concentration, that may assist in the identification of potential soil erosional areas.

As per the literature, the potential of using a UAV for the purpose of mapping gully erosion is validated, thus this thesis will look at how this technology can be implemented into the field and potentially improve the understanding of gully erosion.

7.3 A Comparison of 3-Dimensional Orthomosaic Software, gully mapping, Okhombe Valley, Kwazulu-Natal Drakensberg, South Africa.

3-Dimensional (3D) mapping of objects, including the 3D mapping of landscapes which was completed by using cumbersome and expensive equipment that reproduces 3D images that are of relatively low accuracy, are not a new technology (William *et al*, 2016). However, moving this application across to gully systems mapping is an innovative approach (Knight *et al*, 2007) and was the aim of this chapter, i.e., to determine if civil engineering technology can be implemented to 3D map soil erosion landscapes.

Mapping objects of known dimensions was accomplished by obtaining multiple images of objects with known dimensions and volumes at various heights. These images were processed through the multiple on- and off-line software available, and dimension and volumetric measurements were calculated by the software. First, the 3-dimensional computer-generated model was visually inspected to determine how accurately the software replicated the known object — using the measurement tool on the software that measured both dimension and area to obtain the computer-generated dimensions. These calculations are compared to the known dimensions of the objects. Various size objects were used to ensure that each software was able to map multiple-size objects and to facilitate comparison across software packages. This process was replicated at multiple heights to determine if the accuracy in terms of dimension decreases with altitude. The three software packages were *Pix4DMapper*, *AgiSoft MetaShape* and *DroneDeploy*. Of these three, *DroneDeploy* is online.

The results proved that it was possible to map objects in 3 dimensions using a UAV as all software packages created a 3D map, to some degree of accuracy, of each object. The limitations and issues were uniformity of object colour and texture. From the results, it was determined that *Pix4DMapper* did not replicate the objects at an altitude of 5 and 10 meters well, while *DroneDeploy* was unable to measure any objects with a volume of less than 0.1 m^3. Of the software packages used, *AgiSoft MetaShape* replicated or processed the known objects such that the dimensions reduced with altitude. However, since the online software was not able to map or replicate any objects smaller than 0.1 m^3, this software would not suffice for mapping soil erosion, as a rill would be lost when mapping a gully. Of the two offline software, *AgiSoft MetaShape* was found to be more accurate, reliable, and replicated the objects in terms of dimension and 3D modelling better than *Pix4DMapper*. The length of time taken to process the imagery was a limiting factor for both offline software packages and a computer with high processing power is recommended.

The user can obtain an initial reading that is processed at a lower resolution, which would produce a less accurate rendition, however, allows users to validate and check settings. The aim of the research was to determine if civil engineering software can be implemented in 3D modelling for soil erosion. It was found that by using objects of different sizes it is possible to use this technology to map gully system features effectively. The software accurately mapped both in space and dimensions the known objects. From the results, it was determined that the quantifiable measurements decreased with altitude meaning the closer you are to the object the higher the accuracy. Of all the processing software, *AgiSoft MetaShape* was the most accurate (98% of actual volume across all flying heights tested). Thus, this software can be implemented into the 3D mapping, modelling, and monitoring of soil erosion and soil landscapes.

7.4 UAV Sensor resolution and plant health comparison in Okhombe Valley, KwaZulu-Natal, South Africa.

The advances in UAV onboard sensors, the resolution, wavelengths captured and resultant indices that can be calculated have provided an ideal opportunity to apply UAVs to understanding the geomorphology of changing landscapes (Glendell *et al*, 2017, Chidi *et al*, 2021). The first specific objective was to determine the image resolution (clarity) and accuracy (or image focus) of the sensor and the effects of distance (altitude) on the resolution. Limited battery life in drones requires higher flight elevations to cover large gullies but this comes at a cost of reduced resolution. This was therefore tested by flying the UAV at multiple heights above a Pixel Density Reference Chart (PDRC) at the height of 25 m, 50 m, 75 m, and 100 m. It was found that the ground resolution decreased with height.

The second specific objective was to determine the ideal height to fly the UAV above the ground, to visualise features within the gully system, while still capturing the majority of the gully in a single image. The UAV was flown at multiple heights above the ground and the ground resolution was used to determine the full area covered in a single image. As the sensor has a known number of pixels, this can be used to calculate the full area. It was found that at a height of 25 m, the ground resolution of a pixel was 0.83 cm^2 or 996 m^2 for an entire image. At an altitude of 100 m the area covered by a single pixel on the ground was 11.11cm^2 and a total on-the-ground area of an image was 13 332 m^2. The ideal height was determined to be 50 m, providing a ground resolution of approximately 3 cm^2 with a total area of 3 336 m^2. Each pixel was determined to be small enough to map the finer features found in the gully, such as rill erosion or surface wash, while still being able to capture the full extent of the gully system in a single image.

The third specific objective was to investigate how the processed images, which included plant health indices, from an RGB sensor compared to that of a multi-spectral sensor and then compared to actual vegetation cover, measured from aerial images. Both sensors were installed on the UAV and flown above the gully system. Data captured were processed through the stitching software (*AgiSoft MetaShape*). The RGB sensor determined plant health from the colour reflected off the vegetation, whereas the multi-spectral sensor used multiple wavelengths to determine plant health. It was found that with the RGB sensor, the processed images found 44.7% of the area to be covered with healthy plants, compared to 53.2% from the multi-spectral sensor. Ground truthing determined the healthy plant cover to be 62%, thus both sensors determined lower readings than the actual site. Both systems underestimated healthy plant cover which therefore warrants further research dye to the advantage of being able to use a UAV for such assessments.

These objectives set the initial stages of understanding how a UAV, with either an RGB or multi-spectral sensor, could be applied to mapping a complex gully system and determining gully erosional processes and outcomes.

7.5 The Use of Photogrammetry and UAV Technology to Produce 3-Dimensional imagery of a gully system in Okhombe, Northern Drakensberg, South Africa.

The 3D mapping of soil erosion may assist in understanding the potential movement of soil and may assist researchers in obtaining a better understanding with the assistance of mapping a gully system and sediment erosion (Zhang *et al*, 2023). This chapter determined if the software previously tested (*AgiSoft MetaShape*) by completing a pilot study on measuring objects with known dimensions, can be used to map and 3D render soil erosion features at an accuracy that is adequate for research. At present, the means of mapping soil erosion is expensive, time-consuming, and costly (William *et al*, 2016). One can use satellite images to create a DEM or a DTM to produce a 3D model, however, it has a relatively low level of accuracy and can be costly. Another method is using a rotational laser scanner to scan the interior walls and surfaces of an erosional landscape (Wang *et al*, 2016). This process is time-consuming, labour-intensive, and expensive. With the combination of a UAV and 3-dimensional software, this process may become more time efficient and accurate. This hypothesis was tested for a gully system in the Okhombe Valley, Northern KwaZulu-Natal, South Africa.

A UAV was flown above the ground to obtain images of the gully system at Okhombe River Valley with a high degree of image overlap of approximately 90 to 95%, to produce an orthomosaic image. The images were processed through AgiSoft MetaShape software where the lowest accuracy was first tested and then incrementally increased with each pass, which reduced the time required to process all the images. It was found that the higher the number of images, the better the final resolution of the results. The results showed that with a quarter reduction in the number of images, there was a noticeable reduction in visual accuracy, and the software could not reproduce textures on a fine-grained level such as surrounding vegetation such as low shrubs or gully / erosional surface features such as rills. The software had a softening effect on the 3D-rendered image produced, where the software removes hard/ sharp edges from landforms to make them more rounded for ease of processing. This result proves that for a more accurate image, one would need to capture images with an overlap of 97%. This will produce a visually accurate 3D render that will replicate the site that is captured but possible not be practical due to flight time and data storage requirements.

The second specific objective was to compare the 3D image created from the combination of UAV and stitching software to an on-site manual mapping technique of the same erosional features. This was completed by flying the UAV over the site and capturing images that were then processed through the stitching software. Manual mapping was completed using an Abney level, tape measure and ranging rods to determine distances between interval points both horizontally and vertically across the gully system. The manual mapping results were then manipulated and processed to produce a 3D surface model using Microsoft Excel. These 3D surface models were compared to that of the 3D rendered model produced by the 3D software. The manual mapping of the gully system produced a low-resolution surface model at a one-meter interval, the process was time-consuming and labour-intensive. This system of manually mapping gullies would work on a larger scale, however, when assessing a single gully, the manual mapping of the gully is not accurate enough to capture the details of the gully compared to that produced by the 3D software. The use of the UAV versus the manual method would be determined by the time required in the field, person power available and availability of funds, they both have their place in gully mapping, however, it's dependent on the objectives of the study.

The third specific objective was to determine the accuracy of the *AgiSoft MetaShape* software n rendering various types of soil erosional features, such as gullies, rills, depositional features, and water channels. This was achieved by mapping landscape features including a gully system, rill erosion and a riverbed. These three landscapes were reproduced using 3D modelling software. The final objective was to determine the advantages to mapping of rills, gullies, and riverbeds, as the UAV and *AgiSoft MetaShape* Software produced high-resolution imagery of each landscape and volumetric measurements of the landscape. This would allow the researcher to determine the volume of soil lost in an erosional feature over time. This is imperative for the monitoring of rehabilitation of gully erosion, to determine how and where the sediment is being lost or captured by the rehabilitation methods implemented.

The aims of the research were met, with the outcome being that the software and associated measuring tools are able to map the gully system and associated erosional features and provide an indication of sediment loss through the measuring tool.

7.6 The Benefits of RGB Sensor and Multi-spectral Sensor Mapping of Soil Erosion in a Degraded Landscape using an Unmanned Aerial Vehicle.

The access to chronological aerial images improves our understanding of soil erosion. This is particularly the case due to the time associated, and therefore cost, with ground-based mapping of soil erosion (Karami *et al*, 2015). The primary research aim of this section was to validate the mapping and 3D rendering of sediment erosion and deposition using a UAV and whether it is a tool that will assist in a better understanding of sediment erosion and deposition. Soil erosional landscapes are unsafe and unstable environments, and it can be unsafe for researchers to enter these landscapes to conduct research and collect data. (Droeshcal *et al*, 2017). The use of unmanned vehicles can significantly reduce that risk as the operator can remain at a safe distance from the gully and unstable soil.

The first specific objective was to determine the suitability of the Altum multi-spectral sensor to monitor sediment movement. The Altum camera provided GeoTiff, 3D maps, pdfs and shape files that could be imported into GIS software for further spatial analysis. The results showed areas of potential areas of erosion, and this then could be used to assist the community in determining the best solution for livestock management in the daily up and down slope migration. The ongoing discussions between the researchers and community in the Okhombe River Valley area are vital as this relationship allows for a better understanding of the impact of the erosional processes in the region, with a focus on the gully system and livestock management. The intention is to develop proactive community-driven solutions that can be self-monitored. The researcher and community are able to collaborate to determine areas of potential erosion from livestock and monitor the progress in rehabilitation and mitigation methods implemented. This collaboration is vital as the community has constant access to the site for monitoring while the researcher has the ability to input their expertise. The drone imagery potentially provides a useful visual tool for discussing gully development and mitigation strategies as well as monitoring and evaluation of mitigating strategies.

The second specific objective was to critically review the process of UAV application and stitching software and consider how the results can assist in obtaining a better understanding of sediment movement. Future use of the UAV to map gully systems would need a transdisciplinary approach where experts from an array of disciplines such as engineering, soil science, hydrology, and geomorphology work in tandem with social scientists to obtain an understanding of what is necessary to monitor these gully systems and assist the community in developing coping strategies to reduce erosion. The UAV and stitching software allowed for a cross-sectional measurement of the gully, which would assist in the monitoring of sediment movement over time. The manipulation of the software produced maps of potential areas of concentration of overland flow, which could be areas of potential erosion.

Erosional landscapes or gully erosion features are complex shapes and can be difficult to digitally replicate. This said the UAV has the ability to map a gully, rill and riverbed morphology which can be useful for future research. The ideal sensor for the capturing of gully erosion is the multi-spectral sensor, due to is diverse abilities in produces multiple map types, however the RGB sensor is a cheaper alternative. The low cost of acquiring a UAV and the low learning curve makes it an ideal tool for the mapping of gullies and monitoring erosion.

7.7 Conclusion

As UAVs become more, accessible, cost-effective, and user-friendly, there will be a rapid development in the access to UAV technology and associated hard- and soft-ware that will lead to a diversity of spatial applications. Hence the potential to develop the technology for gully mapping and to use the technology to inform sediment transport, record erosion and deposition, use outputs to visually engage with community members, and apply the measurements to monitor and inform management strategies will increase. The present research illustrates this potential use of UAVs in gully system mapping and foresees the technology becoming a standard spatial tool. Critical is the parallel development of the software which will become more readily available, both on- and offline. The appropriate UAV, camera, flying height and software can be used to detect, map and measure rill erosion, gully erosion and riverbeds in a 3D rendered image. The overarching aim of this research was to determine if it was possible to map a gully system with the use of a UAV and stitching software. It was found to be a suitable tool, proving the potential for further avenues of studies within this field. With the improvement in technology and the increase in its accessibility, the chances of community-driven research projects become more possible. Allowing researchers to obtain a better understanding, monitoring and mitigation against the increase in erosion and finding a balance between the needs of the community, with regards to livestock management, and the needs of the environment.

References

Chidi, C., Zhao, W., Chaudhary, S., Xiong, D. and Wu, Y. (2021). Sensitivity Assessment of Spatial Resolution Difference in DEM for Soil Erosion Estimation Based on UAV Observations: An Experiment on Agriculture Terraces in the Middle Hill of Nepal. *International Journal of Geo-Information's*, 10 (28), 1-17.

Droeshcal, D., Schwarz, M. and Behnke, S. (2017). Continuous Mapping and Localization for Autonomous Navigation in Rough Terrain Using a 3D Laser Scanner. *Robotics and Autonomous Systems*. 88, 104 – 115.

Glendell, M., McShane, G., Farrow, L., James, M.R., Quinton, J., Anderson, K., Evans, M., Benaud, P., Rawlins, B., Morgan, D., Jones, L., Kirkham, M., Debell, L., Quine, T.A., Lark, M., Rickson, J. and Brazier, R.E. (2017). Testing the utility of structure from motion photogrammetry reconstructions using small unmanned aerial vehicles and ground photography to estimate the extent of upland soil erosion. *Earth Surface Processes and Landforms*. 42(12), 1860 – 1871.

González, M. and Rodriguez, P. (2017). Monitoring Soil Erosion by Raster Images: From Aerial Photographs to Drone Taken Pictures. *European Journal of Geography*. 7(5), 117 – 129.

Jordan, B. (2015). A Birds Eye View of Geology: The Use of Micro Drones/UAV in Geologic Fieldwork and Education. *The Geological Society of America*. 25(7), 42 - 43.

Karami, A., Khoorani, A., Noohegar, A., Shamsi, S. and Moosavi, V. (2015). Gully Erosion Mapping Using Object-Based and Pixel-Based Image Classification Methods. *Environmental and Engineering Geoscience*. 20 (2). 101 – 110.

Kariminejad, N., Sepehr, A., Poesen, J. and Hassanli, A. (2023). Combining UAV Remote Sensing and Pedological Analysis to Better Understand Soil Piping Erosion. *Geoderma*. 429 (2023), 1 – 15.

Knight, J., Spencer, J., Brooks, A., and Phinn, S. (2007). Large Area, High-Resolution Remote Sensing Based Mapping of Alluvial Gully Erosion in Australia's Tropical Rivers. *In Proceedings of the 5th Australian Stream Management Conference: Australian Rivers: Making a difference, New South Wales, Australia*, 199–204.

Lu, D., Li, G., Valladares, G. and Batistella, M. (2004). Mapping Soil Erosion Risk in Rondônia, Brazilian Amazonia: Using RUSLE, Remote Sensing and GIS. *Land Degradation and Development*. 15 (5), 499 -512.

Merkert, R. and Bushell, J. (2020). Managing the Drone Revolution: A Systematic Literature Review into the Current Use of Airborne Drones and Future Strategic Directions for Their Effective Control. *Journal of Air Transport Management*. 89 (2020), 1 – 10.

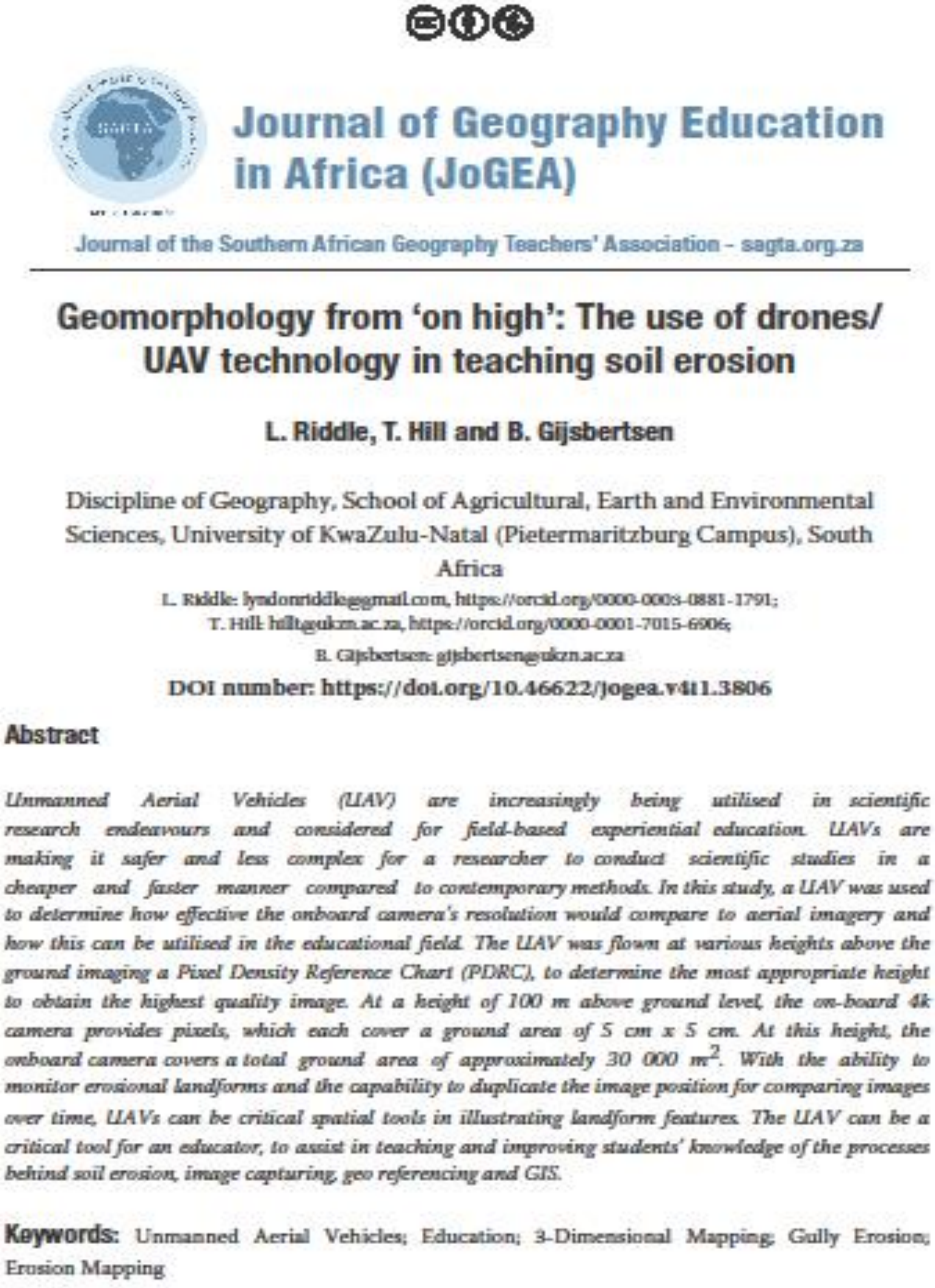
Valentin, C., Poesen, J. and Yong, Li. (2005). Gully Erosion: Impacts, Factors and Control. *Catena*. 63(2-3), 132 – 153.

Wang, R., Zhang, S., Pu, L., Yang, J., Yang, C., Chen, J., Guan, C., Wang, Q., Chen, D., Fu, B., and Sang, X. (2016). Gully Erosion Mapping and Monitoring at Multiple Scales Based on Multi-Source Remote Sensing Data of the Sancha River Catchment, Northeast China. *International Journal of Geo-Information*. 5 (11), 1 - 17.

William, R., Tooth, S. and Gibson, M. (2016). The Sky is the Limit: Reconstructing Physical Geography from an Aerial Perspective. *Journal of Geography in Higher Education*. 41(1), 1 - 13.

Zhang, G., Zhao, W., Yan, T., Qin, W. and Miao, X. (2023). Estimation of Gully Growth Rate and Erosion Amount Using UAV and Worldview-3 Images in Yimeng Mountain Area, Chine. *Remote Sensing*. 15 (1), 1-17.

APPENDIX 1



Journal of Geography Education in Africa (JoGEA)

Journal of the Southern African Geography Teachers' Association – sagta.org.za

Geomorphology from 'on high': The use of drones/ UAV technology in teaching soil erosion

L. Riddle, T. Hill and B. Gijsbertsen

Discipline of Geography, School of Agricultural, Earth and Environmental Sciences, University of KwaZulu-Natal (Pietermaritzburg Campus), South Africa

L. Riddle: lyndonriddle@gmail.com, https://orcid.org/0000-0003-0881-1791;
T. Hill: hillt@ukzn.ac.za, https://orcid.org/0000-0001-7015-6906;
B. Gijsbertsen: gijsbertsen@ukzn.ac.za

DOI number: https://doi.org/10.46622/jogea.v4i1.3806

Abstract

Unmanned Aerial Vehicles (UAV) are increasingly being utilised in scientific research endeavours and considered for field-based experiential education. UAVs are making it safer and less complex for a researcher to conduct scientific studies in a cheaper and faster manner compared to contemporary methods. In this study, a UAV was used to determine how effective the onboard camera's resolution would compare to aerial imagery and how this can be utilised in the educational field. The UAV was flown at various heights above the ground imaging a Pixel Density Reference Chart (PDRC), to determine the most appropriate height to obtain the highest quality image. At a height of 100 m above ground level, the on-board 4k camera provides pixels, which each cover a ground area of 5 cm x 5 cm. At this height, the onboard camera covers a total ground area of approximately 30 000 m^2. With the ability to monitor erosional landforms and the capability to duplicate the image position for comparing images over time, UAVs can be critical spatial tools in illustrating landform features. The UAV can be a critical tool for an educator, to assist in teaching and improving students' knowledge of the processes behind soil erosion, image capturing, geo referencing and GIS.

Keywords: Unmanned Aerial Vehicles; Education; 3-Dimensional Mapping; Gully Erosion; Erosion Mapping

Introduction

Advancement in remote sensing technology has improved our ability to map, observe, quantify, and understand soil erosion processes (Glendell, 2017), in particular through the use of aerial and satellite images for mapping and investigating the progression of landscapes (Gonzáles & Rodriguez, 2017). Furthermore, remote sensing has assisted in determining landscape and land use change, allowing us to understand and interpret changes of the past which in turn could elicit present processes and predict future changes with more certainty. In developing remote sensing technology, autonomous/unmanned vehicles (UV) are increasingly playing a critical role in scientific research, particularly in regions that are inaccessible and due to the relative ease of acquisition, setting-up, piloting and capturing data Gonzáles & Rodriguez, 2017.

The process of geomorphological research is to constantly view and record the changes in landforms (Toth *et al*, 2016). This has been improved through the use of aerial imagery from manned craft or satellite images, however, these are time-consuming, costly and of a relatively low resolution. UAVs are able to acquire the image at a reduced cost and within a shorter time period. A UAV is able to carry and transport a myriad of payloads dependent on the researcher's requirements. UAVs are able to acquire aerial photographs under high cloud cover conditions by flying below the clouds and obtaining uninterrupted imagery. This is the case in humid regions where cloud cover is persistent and may negatively affect the images from a manned craft or satellite image (Kah & Wich, 2012). Map and monitoring soil erosion on-site can be difficult due to the inaccessibility of each site, for example, steep-sided slopes, gullies, and unstable soils. We argue that a UAV allows the researcher improved access to observe and map the erosion site without these limitations. Furthermore, little experience is required to pilot the UAV and if damaged or lost they can be replaced, unlike a manned vehicle. With the live relay of information to the UAV pilot, if the UAV is lost or cannot be retrieved, the data are still available.

UAV in full

UAV technology continues to advance, from the first remote control fixed-wing plane to the more stable, technologically advanced quadcopters of today. The fixed-wing has and still is, used due to its relative ease of use although image quality is low, as fixed-wing planes cannot remain in a stationary aerial position and must fly parallel to the ground. Thus, they are affected by turbulence which alters image quality due to vibration. Many UAVs take the form of a 4-propeller arrangement in an ‘X’ shape with the propellers at the end on each arm (quadcopter), they are electric and have an independent motor driving each propeller. This configuration allows for stable flight, which is ideal for stable imagery. Many UAVs are fitted with a motorised gimbal which is an independent hardware attachment that links a camera to a vehicle. This allows for the independent movement of a vehicle while the camera remains stationary. A 3-axis gimbal allows for movement along 3 separate axes and is a mechanical device with 3 motors on each axis which keeps a payload stable and isolated from the aerial vehicle.

Payloads for a UAV are dependent on the lifting capacity, whilst many small UAVs have a camera which is designed specifically for that UAV. However, market cameras can be placed on a UAV if the camera does not exceed the lifting capacity of the UAV. UAVs can range in price from a few hundred Rand for an entry-level drone with a camera installed, to hundreds of thousands of Rand for a top-of-the-range drone with a high-definition camera and sensors depending on the technology and the camera. A cautionary note, the lower-end drones have short flight times (5 to 8 minutes), compared to the higher end which can have up to a 30-minute flight time. GPS, barometers, and 360-degree sensors have been placed on the high-end UAV to improve the stability of the craft in flight. Many UAVs are linked to a GPS and can hover above a point without user/pilot interaction. One of the leading drone brands has installed sensors on board the UAV facing forward, upward, and downward, to help prevent the UAV from flying into surrounding obstacles, making it safer to fly. The sensors will stop the UAV when it comes too close to an obstacle.

Methods

Our intention was to compare an off-the-shelf UAV against recent aerial photography of a researched gully/soil erosion site to determine effectiveness, operability, and resolution to help interpret the site based on resolution, in this case, on-the-ground pixel density. A pilot study was conducted to determine if the Pixel Density Reference Chart (PDRC) would be seen at various altitudes, with images taken at 10 m intervals (Plate 1, Image E). Subsequently, due to the difficulty in spotting the PDRC at higher altitudes, the UAV was flown above a plastic sheet (1.5m x 5m) with a pixel density reference chart (PDRC) placed on top to assist in identifying the PDRC from the UAV. This method will assist the user to identify the PDRC and place the UAV in the ideal aerial position. Initially, an altitude difference of 10 m was used, however, little variation was evident thus a greater interval could be used. The plastic sheet assisted in the alignment of the UAV with the PDRC, this made it easier for the pilot to visualise the PDRC from the air. The UAV was flown at varying heights (25, 50, 75 and 100 m) above the PDRC and images were captured at each height. The images were uploaded to a photo-editing program, to observe individual pixels and measure the number of pixels in each block (eg.10 pixels per 10cm x 10cm block). The two pilot studies proved the validity of the methods, which were then implemented at the study site to determine if the methods would work under field-based conditions and in particular for gully erosion.

Results

As expected, the PDRC becomes increasingly difficult to observe with increasing height, however, one is able to increase magnification on-screen and ‘zoom into the image’, thus still being able to count the number of pixels per 10cm x 10cm block (Plate 1). To improve the resolution, one would need to fly the UAV lower. The PDRC was placed on a white plastic strip measuring 5m by 1.5m, with the test pattern on the bottom left corner. The pixel density changed for the pilot study, the initial test with the plastic sheet, and the final test at the study site. This could be an effect of adverse weather conditions, where a slight haze may reduce the effectiveness of the camera to read the highest number of pixels at varying heights (Hodgson *et al*, 2018). From this test, it was determined that when a UAV is flown at a height of 100m above ground level, each pixel covers an area of 5cm by 5cm (25 cm^2).

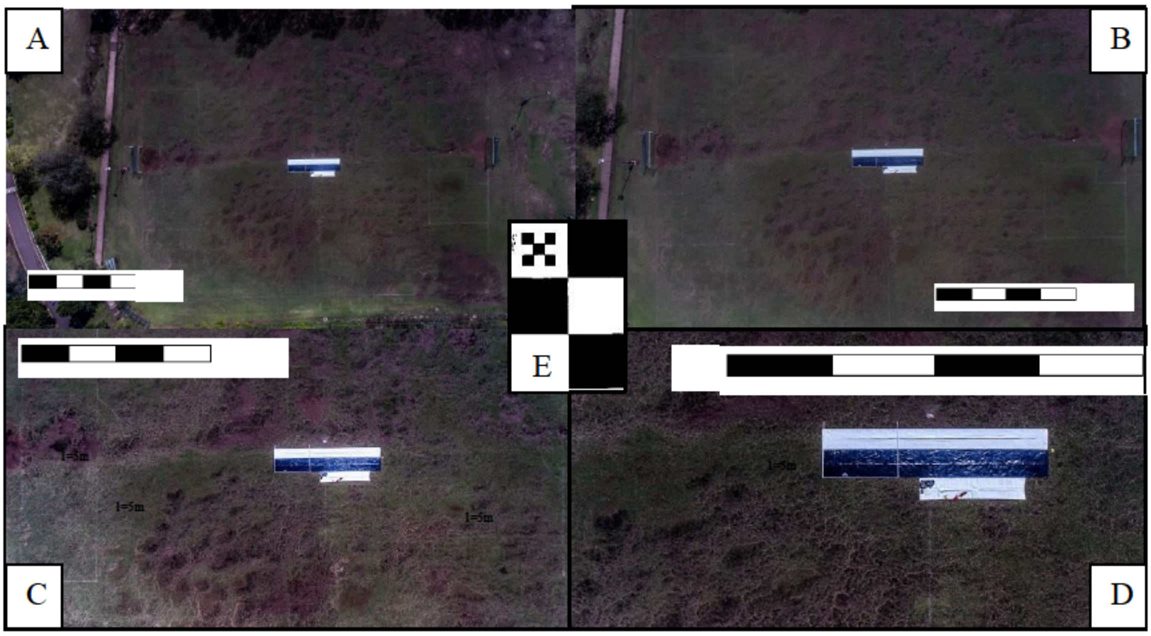


Plate 1: The pilot study images from the UAV at different heights focussing on a test pattern sheet for measuring pixel density, to determine the pixel density of each image at each height. An at a height of 100m, B at a height of 75m, C at a height of 50m, D at a height of 25m and E image of the PDRC. Scale is dependent on the height at which each image is taken and is shown in the corner of each image.

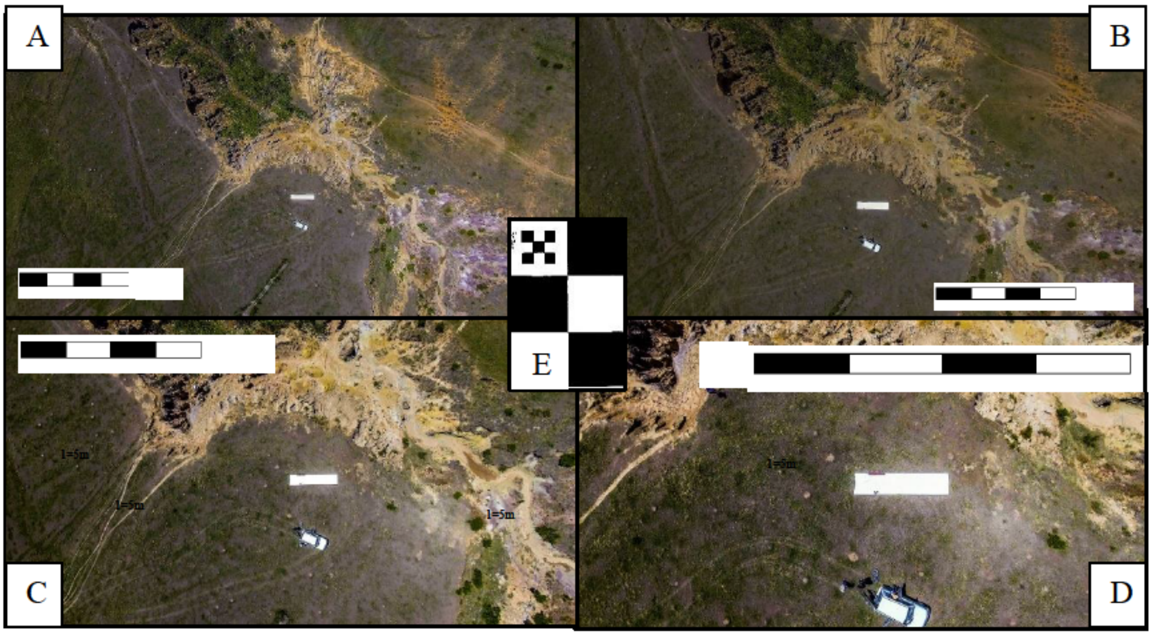


Plate 2: Image from UAV taken at Okhombe valley showing severe gully erosion. The images were taken at different heights focusing on a test pattern sheet for measuring pixel density. A at a height of 100m, B at a height of 75m, C at a height of 50m, D at a height of 25m and E image of the PDRC. Scale is dependent on the height at which each image is taken and is shown in the corner of each image.

	Pilot	Test flight with a plastic sheet	Study Site
Height above ground (m)	Area of a single pixel (cm^2)	Area of a single pixel (cm^2)	Area of a single pixel (cm^2)
10	0.08		
20	0.27		
25		0.83	1
30	1		
40	2		
50	5	2.78	4
60	6.25		
70	8.33		
75		6.25	6.25
80	11.11		
90	16.66		
100	25	11.11	16.66

Table 1: Size of pixels against length on the ground at various heights

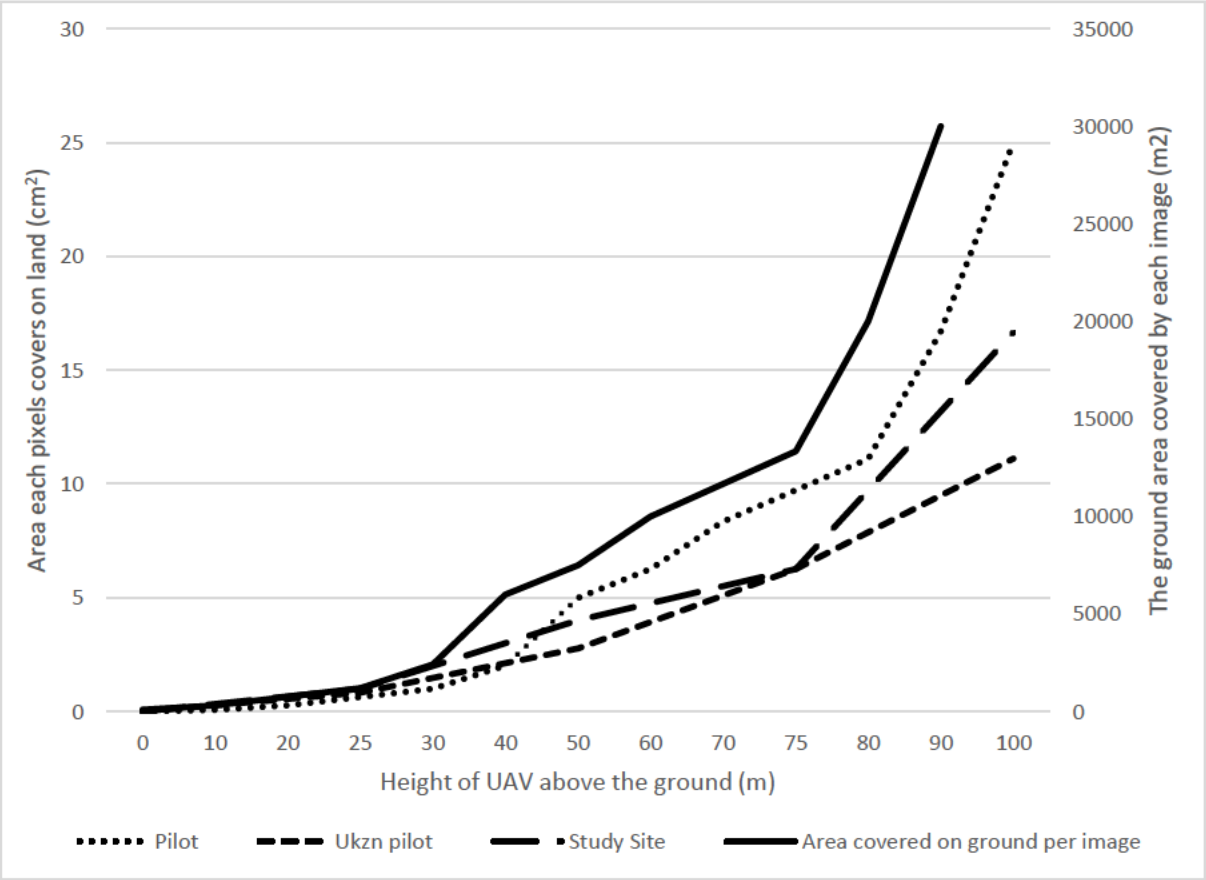


Figure 1: The relationship between pixel density and UAV height.

Discussion

The ideal height at which a UAV with a camera of the same resolution as the camera used in the tests, should fly would be approximately 50m above the ground to obtain the best pixel density on the ground (Table 1). At this height, each pixel covered an area of approximately 2.78cm^2 to 5cm^2. This would not be the optimum height to fly at all sites as there may be natural or man-made features obstructing flight. One would have to assess their environment to determine, at what height the UAV would be safe to fly. A UAV with a resolution of 4096 x 2160 (4K) camera can obtain a spatial resolution of sub 0.05m (on the ground) and cover a ground area of 30000 m^2 from a height of 100m above ground level. This resolution will improve if the UAV flies lower, however, there is of course a compromise as the area covered will decline (Figure 1). This will allow users to obtain an improved image and one can mosaic images together for a high-resolution image. Although these UAV images will be of a high spatial resolution, they lack multi-spectral images (Gonzáles & Rodriguez, 2017). This makes the manipulation of images in GIS difficult as multi-spectral sensors capture images in, and on either side of, the visible light spectrum. These bandwidths are required by GIS programs for the manipulation of images as it allows the GIS user to manipulate the image to view features that are not seen in the visible light spectrum. Multi-spectral image platforms/machinery can be installed onto a UAV if the imagery device has a low enough weight that the UAV will be able to lift. Fan *et al*, (2017) have replaced standard cameras with V-NIR cameras to determine the biomass and leaf area index of a site. This is due to the V-NIR displaying wavelength does not present within the visible light spectrum.

UAVs can perform operations that manned planes and helicopters are unable to carry out, and at a reduced cost. At present, a drone licence to fly commercially is required and the process of obtaining the commercial licence is slow and expensive. As of to date, only 13 Remote Operators Certificates (ROC) in South Africa and several Remotely Piloted Licences (RPL) have been issued. New cell phone applications and programs have been developed which allow the user to demarcate a study area before the flight commences and the UAV will cover the area autonomously. This flight path can be saved and repeated at any stage. The application/program allows the user to determine how high the UAV flies and how much the images overlap. Today’s researcher/student in the field will use a digital camera, GPS, smartphone, and laptops, (William *et al*, 2016) and a one-day UAV will be the field kit. A field survey conducted by William *et al*, (2016), stated that students were interested and were more engaged with the use of technology in the field.

Use of UAV in *field-based Education*

As the skills required to fly and collected data from a UAV are generally easy to obtain, it is possible for students to learn how to operate and manage the remote approach to data collecting. The platform does not require a landing area and can be launched and caught by hand, making it more accessible and user-friendly in an outdoor classroom situation. UAVs are providing GIS and Remote Sensing students with the opportunity to create maps for a GIS program from data collected to a final product. They are able to capture aerial imagery of their study site and transfer these data into the GIS program for analysis and interpretation. This provides GIS students with a ‘real-life’ field-based application to understand and be skilled in aerial image capture and up-loading onto an appropriate software analysis package. Mapping exercises can be established for students to conduct and collect using a drone, and then interpret them (Jordan, 2015). At present, there is a gap between acquiring imagery and the use of that image on computer software. The use of UAVs may encourage the user to learn the process from imagery on the UAV to the imagery needed for remote sensing software (William *et al*, 2016). Analysers take the images for granted and are not concerned with the process of acquisition. This will make the UAV a good training tool for students to learn the entire process of acquiring the image, then processing the image to be uploaded onto computer software, and finally manipulating the image to test various attributes needed for the research.

As technology continues to develop and there is a need to ensure students are acquainted with the latest technology to ensure skill development and vocational training, the UAV skills set can provide both the latest technological know-how and serve as a case study of spatial skills development. Furthermore, the relatively expensive setup will bring the technology closer to schools and universities (William *et al*, 2016). By way of example, a UAV can be used to monitor crops and soils pre-harvesting and then post-harvesting. This would be a great asset to harvesters to refine the process for a higher crop yield and reduce the effects on the soil. At present, the system is being incorporated into a sediment yield project for different land use types as the researchers seek out the best sites for run-off plots and note changing land use patterns over time – we are able to cover a large area quickly. The ability to input pre-determined flight paths allows us to re-fly the same route over time. The vast array of applications that a UAV can use is only dependent on the user.

UAVs can be used to map rivers in high definition, and 3-dimensional(3D) mapping of geological or man-made structures (Jordan, 2015). The 3D mapping can be used to accurately map the inside of a gully over a period of time to monitor the change. UAVs can be used in terms of site surveying for a geological engineer or structural engineer. This will allow a pilot to stay stationary and fly the UAV to observe and photograph various features of interest in less time than it would if the pilot would have to walk. This observation technique could be taught in universities to use UAVs to observe different structures and identify various structures from the safety of a controlled environment.

UAVs can be used in future for conservation research such as anti-poaching techniques (Kah & Wich, 2012). This will allow students, schools, universities, and countries that cannot afford to purchase expensive GIS programs and images (e.g., Quickbird, Ikonos) to use a UAV with the free GIS software to analyse the data at a reduced cost (Kah & Wich, 2012). A 3D scanner can be attached to the UAV and computer models with the exact specification can be created. A UAV can be used to map a gully. This can be done over various periods of time to determine how the gully morphs and where the gully may be eroding faster. This may in the future help researchers to determine areas that may be prone to erosion or determine a method to predict the occurrence of erosion.

A prototype UAV has been constructed to collect hyperspectral and hyperspatial data, with bandwidths from 4 to 5nm and spatial resolution of 2-5cm (Lucieer *et al*, 2014). This allows for the mapping of biochemical and biophysical attributes of vegetation communities, such as composition and health (Lucieer *et al*, 2014). The idea is to develop this approach to include the agricultural sector to allow for a rapid appraisal technique, which could be deployed to monitor crops over time. Thus, one is able to undertake pre- and post-treatment on various crops,

UAVs can be used to remotely monitor and analyse resource management and impacts from said resources. Which implies, the remote monitoring of wildlife conservation. For example, for the migration of wildlife. This will allow both the educator and student to track the paths of animals to get a better understanding of the said animal. The UAV as a tool is a rapid data recovery technique and can be utilised for the monitoring of threatened wildlife or ecosystems (Hodgson *et al*, 2018). This may have saved the lives of nearly extinct species as it will be an early warning system. A UAV can be set to follow a single animal and that animal's path will be tracked without the pilot having to control the craft. UAVs or Unmanned Land Vehicles (ULV) are able to sample areas that are too difficult or too dangerous to access. Sampling can become a completely autonomous task, completely removing human error or contamination from soil samples. This will make the results of the study more accurate and precise. UAVs are being investigated to see how they can be applied for military uses as well as search and rescue.

As UAV technology advances, so will the capability of the UAV. Longer battery life, autonomous flight (already exists), better imagery, a variety of images (thermal, infrared) and many more technologies will be installed on board UAVs in the future. 3D laser scanners can be installed to obtain a micro-landscape layout of an area and allow the relative personnel to analyse and adjust for their requirements. Infrared scanners and thermal imagery can be installed on a UAV for desired projects and outcomes. Autopilot systems (ArduPilot Mega) allow users to plan routes for the UAV to take without physically controlling the UAV (Kah & Wich, 2012). This will allow the UAV to take off, fly a set route, land back at the take-off point, charge and download its data automatically. This makes the monitoring processes quicker and user-free. UAVs have been used to digitally count the amounts of ducks in any given area (Hodgson *et al*, 2018). The study conducted by Hodgson *et al*, (2018), determined that the use of a UAV to count the number of ducks in a given area was more accurate the counting by a human on land. This was because no duck would be counted twice or missed out.

Limitations

Of primary concern are the natural conditions of operation, technological issues, and legislation (Jordan, 2015). Many of the existing UAVs are not waterproof thus flying in rain or inclement weather is not feasible, although water-proof models are under development. These UAVs have the ability to transition from air to water, land on water and submerge under water whilst in operation. High winds are an issue due to the smaller size and can be blown off-course. This said, the UAVs that have onboard GPS are able to fight against the wind and keep the UAV in the same position or path, although this does impact energy usage and hence battery life.

Currently in South Africa, flying a UAV legally for commercial use may be out of range financially for many researchers and educators. Commercial use is classed as any activity that the UAVs generates financial gain. An RPL and a ROC are required. The RPL allows a drone pilot to fly said UAV for a company that possesses a ROC (www.htxt.co.za; www.prowings.co.za). While the ROC is expensive and takes a minimum of one year to acquire (Schmidt, 2016). The laws are put into place to protect all flying vehicles in the sky; however, the UAV licences are presently perceived as being unrealistic and preventing the use of UAVs in areas that may be useful.

Conclusion

As technology advances, so will the UAV technology and the ability to use UAV in a multitude of applications appropriate to teaching and research within the geographical field. A UAV is simple to use and can be purchased from many electronic stores in South Africa. UAVs offer images that manned aerial vehicles cannot offer and still be safe to operate. This said, currently in South Africa, due to the laws and legislation around the use of a UAV for commercial gain (i.e., teaching students to use the drone, thus meaning the teacher is being paid) is illegal without the possession of an RPL and ROC, which is expensive and time-consuming. Until laws are changed to allow a pilot to make it cheaper and faster to obtain these licences, UAVs in South Africa will be for the elite and large companies, inhibiting their use in education and research.

The UAV takes erosion monitoring to the next level by assisting the user in getting rapid data pre-, during and post-erosional events in a minimal timeframe. The potential for the UAV to be a standard tool for educators or researchers is very high and should be considered. The world is becoming an autonomous machine, why should educators and researchers remain in the past?

References

DJI, 2017. *Phantom 4.* [Online], Available at: www.dji.com. [Accessed 7th May 2017].

Glendell, M.; McShane, G.; Farrow, L.; James, M.R.; Quinton, J.; Anderson, K.; Evans, M.; Benaud, P.; Rawlins, B.; Morgan, D.; Jones, L.; Kirkham, M.; Debell, L.; Quine, T.A.; Lark, M.; Rickson, J. and Brazier, R.E. (2017) Testing the utility of structure from motion photogrammetry reconstructions using small unmanned aerial vehicles and ground photography to estimate the extent of upland soil erosion. *Earth Surface Processes and Landforms*. 42(12). Pg. 1860 – 1871.

Fan, X.; Kawamura, K.; Xuan, T.D.; Yuba, N.; Lim, J.; Yoshitoshi, R.; Minh, T. N.; Kurokawa, Y. and Obitsu, T. (2017). Low-cost visible and near-infrared camera on an unmanned aerial vehicle for assessing the herbage biomass and leaf area index in an Italian ryegrass field. *Japanese Society of Grassland Science*. Pg. 1 – 6.

Gonzalez, M.E.P. and Rodriguez. P.G. (2017). Monitoring soil erosion by raster images: from aerial photographs to drone take images. *European Journal of Geography*. 7(5). Pg. 117 – 129.

Hodgson, J.; Mott, R.; Baylis, S.; Pham, T.; Wotherspoon, S.; Kilpatrick, A.; Segaran, R.; Reid, I.; Terauds, A. and Koh, L. (2018) Drones Count Wildlife More Accurately and Precisely Than Humans. *Methods in Ecology and Evolution*. Pg 1-8.

Jordan, B.R. (2015). A bird’s eye view of geology: The use of microdrones/UAVs in geologic fieldwork and education. *The Geological Society of America*. 25(7). Pg. 50 – 52.

Kah, L.P. and Wich, S.A. (2012). Dawn of drone ecology: Low-cost autonomous aerial vehicles for conservation. *Tropical Conservation Science*. 5(2). Pg. 121 – 132.

Lucieer, A.; Malenovský, Z.; Veness, T. and Wallace, L. (2014). HyperUAS – Imaging spectroscopy from a multirotor unmanned aircraft system. *Journal of Field Robotics*. 31(4). Pg. 571 – 590.

Matos, C., 2015. *How to get a drone licence in South Africa.* [Online] Available at: http://www.htxt.co.za/2015/11/26/how-to-get-a-drone-licence-in-south-africa/ [Accessed 7 May 2017].

ProWings, 2015. *Remote Pilot Licence.* [Online] Available at: http://www.prowings.co.za/remote-pilot-licence/
[Accessed 7 May 2017].

Schmidt, M., 2016. *Costly,clunky aviation rules clip our wings say drone operators.* [Online] Available at: https://www.businesslive.co.za/bd/companies/transport-and-tourism/2016-11-23-costly-clunky-aviation-rules-clip-our-wings-say-drone-operators/
[Accessed 7 May 2017].

Smith, K.W. (2015). Drone technology: Benefits, risks and legal considerations. *Seattle Journal of Environmental Law*. 5(1). Pg. 291 – 302.

Toth, C.A.; Barkoczi, N.; McIntosh, R.W. and Plasztan, Z.J. (2016). Studying the development of fluvial landforms in the Berettyo-KOROS region using geoinformatic methods. *Landscape and Environment*. 10(3-4). Pg. 137 – 144.

William, R.D.; Tooth, S. and Gibson, M. (2016). The sky is the limit: Reconstructing physical geography from an aerial perspective. *Journal of Geography in Higher Education*. 41(1). Pg. 134 – 146.