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Too much of a good thing? The role of detailed UAV imagery in characterising large-scale badland drainage characteristics in South-eastern Spain

Abstract

Some arid and semi-arid areas experience high erosion rates as a consequence of their geological and climatic conditions. This can lead to the development of badland environments characterised by very high drainage densities and the occurrence of a range of distinctive landforms indicative of fluvial dissection. These occur along a spectrum of scales and vary from small-scale arroyos or ramblas to large-scale rills and gullies. Drainage networks comprising the larger landforms can be easily identified using traditional remote sensing methods, such as satellite or aerial imagery, and are therefore amenable to morphometric analyses. The smaller landforms however are not so easily detected. As a result, studies to date have been largely restricted to their direct field observation which is problematic due to their inherent inaccessibility, often on steep, unstable slopes. However, with the advent and popularisation of Unmanned Aerial Vehicles (UAV), also known as drones, those landforms and geomorphological characteristics which were once invisible to remotely sensed aerial data can be incorporated into more detailed research.

By using one of the most extensively studied badland locations in Europe - the Tabernas Desert in South Eastern Spain - this paper describes the characterisation of a large-scale drainage basin (294m^2) using high definition orthophotography and DEM collected from an unmanned rotorcraft and processed using structure from motion software. Results provide an extremely detailed 3D reconstruction of the study site, and solve one of the inherent issues working with such large scales, namely the significant difference between 2D and 3D measurements. The paper concludes by comparing the results obtained with the UAV with those obtained using existing remotely-sensed imagery and by exploring the challenges experienced when working with bespoke high-resolution aerial imagery, such as when too much detail becomes an issue, and the role of this increasing resolution of observation in geomorphological and hydrological analysis.

Keywords: Unmanned Aerial Vehicles, Drainage density, Badland, 3D measurements, scale

1.Introduction

Geomorphological research frequently involves the quantitative description and analysis of the constituent landforms that occur within a particular landscape. These quantitative approaches have been applied with particular enthusiasm to the study of drainage basins following the pioneering work of Horton (1945). This work heralded a shift in emphasis from largely qualitative approaches to the study of landscape to a more systematic and objective quantitative approach. Horton quantified the drainage basin and its associated stream network according to a series of parameters including stream orders and drainage density and went on to develop what were regarded to be fundamental laws that explain the functioning of drainage basins. Subsequent work (Strahler 1957, 913-920) suggested that some drainage basins are characterised by geometries and relationships that are replicated at different spatial scales of observation, forming the basis for the development of equations that can predict certain aspects of their behaviour such as sediment delivery.

Badland environments associated with the intense fluvial erosion and dissection of easily erodible substrates feature some of the most complex drainage networks visible on Earth. As such they provide an ideal setting in which to apply quantitative drainage basin analyses, particularly in view of their role in delivering both water and sediment into the wider catchments of which they form a part, their potential contribution to flood events and their future response to climate change (e.g. Calvo-Cases, Harvey 1996). The measurement of the intricate networks of small rills and gullies that form a characteristic component of badland drainage basins has however proven problematic. These features are generally too small to be visible within traditional remotely-sensed imagery due to their limited resolution and are also difficult to measure within the field due to their association with steep and often unstable slopes. In addition, the absence of detailed slope information has to date hampered the ability of researchers to determine the development of drainage networks in three-dimensions. As such, these detailed features have proven difficult to map accurately and systematically and the analysis of the associated drainage basins can therefore often be seen as being incomplete.

The development of Unmanned Aerial Vehicles (UAVs), popularly known as drones, provides an ideal platform capable of acquiring the high-resolution imagery required to resolve large-scale rills and gullies in three-dimensions within badland environments. They therefore present an opportunity to extend systematic quantitative measurements to this previously remotely undetectable and inaccessible component thereby allowing complete assessment of the drainage networks incorporating drainage features at different scales. Therefore the aims of this paper are to: (1) characterise the drainage system of a large-scale study site by using a combination of UAV imagery and Structure from Motion methods, (2) to assess the potential differences between 2D and 3D measurements and (3) to consider the implications of the ability to acquire very high resolution data for the geomorphological and hydrological analyses of drainage basins

2. Background

2.1 The hydrology of badland environments

Badland environments are found in many parts of the world and are typically associated with semi-arid climatic regimes and the occurrence of impermeable and unconsolidated surface materials. The associated limited vegetation cover and periodic high intensity rainfall facilitates high erosion rates and the formation of intensely eroded and dissected landscapes, with bare, steep slopes and characteristic patterns of alternating gullies and sharp-crested ridges (Gallart et al. 2013, 4-11).

Badland development is classically attributed to the process of surface runoff or overland flow. According to the Hortonian model of infiltration excess overland flow, the combination of high precipitation intensities with low substrate permeabilities and infiltration rates is ideally suited to rapid runoff generation (Horton 1932, 350-361). The runoff initially generated as laminar sheet flows is rapidly concentrated into small channels by surface irregularities that in combination with steep slopes, limited vegetation and unconsolidated substrates lead to rapid erosion and the development of rills and gullies. Considerable research effort has focused on improving our understanding of the denudation and morphogenetic evolution of badland areas (Buccolini et al. 2012, 41; Cappadonia et al. 2016, 851-862) (Alexander et al. 2008, 83-90) that has significant implications for the determination of landslide susceptibility (Coco and Buccolini 2015, 779-784) as well as the calculation of rates of soil erosion and sediment yields in these sensitive semi-arid environments (Nadal-Romero et al. 2011, 297-332).

Badlands may be likened to small hydrographic basins, characterised by dense, hierarchical and evolving drainage systems (Buccolini et al. 2012, 41). As such they are ideally suited to the quantitative description of drainage nets as originally devised by Horton (Horton 1932, 350-361; Horton 1945, 275-370) whereby any drainage basin's properties can be expressed according to a range of parameters including stream order, drainage density, bifurcation ratio and stream-length ratio, and there is a history of applying these methods to ephemeral basins such as those found in badland areas. The process of ordering the streams within a drainage network provides a key method within these analyses. Horton (1945) was the first to develop a system in which all the unbranched fingertip tributaries were labelled as first order. When two first order streams meet, a second order stream is formed; and where two second order streams meet a third order stream is created and so on. This method was subsequently modified by Strahler (1957), creating the "Horton-Strahler method" that has become one of the most widely used. A key concern about the use of this method relates to the lack of any quantitative impact of recognition of the addition of lower order streams into the main stream channel. This has been addressed within subsequent stream ordering systems developed by Shreve (1966) and Scheidegger (1965) that total the orders of the joining streams and thereby mathematically incorporate all the components of a drainage network. An additional critique of this concept of stream orders that the definition of a first-order stream depends on the scale of map used (Leopold and Miller 1956). Despite these shortcomings, these relationships have ultimately led to the mathematical prediction of flow associated with a precipitation event (Scheidegger 1965, 187-189) and form the basis of hydrological prediction today, in addition to the consideration of stream order in the analysis of other variables such as the categorisation of biological systems along ephemeral watercourses (Warren et al. 1984, 89).

Drainage density is a key parameter used within quantitative drainage basin analyses that is defined as stream channel length divided by the catchment area (Horton 1932, 350-361; Horton 1945, 275-370). Badlands are characterised by high drainage densities with values of over 50 commonly being reported (Smithson, Addison, and Atkinson 2008) and (Schumm 1956, 597-646) for example reporting a value of 603 for the Perth Amboy badlands in New Jersey, USA. This reflects the presence of intricate networks of gullies (well-defined, v-shaped channels tens of cms in width) and smaller scale, more impermanent rills (a few cms in width). Catchment responses to storm events are influenced by these channel networks, with higher drainage densities leading to flashier hydrograph responses and higher peak discharges. As a consequence, drainage density is widely regarded as a key drainage basin property that determines a catchment's efficiency, its hydrological response to a precipitation event and consequently the magnitude and frequency of flood events.

More recent studies have reported on potential links between slope morphometry and denudational processes (Cappadonia et al. 2016, 851-862), drainage density and slope angle (Lin and Oguchi 2004, 159), slope angle and aspect on vegetation cover (Cantón et al. 2001, 65; Nadal-Romero et al. 2014, 1705-1716) and drainage networks and landslide susceptibility (Coco and Buccolini 2015, 779-784). These studies have indicated that the emerging relationships between drainage density and slope angle are complex demonstrating both positive and negative correlations in different environments (Lin and Oguchi 2004, 159). The development of these relationships over time also requires further study using high resolution methods (Lin and Oguchi 2004, 159). (add Gallart et al. 2013).

The quantification of drainage density and associated variables is fundamentally dependent upon an ability to accurately measure the entire drainage network, with careful consideration needed on the extent of the drainage network that can be determined by the different scales of analysis possible from different maps, imagery and field surveys. Early attempts to measure the drainage density using cartographic maps quickly revealed problems in this regard with the lack of detail coupled with operator differences leading to considerable variations in the values of drainage density reported within the early literature (Gregory and Walling 1968, 61-68). Small channels were rarely depicted on maps leading to the use of other features such as contour crenulations to infer their presence and devise alternative parameters related to drainage density such as texture ratios (Smith 1950, 655-668). Most fundamentally, the stream networks were typically measured in two dimensions even though they were known to occur on three dimensional surfaces resulting in the development of slope corrections that attempted to consider the influence of relief and slope angle (Strahler 1957, 913-920).

Subsequent research in badland areas has utilised a range of techniques including geomorphological surveying (Cappadonia et al. 2016, 851-862), *in situ* and *ex situ* experimental plots (Cantón et al. 2001, 65; Kuhn and Yair 2004, 183)

, GIS techniques (Coco and Buccolini 2015, 779-784) and analytical and digital photogrammetry (Lin and Oguchi 2004, 159). However, in spite of the associated technological developments, the limited detail and resolution of the maps or imagery employed have generated particular measurement problems in these environments. In addition, more fundamental questions remain including what constitutes a drainage network and whether intermittent or ephemeral streams should be included.

2.2 UAVs and SfM as tools to create aerial imagery

The use of UAVs in the study of geomorphologic features is increasing dramatically due to the easier elaboration and processing of the data derived from Structure from Motion (SfM) processing. SfM is a method based on computer visualization techniques and picture-based 3D-surface reconstruction algorithms (Snavely 2009). Whilst traditional methods such as generation of Digital Elevation Models (DEMs) based on photogrammetry or the use of LiDAR still require expensive equipment and specialized user expertise to process data and improve its quality (Micheletti, Chandler, and Lane 2015, Chap. 2, Sec. 2.2.), SfM does not require additional equipment, just a camera and adequate software.

SfM is also becoming increasingly popular because of the emergence and increasing accessibility to UAVs and the development of soft-copy triangulation and image-based terrain extraction algorithms, which have radically enhanced the quality of the terrain data that can be derived from overlapping stereo-pairs (Chandler 1999, 51-63; Lane, Richards, and Chandler 1994, 349-368). Therefore, SfM survey techniques enable the rapid generation of dense topographic models using imagery from consumer-grade digital cameras which can then be georeferenced (Vericat, Smith, and Brasington 2014, 164-176). Overall, SfM has substantial potential to revolutionise the acquisition and accessibility of high resolution topographic data, potentially permitting the study of erosion rates over a range of spatial scales with a single technique (Smith and Vericat 2015, 1656-1671). In comparison, available data from conventional platforms, such as satellites and manned aircraft, is typically in the range of up to 20-50 cm/pixel, whilst UAVs are capable of obtaining data as detailed as 1 cm/pixel (Turner, Lucieer, and Watson 2012, 1392), or even more as this study shows. This is due to the full control of the user over the gathering and processing of the data, in which the decision of the operator over what kind of camera and flight path is used will influence the final results. A range of cameras can be used, but a digital SLR camera equipped with fixed focus lens will usually generate the most accurate data as widely varying zoom settings can cause difficulties (Shortis, Robson, and Beyer 1998, 165-186; Sanz-Ablanedo, Chandler, and Wackrow 2012, 210-226), but this will come at a cost, as not all UAVs can carry such heavy equipment. SfM photogrammetry differs from traditional photogrammetric approaches by providing full flexibility in the design of the flight mission and reduces the need for a pre-defined set of ground control points, visible points at known three-dimensional positions (Westoby et al. 2012, 300). The main difference from conventional photogrammetry is that issues such as the geometry of the scene, camera position and orientation are solved with the creation of a database of features, a 3D point cloud, resulting from the overlapping of images.

This process involves the automatic finding and matching of a limited number of common features between images which are then used to establish both interior and exterior orientation parameters (Micheletti, Chandler, and Lane 2015, Chap. 2, Sec. 2.2.). Furthermore, cameras with built in GPS can generate data which is automatically georeferenced, facilitating and improving the pair matching process.

The study of complex features and rough terrain where the data generated by LiDAR is incomplete or erroneous can be addressed with SfM, as the gathering of a very precise 3D point cloud generates a very realistic scene. Authors who studied gullies in arid landscapes (Kaiser et al. 2014, 7050), stated that, along with traditional monitoring tools, SfM is a very powerful technique in the analysis of soil loss providing very precise results when compared to publicly sourced data (Vericat, Smith, and Brasington 2014, 164-176). Other successful studies using SfM in geomorphological and applied research have been carried out in relation to the calving dynamics of glaciers (Ryan et al. 2015, 1-11), small-scale glacial landform reconstructions (Westoby et al. 2012, 300), quantification of dryland vegetation structure (Cunliffe, Brazier, and Anderson 2016, 129), measure of the snow depth (Marti et al. 2016, 1361-1380), erosion/accretion areas in coastal environments (Long et al. 2016, 387), as well as mineral resource exploration, land use survey, marine environmental monitoring, water resource development, crop growth monitoring and assessment, forest protection and monitoring or natural disaster monitoring and evaluation (Li et al. 2015, 12606; Estrany et al. 2016, 69-87). However, as with any new technological development the application of UAVs and SfM, leading to a significant shift in the availability of high resolution field data needs to be carefully considered, to ensure the appropriate use of these technologies.

3. Methodology

In order to explore the utility of UAVs as a means of mapping large-scale rills and gullies and quantifying the characteristics of small drainage basins, a study site located very close to the Tabernas Wilderness Area –Paraje Natural in Spanish- and the Mini-Hollywood theme park was chosen (Figure 1). The site was chosen because it is easily accessible by road and frequently visited by students and geotourists (Hose 2007, 259-276). While it showcases a prime example of a badland environment, it is outside of the protected area, providing fewer flight and access constraints. The selected drainage basin displays a very small surface area (294 m^2) and forms part of a very steep slope which has been formed by the lateral fluvial erosion of a relatively small hill with a prominence of 29m above the river bed. This very steep slope and the presence of easily eroded Tortonian mudstones (Calvo-Cases and Harvey 1996, 725-735; Harvey 1982, 336) coupled with the semi-arid climatic regime of the area (Lázaro et al. 2008, 252)

featuring sporadic episodes of torrential rain (Poesen and Hooke 1997, 157-199) and the limited vegetation cover (Nogueras et al. 2000, 203-215) has promoted the development of a localised badland environment.

[Figure 1 near here]

To create a highly detailed map of such a small basin a low flight of 15m above the highest point of the basin at a low speed of 4m/s was carried out using a Steadidrone Qu4d X quadcopter. Three consecutive and identical flights were performed on 13/01/2016 when the Sun was at its zenith to minimise shades and on a day when atmospheric conditions were ideal, as there was virtually no wind or clouds and the air was clear. The flight path was designed as to guarantee enough overlap (Eisenbeiss and Sauerbier 2011, 400-421) and to cover the study area completely (Figure 2). Two sensors were used; a GoPro Hero4 which, due to its shorter focal length and high time-lapse rate, was used to create 3D visualisations of the broader study area, and a modified[1] 20.2 megapixels Canon S100 to obtain the highly detailed imagery of the study site in which this study is based. This camera was set so its focal length was equivalent to 50mm, a value commonly used in UAV photography (Haala, Cramer, and Rothermel 2013, 183-188; Saleri et al. 2013, 497-502; Zhang and Elaksher 2012, 118-129) which provides higher levels of detail than shorter lengths while still delivering the necessary amount of image overlap given the flight design. The images obtained during the flight were processed using the structure from motion software Agisoft PhotoScan Professional. In order to improve and corroborate the spatial accuracy of the imagery they were georeferenced using two methods, the camera's internal GPS and 11 ground control points placed on and around the study site - . Out of this process, three products were created, an orthophotograph with a pixel resolution of 6.63mm, a Digital Surface Model (DSM) and Digital Terrain Model (DTM) both with a pixel resolution of 26.54mm.

[Figure 2 near here]

The generated DTM was used to identify the channel network of the study area by using a combination of the hydrology modules of QGIS (Thiede et al. 2016) and ArcGIS (Johnson 2016), as some streams that where not captured by one where identified by the other and vice versa due to them using different algorithms. Once created, the stream network was visualised in 3D (Nobajas and Nadal 2015, 211-223) and it was found that a few very short streams–less than 10cm in length- had exaggerated elevation changes provoked by errors in the DTM creation. This resulted from some small plants and debris not being adequately removed, so those stream sections which had unreasonable elevation changes were eliminated. Finally, the generated channel network was overlaid on top of the orthophotograph to visually check if any streams were badly located or absent, but apart from a few very minor discrepancies which were manually corrected, all of them were adequate.

Once all the streams were vectorised and a highly detailed DTM was created it was possible to accurately calculate a series of variables which can be used to characterise a drainage basin. Thanks to the currently available GIS methods the measurements can be automated and the elevation change taken into account, allowing calculating surfaces and distances both in 2D and 3D, something which was previously difficult. As previously, and as a way of

[1] The filter was changed so it recorded Near Infrarred, Green and Blue (NGB) and the camera's firmware was replaced using the Canon Hack Development Kit (CHDK) including a UAV add-on.

assuring the most accurate results, both ArcGIS and QGIS were used to calculate all the variables, and, if any difference existed between them, the results were averaged.

By processing UAV imagery using Structure from Motion software and more traditional GIS methods a series of results, including visualisations and measurements, were generated. As figure 3 shows, 3D recreations of the study site were created, allowing the interactive visualisation of the basin and its stream network. In order to create these visualisations, imagery from the GoPro 4 camera was used as it provided RGB imagery and due to its broader field of view it allowed representation of a larger area, which permitted understanding of the studied basin within its wider geomorphic context. Two different software packages were used to create these visualisations, ESRI's ArcScene and Agisoft's Photoscan, as it was found that the first allows easily overlaying GIS layers while the second provides better rendering capabilities.

[Figure 3 near here]

4. Results

The orthophotograph of the study site, with a resolution of 6.63mm per pixel (figure 4a), allows, the identification of small rills associated with the initial channelization of sheet flow and an associated focusing of fluvial erosion as well as the larger gullies into which they feed. The modelled channel network was ordered using Strahler's ordering method (Strahler 1964, 4-39/4-76) that provides a hierarchic representation of the study site's drainage system (figure 4b) helping to characterise the spatial distribution, geometry and density of the basin's stream network.

[Figure 4 near here]

The results of the quantitative drainage basin analyses undertaken on the catchment are summarised in table 1. This illustrates the very high resolutions that can be attained with pixel resolutions of 8mm and 30mm for the orthophotograph and DEM respectively. The marked differences in the measured values in basin area, channel length and drainage/stream density values measured in both two and three dimensions demonstrate the influence of the high elevation change and significant slope angles of the basin on the quantification of these parameters. The calculated measurement of the drainage density is relatively low in comparison to the estimates generated by smaller scale studies on larger badland catchments which can reach values >100 (e.g. Schumm, 1956). However, the intricacy of the drainage network is highlighted by the development of a Strahler order value of 5 within the confines of a small drainage basin.

[Table 1 near here]

5. Discussion

Analysis of the drainage characteristics and geomorphological processes of badland environments has previously taken place using a series of methods such as the analysis of topographic maps, *in situ* or *ex situ* simulation experiments, aerial digital photogrammetry, or fieldwork. All these methods suffer from a series of limitations such as cost, data resolution, or danger to the researcher due to the slopes' inclination and instability (figure 5), a fact which has hindered the study of large-scale badland environments. This is the case for this study area, where there is a lack of detailed data currently available with the most detailed DEM accessible for the study area having a resolution of 5 meters, almost 200 times coarser than the one used in this paper (Instituto Geográfico Nacional 2016a)

. Even new developments in publicly-sourced data, such as the use of Lidar to produce DEMs, pale in comparison to the level of detail attainable with the use of UAVs. For instance the study area will soon have a 1 meter resolution Lidar generated DEM published by the Instituto Geográfico Nacional, the Spanish public mapping agency (Instituto Geográfico Nacional 2016a)

, but even then the DEM's resolution will be almost 40 times less detailed than the one used in this paper. Such a coarse resolution makes it unsuitable for studying very small basins such as the one used in this paper, as figure 5 shows. UAVs therefore provide the opportunity for a cheaper, quicker and less hazardous way of collecting data, as well as the opportunity to make much finer-scale observations of the basin's characteristics, in addition to the potential to generate quantitative measures of channel length and basin area in both 2D and 3D.

[Figure 5 near here]

This enhanced resolution has provided the opportunity to resolve small drainage networks that have previously proven undetectable to studies utilising topographic maps or remotely-sensed imagery. Following his study of the Perth Amboy Badlands that made use of detailed topographic base maps, Schumm (1956) noted that Horton's early quantitative analyses of drainage networks were likely to have omitted the first and second order streams with measurements being restricted to the blue drainage symbols evident on the poorer quality maps. An early study of stream order of ephemeral streams by Leopold and Miller (1956) explored the importance of the scale of measurement in determining stream order. Using field mapping of the drainage channels evident in (although still of larger dimensions than those included in this study through UAV imagery) a stream which appeared as a first order channel on a smaller-scale map, they determined that these channels were actually of fifth order. They consequently corrected the stream order of larger drainage basins by adding 4. Similarly, this paper's use of UAV imagery and image processing techniques suggests that in areas of badland topography, these early approaches may in fact have missed the first five stream orders. The question of what should be included as a first order stream is not a new one. For example, Warren et al. (1984:94) described the main problem of applying the stream order concept to ephemeral drainage systems as determining where a first order stream begins, claiming that it is arguable whether the abundant small depressions that accumulate and carry-run off constitute differentiated water courses (Warren et al. 1984, 89).

They classify such features as ‘rivulets’ which they distinguish from ‘first order washes’ using several of their own criteria.

In this respect, the use of modern technologies provides the opportunity to further these earlier endeavours and “afford data more precisely representative of the natural development of drainage systems than old maps” (Schumm, 1956, p605), which may have implications to the quantification of drainage characteristics. For example, the use of such technologies may show that the actual drainage densities of badland areas are actually much higher than those previously reported with these headwater networks having previously been excluded from smaller-scale analyses, whilst also allowing the potential to accurately include 3-D measurements. However, such reconsideration of these ‘early endeavours’ may require the geomorphological and hydrological community to reconsider what constitutes a first order stream at this finer resolution of study, and to question what level of detail may be ‘too much’ detail. It may be that consideration of the temporal rather than just the spatial characteristics of these features is necessary in such a classification. In an ephemeral basin, drainage features will only be active for short periods of a year, perhaps only a few hours in each year. Smaller features such as rills may be produced during a single storm event, but may decay over time as the divides between them break down. Schumm (1956) reported rills being destroyed over an annual cycle due to different seasonal processes in contrast to gullies which have greater permanence. Therefore it may be that the permanence of ephemeral drainage features can be used as a key criterion in deciding what should be classed as a first order stream.

Even though these techniques allow such fine resolution of drainage features to be identified, subterranean drainage features, remain invisible, and therefore do not necessarily provide a complete picture of all the drainage components. Studies have suggested that the denudation of badland areas may not always be restricted to surface runoff due to the presence of subsurface piping whose operation can further influence the resultant drainage network (Harvey 1982, 336). Care therefore needs to be taken to explore the full range of drainage processes present.

This paper has focused on the quantification of drainage network characteristics. However, the generation of such high resolution imagery has a wider range of potential geomorphological and hydrological applications. For example, it has been demonstrated that erosion rates vary in response to spatial variations in the physical and geochemical properties of soils, which has brought into question the assumption of universally high erosion rates in badland regions (Faulkner, Alexander, and Wilson 2003, 243-254). For example, in the badlands of the Tabernas Basin, where extensive research on erosional processes at the microcatchment scale have been carried out, erosion rates have been shown to be much lower than might be expected due to small-magnitude, low intensity rainfall events coupled with protective plant cover (Cantón et al. 2001, 65)

. The use of repeat UAV flights before and after rainfall events of different intensity at microcatchment scale, has the potential to generate high resolution time lapse imagery that could prove invaluable to the understanding of the controls of runoff processes and resultant water and sediment yields at a hillslope scale (Nadal-Romero et al. 2011, 297-332). The ability to measure both in 2D and 3D is quite important as due to the scale and slope that small badland basins have, significant differences between both measurements can arise. When measuring drainage density or other hydrological variables using topographic maps, the 2D-3D channel length difference ratio is highly dependent on the basin size, since small-scale river systems are not as strongly influenced by elevation changes as large scale ones. While major river systems have a marginal difference between their 2D and 3D lengths due to the large imbalance between their elevation and length measurements, in the studied basin the difference between 2D and 3D distances is much greater due to the characteristic roughness of badland environments. Therefore, using 3D measurements in lieu of 2D measurements becomes highly relevant when working at such levels of detail in order to take into account the actual channel length and basin area. Moreover, thanks to the ability GIS software has to measure the 3D distance on a pixel by pixel basis it is possible to do so precisely –i.e. without needing to assume a constant slope.

In order to effectively measure in either dimension it is important to use the appropriate methods to generate the base 3D model, and the popularisation of Structure from Motion software and its ever increasing improvement has allowed users to easily create bespoke remotely-sensed aerial data. The software advances have come at a time when the use of autonomous UAVs is increasingly popular, which has created a powerful combination that is likely to transform how aerial imagery is gathered and used (Everaerts 2008, 1187-1192; Remondino et al. 2011, C22; Zongjian 2008, 1183-1186). However, the processing of the generated data is not as straight forward as the theory would suggest because there are myriad potential issues that still hinder the rapid popularisation of the methodology described in this paper. New challenges have arisen due to the use of extremely detailed DEMs; such as working at scales larger than 1:1, the 'dome effect' (Micheletti, Chandler, and Lane 2015), or pixel sizes where small irregularities –e.g branches or pebbles- are mapped and influence the resulting DEM. Such issues raise new conceptual questions such as what is he optimum level of detail, what is the minimum size a stream should have in order to be considered as such. Therefore, while the speed at which data can be processed and reduced risk means that the combination of UAVs and SfM software will be increasingly used to study environments which were previously difficult to work on, such as badlands, it will become necessary to consider the theoretical and methodological challenges such techniques generate.

6. Conclusion

The use of UAVs to map the large-scale geomorphological characteristics associated with the drainage networks on a single slope scale within a badland environment generates levels of detail not available previously. Even if new issues need to be solved and the process presents certain difficulties which require training, the advantages gained by using this method instead of manual data gathering or publicly sourced data greatly outweigh the complications. The fact that data can be gathered at sub-centimetre level whilst avoiding the dangers of having to physically climb the steep and unstable slopes make the use of UAVs an ideal tool to study these kinds of environment. Additionally, the ability to process data both in 2D and in 3D means that much better hydrological metrics can be obtained, allowing gaining a greater understanding of processes which can allow geomorphologists to predict phenomena such as landslide susceptibility, soil erosion, or the hydrograph response, pattern and amount of soil erosion in response to storm events. The comparative ease which comes with the use of UAVs means that it is now possible to perform repeat surveys of a slope, for example pre and post a storm event. This provides the opportunity to undertake *in situ* studies of denudational processes and hillslope evolution that will improve our understanding of runoff processes over time. Repeat measurements by UAV will also allow greater study of the influence of small-scale heterogeneity of hillslope characteristics on runoff and denudational processes. This allows slope-scale studies to be carried out without needing experimental setups.

The ability to measure and quantify these small-scale drainage features that have hitherto remained largely invisible to geomorphological investigations allows their integration into catchment-scale investigations. This allows the accurate calculation of key drainage basin attributes such as drainage density that have almost certainly been previously underestimated. In so doing, this provides the opportunity to reappraise the validity of existing long established laws and relationships such as those between drainage density and drainage area at smaller scales of analysis, as well as bringing into question the concepts of stream order and the scale at which first order streams should be determined. The availability of finer resolution imagery derived from UAVs therefore has significant implications for the geomorphological and hydrological research . Such technological developments provide to the opportunity to both re-examine hydrological relationships determined from larger resolution measurements of drainage networks, and to enhance our understanding of the role of large-scale spatial variation of surface features on runoff processes. However, the potential for acquisition of such detailed imagery, also requires the consideration of what is the appropriate level of detail required to answer a particular research question, and the need for the remote sensing, geomorphological and hydrological communities to work together to ensure the address the many questions that the access to these technological developments raise.

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7. References

Alexander, RW, A. Calvo-Cases, E. Arnau-Rosalén, AE Mather, and R. Lázaro-Suau. 2008. Erosion and stabilisation sequences in relation to base level changes in the el cautivo badlands, SE spain. Geomorphology 100 (1): 83-90.

Buccolini, Marcello, Laura Coco, Chiara Cappadonia, and Edoardo Rotigliano. 2012. Relationships between a new slope morphometric index and calanchi erosion in northern sicily, italy. Geomorphology 149-150 : 41.

Calvo-Cases, A., and AM Harvey. 1996. Morphology and development of selected badlands in southeast spain: Implications of climatic change. Earth Surface Processes and Landforms 21 (8): 725-35.

Cantón, Y., F. Domingo, A. Solé-Benet, and J. Puigdefábregas. 2001. Hydrological and erosion response of a badlands system in semiarid SE spain. Journal of Hydrology 252 (1-4): 65.

Cappadonia, Chiara, Laura Coco, Marcello Buccolini, and Edoardo Rotigliano. 2016. From slope morphometry to morphogenetic processes: An integrated approach of field survey, geographic information system morphometric analysis and statistics in italian badlands. Land Degradation & Development 27 (3): 851-62.

Chandler, Jim. 1999. Effective application of automated digital photogrammetry for geomorphological research. Earth Surface Processes and Landforms 24 (1): 51-63.

Coco, L., and M. Buccolini. 2015. The effect of morphometry, land-use and lithology on landslides susceptibility: An exploratory analysis. Paper presented at Geotechnical Safety and Risk V: Fifth International Symposium on Geotechnical Safety and Risk (ISGSR) 2015, .

Cunliffe, Andrew M., Richard E. Brazier, and Karen Anderson. 2016. Ultra-fine grain landscape-scale quantification of dryland vegetation structure with drone-acquired structure-from-motion photogrammetry. Remote Sensing of Environment 183 : 129.

Eisenbeiss, Henri, and Martin Sauerbier. 2011. Investigation of uav systems and flight modes for photogrammetric applications. The Photogrammetric Record 26 (136): 400-21.

Estrany, Joan, Aleix Calsamiglia, Marc Carriquí, Julián García-Comendador, Miquel Nadal, Josep Forteza, Maurici Ruiz, Bartomeu Alorda, and Jorge Gago. 2016. Ecogeomorfologia i drons com a eines de gestió dinàmica postincendi. el cas de la comarca del pariatge, mallorca. Treballs De La Societat Catalana De Geografia(80): 69-87.

Everaerts, Jurgen. 2008. The use of unmanned aerial vehicles (UAVs) for remote sensing and mapping. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences 37 : 1187-92.

Faulkner, Hazel, Roy Alexander, and BR Wilson. 2003. Changes to the dispersive characteristics of soils along an evolutionary slope sequence in the vera badlands, southeast spain: Implications for site stabilisation. Catena 50 (2): 243-54.

Gallart, Francesc, Michela Marignani, Nuria Pérez-Gallego, Elisa Santi, and Simona Maccherini. 2013. Thirty years of studies on badlands, from physical to vegetational approaches. A succinct review. Catena 106 : 4-11.

Gregory, KJ, and DE Walling. 1968. The variation of drainage density within a catchment. Hydrological Sciences Journal 13 (2): 61-8.

Haala, N., M. Cramer, and M. Rothermel. 2013. Quality of 3D point clouds from highly overlapping UAV imagery. ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences XL-1/W2 : 183-8.

Harvey, A. 1982. The role of piping in the development of badlands and gully systems in south-east spain. Badland Geomorphology and Piping 317 : 336.

Horton, Robert E. 1945. Erosional development of streams and their drainage basins; hydrophysical approach to quantitative morphology. Geological Society of America Bulletin 56 (3) (March 01): 275-370.

———. 1932. Drainage-basin characteristics. Eos, Transactions American Geophysical Union 13 (1): 350-61.

Hose, Thomas. 2007. Geotourism in almeria province, southeast spain. Tourism: An International Interdisciplinary Journal 55 (3): 259-76.

Instituto Geográfico Nacional. Cobertura LiDAR. in Instituto Geográfico Nacional [database online]. 2016a [cited 17/08/2016 2016]. Available from http://pnoa.ign.es/coberturalidar.

———. Modelo digital de elevaciones. in Instituto Geográfico Nacional [database online]. 2016b [cited 28/09/2016 2016]. Available from https://www.ign.es/ign/layoutIn/modeloDigitalTerreno.do.

———. Plan nacional de ortofotografía aérea. in Instituto Geográfico Nacional [database online]. 2016c [cited 28/09/2016 2016]. Available from http://pnoa.ign.es/.

Johnson, L. E. 2016. Geographic information systems in water resources engineeringCRC Press.

Kaiser, Andreas, Fabian Neugirg, Gilles Rock, Christoph Müller, Florian Haas, Johannes Ries, and Jürgen Schmidt. 2014. Small-scale surface reconstruction and volume calculation of soil erosion in complex moroccan gully morphology using structure from motion. Remote Sensing 6 (8): 7050.

Kuhn, Nikolaus J., and Aaron Yair. 2004. Spatial distribution of surface conditions and runoff generation in small arid watersheds, zin valley badlands, israel. Geomorphology 57 (3-4): 183.

Lane, S. N., K. S. Richards, and J. H. Chandler. 1994. Developments in monitoring and modelling small-scale river bed topography. Earth Surface Processes and Landforms 19 (4): 349-68.

Lázaro, R., Y. Cantón, A. Solá-Benet, J. Bevan, R. Alexander, L. G. Sancho, and J. Puigdefábregas. 2008. The influence of competition between lichen colonization and erosion on the evolution of soil surfaces in the tabernas badlands (SE spain) and its landscape effects. Geomorphology 102 (2): 252.

Leopold, L. B., and J. P. Miller. 1956. Ephemeral streams; hydraulic factors and their relation to the drainage net.

Li, Hongguang, Xinjun Li, Wenrui Ding, and Yuqing Huang. 2015. Metadata-assisted global motion estimation for medium-altitude unmanned aerial vehicle video applications. Remote Sensing 7 (10): 12606.

Lin, Zhou, and Takashi Oguchi. 2004. Drainage density, slope angle, and relative basin position in japanese bare lands from high-resolution 'DEMs'. Geomorphology 63 (3-4): 159.

Long, Nathalie, Bastien Millescamps, Benoît Guillot, Frédéric Pouget, and Xavier Bertin. 2016. Monitoring the topography of a dynamic tidal inlet using UAV imagery. Remote Sensing 8 (5): 387.

Marti, R., S. Gascoin, E. Berthier, M. de Pinel, T. Houet, and D. Laffly. 2016. Mapping snow depth in open alpine terrain from stereo satellite imagery. The Cryosphere 10 (4): 1361-80.

Micheletti, Natan, Jim H. Chandler, and Stuart N. Lane. 2015. Structure from motion (SFM) photogrammetry.

Micheletti, Natan, Jim H. Chandler, and Stuart N. Lane. 2015. Structure from motion (SfM) photogrammetry. In Geomorphological techniques., eds. L. E. Clarke, J. M. Nield, Chap. 2, Sec. 2.2. London: British Society for Geomorphology.

Nadal-Romero, Estela, Juan Fransisco Martínez-Murillo, Matthias Vanmaercke, and Jean Poesen. 2011. Scale-dependency of sediment yield from badland areas in mediterranean environments. Progress in Physical Geography 35 (3): 297-332.

Nadal-Romero, Estela, Kristien Petrlic, Els Verachtert, Esther Bochet, and Jean Poesen. 2014. Effects of slope angle and aspect on plant cover and species richness in a humid mediterranean badland. Earth Surface Processes and Landforms 39 (13): 1705-16.

Nobajas, Alexandre, and Francesc Nadal. 2015. From historical map to online 3D recreation: The 1861 cadastral map of horta (barcelona). Cartography and Geographic Information Science 42 (3) (05/27; 2015/08): 211-23.

Nogueras, Pascual, Francesc Burjachs, Francesc Gallart, and Joan Puigdefàbregas. 2000. Recent gully erosion in the el cautivo badlands (tabernas, SE spain). Catena 40 (2): 203-15.

Poesen, J. W. A., and J. M. Hooke. 1997. Erosion, flooding and channel management in mediterranean environments of southern europe. Progress in Physical Geography 21 (2) (June 01): 157-99.

Remondino, Fabio, L. Barazzetti, Francesco Nex, Marco Scaioni, and Daniele Sarazzi. 2011. UAV photogrammetry for mapping and 3d modeling–current status and future perspectives. International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences 38 (1): C22.

Ryan, J. C., A. L. Hubbard, J. E. Box, J. Todd, P. Christoffersen, J. R. Carr, T. O. Holt, and N. Snooke. 2015. UAV photogrammetry and structure from motion to assess calving dynamics at store glacier, a large outlet draining the greenland ice sheet. The Cryosphere 9 (1): 1-11.

Saleri, R., V. Cappellini, N. Nony, L. De Luca, M. Pierrot-Deseilligny, E. Bardiere, and M. Campi. 2013. UAV photogrammetry for archaeological survey: The theaters area of pompeii. Paper presented at Digital Heritage International Congress (DigitalHeritage), 2013, .

Sanz-Ablanedo, Enoc, Jim H. Chandler, and Rene Wackrow. 2012. Parameterising internal camera geometry with focusing distance. The Photogrammetric Record 27 (138): 210-26.

Scheidegger, Adrian. 1965. The algebra of stream-order numbers. United States Geological Survey Professional Paper: 187-9.

Schumm, Stanley A. 1956. Evolution of drainage systems and slopes in badlands at perth amboy, new jersey. Geological Society of America Bulletin 67 (5): 597-646.

Shortis, M. R., S. Robson, and H. A. Beyer. 1998. Principal point behaviour and calibration parameter models for kodak DCS cameras. The Photogrammetric Record 16 (92): 165-86.

Smith, Kenneth Grant. 1950. Standards for grading texture of erosional topography. American Journal of Science 248 (9): 655-68.

Smith, Mark William, and Damià Vericat. 2015. From experimental plots to experimental landscapes: Topography, erosion and deposition in sub-humid badlands from Structure-from-Motion photogrammetry. Earth Surface Processes and Landforms 40 (12): 1656-71.

Smithson, P., K. Addison, and K. Atkinson. 2008. Fundamentals of the physical environment. 4th ed.Routledge.

Snavely, Keith N. 2009. Scene reconstruction and visualization from internet photo collections.University of Washington.

Strahler, Arthur N. 1964. Quantitative geomorphology of drainage basins and channel networks. In Handbook of applied hydrology., ed. V. T. Chow, 4-39/4-76McGraw-Hill, New York; McGraw-Hill, New York.

———. 1957. Quantitative analysis of watershed geomorphology. Eos, Transactions American Geophysical Union 38 (6): 913-20.

Thiede, Rudiger, Tim Sutton, Horst Duster, and Marcelle Sutton. 2016. QGIS training manual. Western Cape, South Africa: Linfiniti Consulting.

Turner, Darren, Arko Lucieer, and Christopher Watson. 2012. An automated technique for generating georectified mosaics from ultra-high resolution unmanned aerial vehicle (UAV) imagery, based on structure from motion (SfM) point clouds. Remote Sensing 4 (5): 1392.

Vericat, D., MW Smith, and J. Brasington. 2014. Patterns of topographic change in sub-humid badlands determined by high resolution multi-temporal topographic surveys. Catena 120 : 164-76.

Warren, Peter L., Arizona Remote Sensing Center, L. Susan Anderson, and Charles H. Lowe. 1984. Stream order in ephemeral watercourses: A preliminary analysis from the sonoran desert R. roy johnson cooperative national park resources studies unit university of arizona. In ARIZONA and the: 89.

Westoby, M. J., J. Brasington, N. F. Glasser, M. J. Hambrey, and J. M. Reynolds. 2012. 'Structure-from-motion' photogrammetry: A low-cost, effective tool for geoscience applications. Geomorphology 179 : 300.

Zhang, Chunsun, and Ahmed Elaksher. 2012. An unmanned aerial vehicle-based imaging system for 3D measurement of unpaved road surface Distresses1. Computer-Aided Civil and Infrastructure Engineering 27 (2): 118-29.

Zongjian, Lin. 2008. UAV for mapping—low altitude photogrammetric survey. International Archives of Photogrammetry and Remote Sensing, Beijing, China 37 : 1183-6.

Captions

Figure 1. Location of the study site within the Iberian Peninsula, the Almería Province and the town of Tabernas. The bottom map shows how the study site –in red- is surrounded, but not within, the protected area –green line.

Figure 2. Flight path and photography locations of the UAV used to obtain the data. Background imagery created by the IGN (Instituto Geográfico Nacional 2016c).

Figure 3. 3D model of the hill where the basin used as a case study is located –highlighted in blue (*a*) and 3D view from above the study site (*b*).

Figure 4. Orthophotography (*a*) and DEM with the channel network hierarchy overlaid of the basin used as the study site (*b*).

Figure 5. Best current publicly available DEM with the studied basin overlaid (*a*) (Instituto Geográfico Nacional 2016b). A group of students trying to measure some of the variables calculated in this paper manually (*b*).

Table 1. Calculated values of the variables used to characterise the study site's hydrologic characteristics both in 2D and 3D.