ASSESSMENT OF PHOTOGRAMMETRIC MEASUREMENTS OF GULLIES WITH CONTRASTING FORM AND SIZE

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Abstract Field techniques allow accurate direct measurements on gully geometry, even in 3D-dimensional coordinates. Accuracy and detail reproduction is limited mainly by experimental setup and density of measurements, and less so by the precision of the measuring equipment. In contrast, remote-sensing techniques permit the coverage of large study areas with a minimum of time and effort. However, the indirect measurements from imagery are known to depend on factors like image resolution, quality of ground control, vegetation cover and image evaluation technique, which strongly influence the measurement accuracy. The objective of the present study was to investigate to what extent the accuracy of 3D gully measurement using photogrammetric techniques depends on gully morphology. At a study site in the Bardenas Reales (Navarre, Spain), field measurements of cross-sections were taken for five gullies with contrasting morphology and dimensions and used as reference data for analysing the errors associated with a corresponding dataset obtained using small-format aerial photogrammetry whose pixel size on the ground is 16 mm).

Results show that volumetric gully measurements by means of photogrammetric techniques are strongly affected by the gully morphology; in particular by its width/depth (W/D) ratio, because of the increasing sun-shadowing and sight-shadowing effects associated with narrower gullies. Only wide, shallow gullies are little affected by this problem. For gullies of an intermediate typology (W/D between 0.5 and 2.5), the accuracy of photogrammetric measurements will much depend on the time of day and the period of the year when the photographs are taken, and narrow/deep gullies (W/D < 0.5) will be likely to be highly inaccurate at any time. Although this study was conducted with a large measurement scale for small (mostly ephemeral) gullies, the W/D ratios judged challenging for photogrammetric analysis in this study are also common for larger-sized gullies of the (permanent) bank gully type.

INTRODUCTION

Hitherto, most of the studies on gully erosion aim to estimate the spatial and/or temporal evolution of either single gullies or gully networks under different situations. With regard to the accuracy of experimental datasets, a field survey makes possible to obtain accurate measurements on gully geometry, even in three-dimensional coordinates, with (relative) ease (Oostwoud Wijdenes and Bryan, 1994). In addition, the accuracy of this direct measurement mainly depends on the researcher's judgment (e.g., to choose the experimental setup and the density of

measurements), rather than in the precision of the measuring equipment used. On the other hand, remote-sensing techniques of gully measuring, in two and three-dimensional coordinates, have been increasingly used (e.g., quantification of volumen loss, Marzolff and Poesen, 2009). Unlike field measurements, these indirect measuring techniques allow covering of large study areas with a minimum of time and effort (e.g., Martínez-Casasnovas et al., 2003). However, the accuracy of the dataset obtained in this way does much depend on the precision of the applied technique (e.g. on image resolution, quality of ground control). Moreover, an accurate gully measurement on three-dimensional coordinates may also (much) depend in the gully morphology (e.g., on the gully width/depth relationship). A gully cross-sectional area is more difficult to assess in a narrow, deeply eroded feature where measuring may be somewhat hindered by shadows cast on gully walls and bottom.

Despite a wealth of studies on monitoring different types of gullies by using remote-sensing technique such as photogrammetry, relatively few efforts have been made to test their accuracy. Therefore the question arises as to what extent the accuracy of gully monitoring using photogrammetric technique depends on gully morphology. The objective of this work is to investigate this issue. To do that, we confront field measurements of cross-sectional areas of gullies with contrasting morphology with a similar dataset obtained using photogrammetry.

MATERIAL AND METHODS

Field and Aerial Survey Within the region of Bardenas Reales (Navarre, Spain, an area of around 4 ha containing a large collection of gullies of different sizes and morphologies, was chosen to carry out the experiments. Five different gullies were selected mainly for the contrasting differences in their W/D ratio. Forty-six ground control points (GCPs) were marked with metal pins in the study area prior to the surveys and their XYZ coordinates measured with a total station in UTM coordinates to an estimated precision of approx. 1 cm. The GCPs were located in the surroundings of the gullies, and, for the largest gully (Gully 1), also within the gully.

With a specially designed kite (Marzolff and Ries, 2007) as a sensor platform, large-scale aerial photographs were obtained over the study area. A non-metric small-format digital camera (Canon EOS 350D with 20 mm lens) is attached to a 6 or 9 m² Rokkaku-type rigid kite. The camera cradle is suspended from a sledge-like gondola running on the kite line and can be rotated horizontally and vertically by remote control to facilitate the capture of both vertical and oblique photographs. Stereoscopic coverage was accomplished "along-track" by taking advantage of the swaying of the kite, by repositioning the kite or by redirecting the kite line. Aerial photography was carried out on October 12 and 14, 2007 from 12h to 17h (GTM+1). Twenty-one out of a large number of images taken were chosen for photogrammetric analysis using LeicaGeosystem's LPS software. The flying height of the images used for stereo-digitizing the gully profiles was approximately 50 m, the original image scale (on camera chip) was 1:2470, and the pixel size on the ground was 16 mm.

Using the software's self-calibrating option with additional lens distortion parameters, a bundle block adjustment was carried out to create two photogrammetric image blocks: one for Gully 1, the other for Gullies 2 to 5. A larger number of images than necessary for covering the area were used for increased stability of the image blocks and to allow for the selection of those with the

best stereoscopic properties in the analysis. To increase relative stability of the non-metric image blocks, a large number of tie points (approx. 100 per image) covering the whole stereo-areas were computed automatically, which significantly improved triangulation results (Marzolff and Poesen, 2009). The triangulation process resulted in GCP residuals of 0.5-1.6 cm (RMSE in x, y and z), image RMS errors of 0.38-0.51 pixels and an exterior orientation accuracy of 1.2-5.2 cm. Thus, the absolute horizontal and vertical accuracy of any given point measured from the stereo model can be expected to be limited by these results to approx. 2-6 cm. As this study relies on 3D measurements taken by visual stereo-digitizing (as opposed to fully automatic terrain extraction), the quality of the photogrammetric restitution was also assessed by visual inspection of the concordance of the stereo-viewed surfaces with the 3D data set of ground control points. Only image pairs where the GCPs could be verified to sit exactly on the ground, just as the operator would have placed them, were used for further analysis, thus avoiding those with inferior orientation accuracy.

In the field, the surface topography of the small gullies (Gully 2-5) was determined at 5 mm intervals in the transverse direction for sections spaced 200 mm in the longitudinal direction using a laser profilometer running along a 2.5 m-long metal bar driven by computer controlled stepping motors (Álvarez-Mozos, 2006). The metal bar, and, hence, the laser were manually aligned and levelled over each of the selected cross-sections. The cross-sections were chosen, wherever possible, devoid of vegetation, otherwise vegetation was gently removed avoiding any alteration of the soil surface. Based on a previous calibration in the lab, the precision of the height measurements (Z coordinate) is 0.5 mm (Álvarez-Mozos, 2006). The XY coordinates of each cross-section were determined by using the total station. It is because of this extremely high accuracy obtainable with the profilometer that the approach of comparing profile measurements of the gullies was chosen for this study, although, spatially, more continuous measurements of the complete form could have been achieved with photogrammetry. At Gully 1, the topographic survey was obtained by means of a total station as the extremely large width and depth of this gully prevented the use of the profilometer. Approximately 5 points/m² were taken in and around the gully and the cross-section profiles, separated 5-8 m, were then derived from a TIN (Triangular Irregular Network) constructed from these points. In sum, 4-6 detailed cross-section elevation profiles were obtained for each of the 5 gullies (24 in total; 4 transects were discarded owing to a malfunction of the ground equipment). These elevation profiles were considered as reference values.

In order to compare the measurement data obtained from the stereo photographs with the the field data (reference values), the same cross-section elevation profiles as those measured in the field were determined from the stereo-models using the stereo-digitizing facilities of LPS. In order to have identical spacings of Z values in each pair of elevation profiles for the error analysis, additional data points were later constructed by linear interpolation in the stereo-photograph dataset.

Data Analysis The accuracy of the photogrammetric measurements was analysed by comparing the 24 pairs of cross-section elevation profiles (PCSEP) resulting from the field survey and the aerial photographs, respectively. The deviation of the cross-section area per measurement interval E_z (m^2) between the reference Z value and the corresponding value obtained from the stereo photograph is quantified as follows:

$$E_z = \left| Z_{sp} - Z_{ref} \right| \Delta x \tag{1}$$

Z_{sp}: elevation data determined from the stereo photograph (m).
Z_{ref}: elevation data determined from the field survey (reference value) (m).
Δx: interval between each Z point along a cross section, equal to 0.005 m for Gully 2-5 while to 0.05 m for Gully 1.

It was evident that profiles of a given PCSEP were not evenly matched along the whole section (not shown). That is, in some portions along a PCSEP, the concordance between both elevation profiles was quite high whereas in other portions it was (much) lower. This resulted in a large dispersion of the E_z values of the different gullies. The strong variability in the E_z values of a given PCSEP caused *average* values of this variable to be rather meaningless. Therefore, instead, we have preferred to quantify the divergence between each PCSEP by a total error E_{zt} defined as the *addition* of all E_z values along the PCSEP or total area of cross-section deviation per PCSEP:

$$E_{zt} = \sum_{i=1}^{n} E_{zi} \tag{2}$$

where E_{zi} is the error determined at a point i along a particular PCSEP, and n is the total number of data points along the PCSEP. In order to calculate E_{zt} for the gully only, not incorporating the surrounding area, the starting and end point of each PCSEP, and, hence, the uppermost gully width, is visually determined from the elevation profile. The lowermost width is also visually defined.

Next, to allow further comparisons, E_{zt} is expressed as a percentage $E_{\%,}$ of the reference cross-section area determined from the raw profilometer (Gully 2-5)/total station (Gully 1) data A_{ref} of the PCSEP:

$$E_{\%} = \frac{E_{zt}}{A_{ref}} 100 \tag{3}$$

So far, we have quantified the measurement errors recorded in a particular PCSEP. Next, in order to calculate the measurement error for a whole gully, $E_{\%T}$ was determined as follows:

$$E_{\%T} = \frac{\sum_{i=1}^{n} E_{\%i}}{n} \tag{4}$$

where $E_{\%i}$ is the $E_{\%}$ error determined in the PCSEP$_i$ of an individual gully, while n is the total number of PCSEP belonging to this gully. $E_{\%T}$ thus expresses the percentage error of gully volume of misestimation of sediment loss for each gully.

RESULTS AND DISCUSSION

The main results for the error analysis of all gullies are given in Table 1. The field survey (apart from Gully 1) and photogrammetric determination, respectively, were identical for all the gullies, so their differences need to be explained with regard to their individual characteristics. Surprisingly, and despite a larger original sampling interval of heights along the cross-section profile, the absolute values of cross-section deviations E_{zt} are not highest for the largest (Gully 1), but for one of the smaller gullies (Gully 4), the latter also exhibiting the largest relative error $E_{\%T}$. At Gully 1, the total error is very small ($E_{\%T}$ = 6.6%) which was in fact expected because of the gully's size and the comparatively large scale of the aerial photograph. Even so, this accuracy is still very high considering that the bottom of Gully 1 contains several patches of dense vegetation, which hampered the view of the ground surface and, therefore, the photogrammetric determination. Although the other gullies are largely devoid of vegetation their measurement errors are much higher and some of the absolute cross-section deviations E_{zt} even exceed those of the much larger Gully 1. Taking into account their morphology characteristics, the total errors of the gullies given in Table 1 seem to vary with their overall shape, the measurement errors being larger for the narrower gullies.

Table 1 Photogrammetric measurement errors for the individual gullies and their corresponding cross-sections. [1] Eq. 2; [2] Eq. 3; [3] Eq. 4 (see text for explanation).

Gully/section	E_{zt}[1] (m^2)	$E_{\%}$[2] (percent)
G1/S1	1.2	4.8
G1/S2	0.8	3.3
G1/S3	1.6	6.5
G1/S4	3.1	11.8
$E_{\%T}$[3] (percent)	6.6	
G2/S1	0.02	27.82
G2/S2	0.01	31.27
G2/S3	0.02	26.37
G2/S4	0.01	27.13
G2/S5	0.01	28.22
G2/S6	0.02	31.47
$E_{\%T}$ (percent)	28.71	
G3/S1	0.02	17.04
G3/S2	0.02	14.54
G3/S3	0.03	14.07
G3/S4	0.03	21.24
G3/S5	0.03	20.99
G3/S6	0.03	17.06
$E_{\%T}$ (percent)	17.49	

G4/S1	0.23	49.70
G4/S2	0.20	42.96
G4/S4	0.13	37.18
G4/S5	0.28	81.33
$E_{\%T}$ (percent)	52.79	
G5/S1	0.08	18.44
G5/S4	0.05	13.16
G5/S5	0.08	19.59
G5/S6	0.09	23.17
$E_{\%T}$ (percent)	18.59	

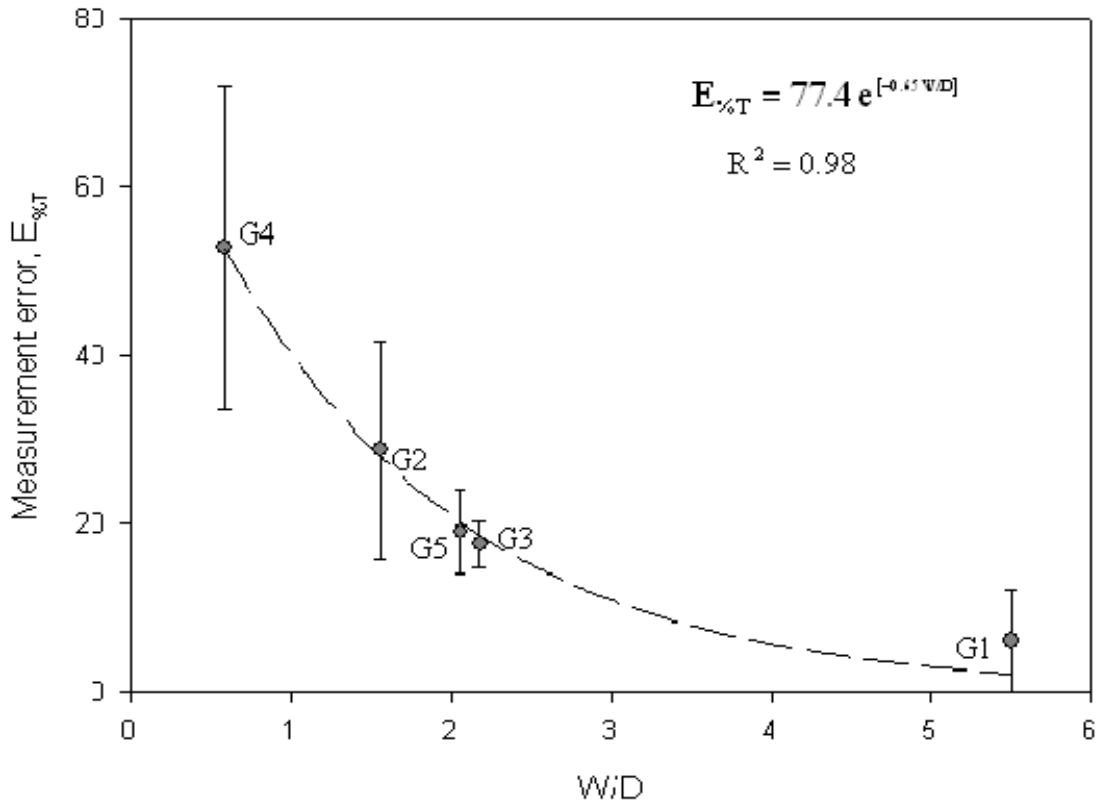

Figure 1 Overall measurement errors of the photogrammetrical assessment $E_{\%T}$ at the individual gullies as a function of the average gully width/depth ratio W/D.

If all the technical conditions (image resolution, photogrammetric orientation accuracy etc.) are the same for the gullies, the reason for this obvious importance of W/D ratio must be sought in its influence on the accuracy with which a heighting point can be placed onto the surface by the stereo-digitizing photogrammetrist; and a point cannot be placed correctly if the surface is not visible or its height not definable owing to a lack of contrast in the image. Both are the case where steep walls obstruct the view either by sight-shadowing or by sun-shadowing. The former is the case when the camera's focal point is not directly above the gully, i.e. the ray of reflected

light between gully bottom and image plane is not orthogonal; the latter is when the sunlight's angle of incidence is not orthogonal. When the sun is at its zenith (or the gully's longitudinal course happens to be aligned exactly with the angle of incidence), the sunrays cast (almost) no shadow at the side and bottom of a given gully. But when the sun is not directly above the gullies, the sunrays will cast shadow and penumbra at the side and bottom of the channel. This shadow hinders the visual interpretation (and thus the photogrammetric determination) of the surface of the gully bottom leading to (considerable) measurement errors. Moreover, a critical point for visual interpretation is reached when the shadow is long enough, and/or the channel narrow or deep enough, to completely cover the gully bottom. Likewise, the gully bottom will be partly or completely obstructed from view, when – depending on the angle of view within the camera's central perspective – the light reflected from the gully bottom cannot reach the lens because the gully wall is in the way.

Sight-shadowing can only be avoided if images exist where the gully is positioned in the image centre. Sun-shadowing is a function of the time and date of image acquisition. Considering that shadow length changes dramatically throughout the day/year depending on its location on the Earth (i.e., latitude and longitude), Fig. 2 was elaborated for the experimental site (42º16'30''N, 1º29'10''W) and for one of the dates of experimentation (October 12, 2007). To do this, Giesen's GeoAstro program (Giesen, 2008) was used. Fig. 2 illustrates the influence of the W/D ratio and time of day on the expected shadow. The inner area on Fig. 2, labelled *partial shadow*, defines the combinations of daytime/gully morphology for which the gully bottom is partially to completely illuminated by the sunlight. The maximal illumination (and hence smallest shadow) corresponds to the moment the sun is at its zenith. Similarly, the outer, critical area labelled *total shadow* marks the moment of the day when the gully bottoms are in total darkness.

Fig. 2 significantly adds to explaining the correlation of measurement error and gully morphology observed in Fig. 1. For a W/D ratio of 0.6 (corresponding to the gully with the largest measurement error; $E_{\%T}$ = 53% at Gully 4), Fig. 2 indicates total shadow at the gully bottom. Gullies 1, 3 and 5, which have the smallest errors and largest W/D ratios, are situated within the partial shadow zone in Fig. 2. Gully 2 being situated in the transition zone between total and partial shadow has accordingly a relative large measurement error.

The sun-shadowing problem could be largely avoided by choosing an overcast day with indirect lighting for the survey – a situation which is, if at all, only possible for low-altitude surveys and never occurs with conventional aerial photography. In order to assess the influence of the date of aerial surveys, the sun-elevation effect as depicted in Fig. 2 was recalculated for the days when the sun reaches its highest and lowest point in the sky at midday leading to the longest (summer solstice) and shortest (winter solstice) days, respectively (Fig. 3). The point of the minimum W/D ratio falling in the partial-shadow zone (W/D = 1.5 in Fig. 2) then moves to 0.5 for summer solstice and 2.5 for winter solstice (Fig. 3). Thus, regardless of the time of year, photogrammetric measurements of narrow/deep gullies (W/D < 0.5) will suffer from a high inaccuracy. By contrast, wide/shallow gullies (W/D > 2.5) may be appropriately illuminated for accurate photogrammetric measurements any time in the year providing an adequate daylight (that is, photographs must be taken at suitable times during the day). For gullies of intermediate typology (W/D between 0.5 and 2.5), the accuracy of photogrammetric measurements will greatly depend on the time of the year photographs are taken.

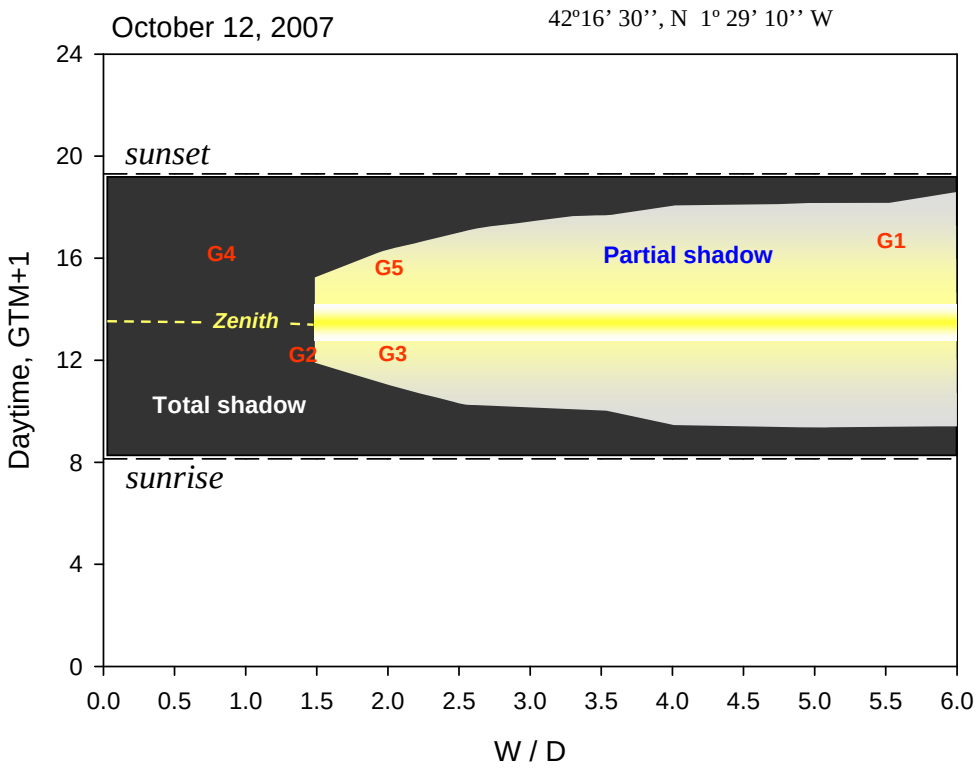

Figure 2 Different combinations of daytime and gully W/D ratio calculated for the experiment site and the date of the aerial survey experimentation, defining two contrasting situations: In the partial-shadow zone, the gully bottom is partially covered by shadow, in the total-shadow zone the gully bottom is totally covered by shadow. Time of image acquisition and W/D ratio for the five studied gullies is indicated by positions of labels G1–G5.

Concerning factors affecting gully morphology, narrow gullies such as Gully 4 are frequently formed when low-intensity, high-frequency rainstorms cause runoff to flow over a limited width in thalwegs, leading to a formation of a channel with a W/D ratio < 1 (Poesen and Govers, 1990). By contrast, intense rains of a short duration favour the formation of gullies with W/D ratio > 1 (Poesen and Govers, 1990). This is consistent with the findings of Casalí et al. (1999) from a large collection of ephemeral gullies in southern Navarre. These gullies, which were formed, or significantly reactivated, during one intense short-lasting winter rainfall, presented a W/D ratio of between 3 and 6. Even larger W/D ratios (approximately. 8) were found in a series of ephemeral gullies in central Mississippi (U.S.A.), whose formation was also related to intense rainfall events of a short duration (Casalí et al., 2000). As regards the type of soil, narrower channels tend to be formed in cohesive soil (Govers, 1992). In addition, flow incision can increase considerably (and hence give rise to small W/D ratios) if a non-resistant sublayer occurs in the soil profile, e.g., calcareous loess loam or loose sands (Poesen and Govers, 1990).

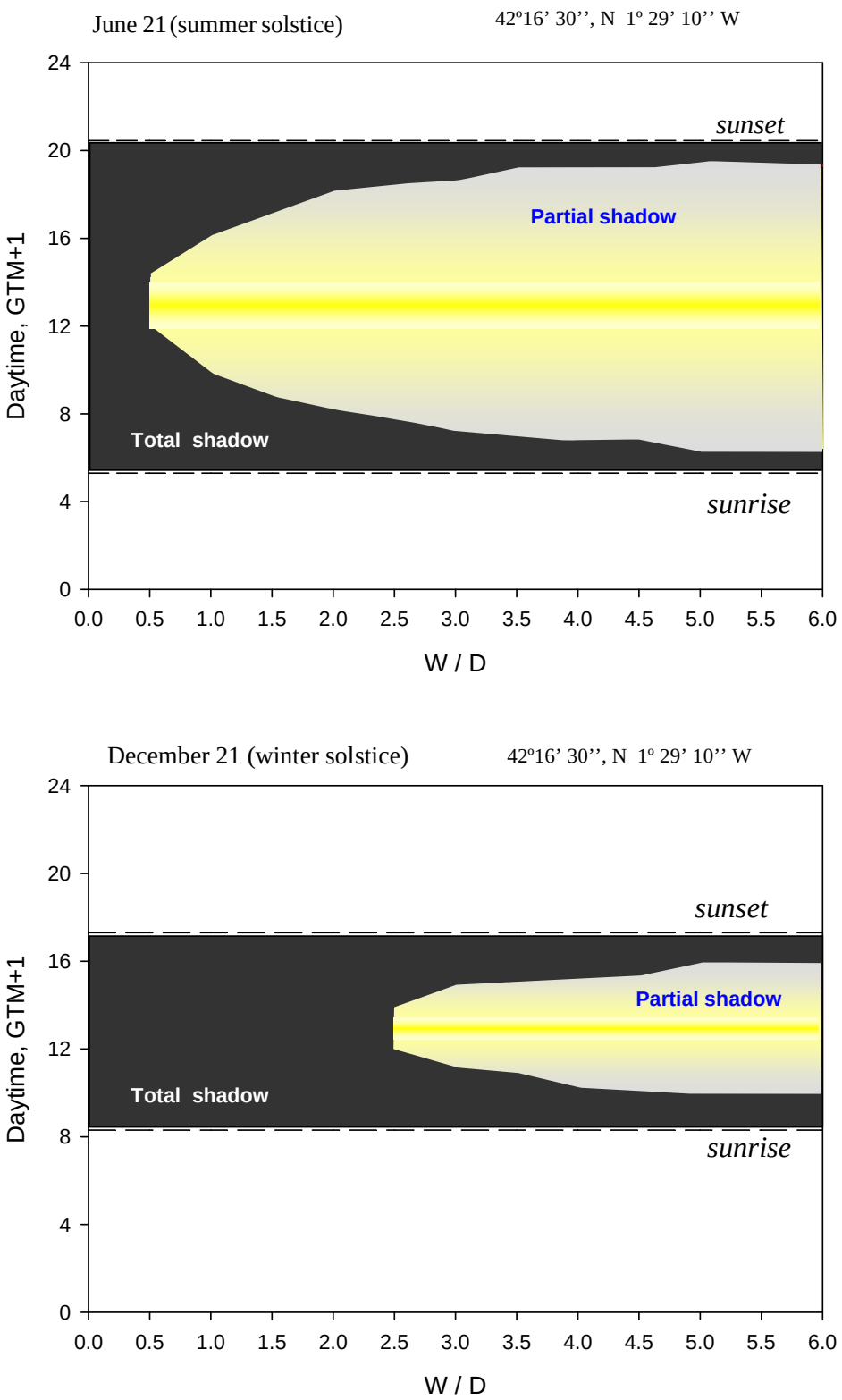

Figure 3 Equivalent to Figure 2, calculated for the extreme lighting conditions of A) summer and B) winter solstice.

CONCLUSIONS

Our findings clearly show that volumetric gully measurements by means of photogrammetric techniques are strongly affected by the gully morphology, particularly by its W/D ratio. The suitability of aerial photographs for stereoscopic analysis is to some extent spoiled by shadows cast over the inner surface of the gullies. This undesirable shadow will depend, on the one hand, on the sunrays' obliquity; on the other, the length of the shadows is a function of the W/D ratio of the channel. Consequently, there are suitable and unsuitable hours during the day, and months throughout the year, to successfully carry out photogrammetric analysis of gullies of different typology. However, the interior of very narrow/deep gullies (W/D < 1) will be totally shadowed anytime during the day and year. Therefore, accurate measurements of this type of gully are extremely unlikely to be obtained by photogrammetry. On the contrary, photogrammetric determination of wide gullies (W/D >4-5) will not cause any significant problems as regards shadows. Photogrammetry appears to also be a reliable technique to measure relative wide ephemeral gullies (W/D >1-2) providing, apart from an adequate sunlight, a good visualisation of the ground surface; that is, their vegetation cover must be negligible. Similarly, the W/D ratio of the channel strongly influences the visibility of the gully interior owing to increasing sight-shadowing with the increasing distance of the gully's image from the airphoto centre.

Whereas this study was carried out using a low-altitude platform and small-format aerial photography – the only option for small gullies in the typical magnitude of ephemeral channels – the results suggest implications for the analysis of larger (permanent) gullies and channels using conventional medium and small-scale aerial photography. The W/D ratios judged to be challenging ones for photogrammetric analysis in this study are also common for larger-sized gullies of the bank gully type.

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