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1 **From experimental plots to experimental landscapes: topography, erosion and**
2 **deposition in sub-humid badlands from Structure-from-Motion photogrammetry**

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10
11 **Abstract**

12
13 In the last decade advances in surveying technology have opened up the possibility of
14 representing topography and monitoring surface changes over experimental plots (<10 m²) in high
15 resolution (~10³ points m⁻¹). Yet the representativeness of these small plots is limited. With
16 ‘Structure-from-Motion’ (SfM) and ‘Multi-View Stereo’ (MVS) techniques now becoming part of the
17 geomorphologist’s toolkit, there is potential to expand further the scale at which we characterise
18 topography and monitor geomorphic change morphometrically. Moving beyond previous plot-scale
19 work using Terrestrial Laser Scanning (TLS) surveys, this paper validates robustly a number of
20 SfM-MVS surveys against total station and extensive TLS data at three nested scales: plots (<30
21 m²) within a small catchment (4710 m²) within an eroding marl badland landscape (~1 km²). SfM
22 surveys from a number of platforms are evaluated based on: (i) topography; (ii) sub-grid
23 roughness; (iii) change-detection capabilities at an annual scale. Oblique ground-based images
24 can provide a high-quality surface equivalent to TLS at the plot scale, but become unreliable over
25 larger areas of complex terrain. Degradation of surface quality with range is observed clearly for
26 SfM models derived from aerial imagery. The modelling findings of James and Robson (2014) are
27 proven empirically as a piloted gyrocopter survey at 50 m altitude with convergent off-nadir
28 imagery provided higher quality data than an UAV flying at the same height and collecting vertical

29 imagery. For soil erosion monitoring, SfM can provide comparable data to TLS only from small
30 survey ranges (~ 5 m) and is best limited to survey ranges of ~10-20 m. Synthesis of these results
31 with existing validation studies shows a clear degradation of root-mean squared error (RMSE) with
32 survey range, with a median ratio between RMSE and survey range of 1:639, and highlights the
33 effect of the validation method (e.g. point-cloud or raster-based) on the estimated quality.

34

35 **Keywords:** badlands; terrestrial laser scanning (TLS); Structure from Motion (SfM); topographic
36 survey; sediment budget.

37

38 **1. Rationale**

39

40 Badlands can be described as well-dissected areas of unconsolidated sediment with sparse or
41 absent vegetation that are unable to support agriculture (i.e. Bryan and Yair, 1982). These highly
42 erodible landscapes make disproportionate contributions to catchment scale sediment budgets
43 (e.g. García-Ruiz et al., 2008; López-Tarazón et al., 2012), control downstream processes in river-
44 channels (e.g. Buendía et al., 2013) and, ultimately, can cause negative consequences to
45 downstream infrastructure (e.g. reservoir siltation; Avendaño et al., 2000). Erosion risk maps and
46 models (e.g. PESERA; Kirkby et al., 2004) can provide a broad-scale assessment of soil erosion
47 rates, but any such models require calibration and validation using observed soil erosion rates
48 under different environments (e.g. climatic conditions) and over representative (large) spatial
49 scales (e.g. catchment scale). New techniques of topographic data acquisition have the potential to
50 deliver this data. This study validates topographic data derived from Structure from Motion
51 photogrammetry at three nested scales to assess the scale at which it can be applied in studies of
52 soil erosion.

53

54 **1.1. Measuring erosion in dynamic landscapes**

55

56 A number of different methods of measuring and monitoring erosion exist. Erosion pins are used
57 commonly to measure the erosion and deposition directly through observed changes in surface
58 level at a given point (e.g. Clarke and Rendell, 2006; Della Seta et al., 2009; Francke, 2009).
59 Despite the observed spatial variability in badland erosion rates (e.g. Kuhn and Yair, 2004; Solé-
60 Benet et al., 1997), the point measurements are typically interpolated, but only over relatively small
61 areas. Over similar-sized areas (up to ~10 m downslope length), bounded plots with sediment
62 collectors catch exported sediment directly (e.g. Lázaro et al., 2008). Again, extrapolation of such
63 plots is problematic (see Boardman, 2006; Boix-Fayos et al., 2006), collectors can fill up rapidly in
64 highly erodible landscapes (Vericat et al., 2014), and data integrate all upslope processes at a
65 single point. Sediment flux is often measured at gauging stations through continuous turbidity
66 records (e.g. Cantón et al., 2001; Mathys et al., 2003) and at larger spatial and temporal scales
67 still, repeat bathymetric surveys of reservoirs or check dams can provide estimates of sediment
68 yield (e.g. de Vente et al., 2005; Batalla and Vericat, 2011). This indirect morphometric approach
69 can also be applied to eroding surfaces at multiple spatial and temporal scales. Repeat
70 topographic surveys have been used to measure soil loss volumes both at plot scales using
71 microprofile meters (e.g. Descroix and Claude, 2002; Sirvent et al., 1997) and at large scales using
72 Terrestrial Laser Scanning (TLS) (e.g. Vericat et al., 2014) or even larger by means of aerial
73 photogrammetry (e.g. Ciccacci et al., 2008).

74

75 Each technique has different strengths and weaknesses, and each one may measure the result of
76 different processes. Discrepancies between these methods have been noted previously (Poesen
77 and Hooke, 1997). Nadal-Romero et al. (2011, 2014) compile sediment yield measurements over
78 87 study sites of eroding Mediterranean badlands and found statistically significant differences in
79 sediment yield measurements obtained from different methods. Yet since no single method covers
80 all spatial scales it is possible that the reported differences in sediment yield between methods
81 actually reflect the different processes that operate at different catchment sizes. At larger scales,
82 footslopes and concavities and other sediment sinks become incorporated into the study area.
83 Sediment connectivity becomes an important factor as the entire range of catchment processes is
84 studied rather than just interrill erosion (Faulkner, 2008; Godfrey et al., 2008; Bracken et al., 2014).

85

86 Clarification of such scale dependencies requires the application of a single method of monitoring
87 erosion over a wide range of spatial and temporal scales. A substantial advantage of the
88 morphometric method (i.e. comparing topographic models obtained at different periods) is that sub-
89 catchments, discrete areas, or even single grid cells of a large study area can be isolated and
90 examined at no extra field cost. Airborne LiDAR has been already applied to examine the
91 topographic structure of badland areas (Bretar et al., 2009; Lopez-Saez et al., 2011; Thommeret et
92 al., 2010), while Vericat et al. (2014) recently presented the use of TLS to produce a fully
93 distributed morphometric sediment budget of a small (36 m²) eroding badland area.

94

95 The challenge of using topographic survey techniques for erosion monitoring is to design and apply
96 a methodology that provides meaningful and high-quality data over a range of spatial scales.
97 Structure-from-Motion with Multi-View Stereo (SfM-MVS) offers a potential solution to the problem
98 of acquiring such high resolution topographic data over a wide range of scales; however, validation
99 of this technique at multiple scales is in its infancy.

100

101 **1.2. Validation of Structure-from-Motion**

102

103 Using a number of standard camera images of a single scene, Structure-from-Motion (SfM) can
104 reconstruct simultaneously camera pose, scene geometry and internal camera parameters. Full
105 details of different steps of the SfM-MVS workflow can be found in Lowe (2004), Snavely et al.
106 (2008), Furukawa and Ponce, (2010) and James and Robson (2012). In short, features in each
107 image are identified and matched. A bundle adjustment algorithm is used to produce jointly optimal
108 estimates of 3D structure and viewing parameters (Triggs et al., 2000). This SfM sparse point
109 cloud has been used as an end point in itself (e.g. Fonstad et al., 2013). However, SfM is often
110 paired with multi-view stereo (MVS) which use the known camera locations to reconstruct a denser
111 point cloud (see Furukawa and Ponce, 2010). Finally, the resultant dense point cloud must be
112 given a scale and georeferenced using ground control points visible in images or point clouds. All

113 SfM-derived data products herein are technically SfM-MVS data, though, following the emerging
114 convention, simply 'SfM' is also used as shorthand.

115

116 In combination, SfM-MVS provides high-resolution topographic data which, in recent years, has
117 been applied and tested in a range of geomorphological settings including volcanic bomb hand
118 samples (e.g. James and Robson, 2012), agricultural fields (e.g. Ouédraogo et al., 2014; Eltner et
119 al., 2014), eroded gullies (e.g. Castillo et al., 2012; Frankl et al., 2015), exposed bars of braided
120 rivers (e.g. Javernick et al., 2014), high water marks of recently flooded ephemeral rivers (e.g.
121 Smith et al., 2014), submerged gravel bed rivers (e.g. Woodget et al., 2014), eroding cliffs (e.g.
122 James and Quinton, 2013), alluvial fans (e.g. Micheletti et al., 2014), lava flows (e.g. Tuffen et al.,
123 2013), glacial moraines (e.g. Westoby et al., 2012; Tonkin et al., 2014), landslide displacements
124 (e.g. Lucieer et al., 2013), and volcanic craters (e.g. James and Varley, 2012).

125

126 Sub-grid data products extracted from point clouds are utilised increasingly in geomorphology (see
127 Smith, 2014 for a review). Moreover, topographic change detection protocols, as described by
128 Wheaton et al. (2010), utilise sub-grid roughness as an error term to determine the minimum level
129 of detection of topographic changes estimated by differencing digital elevation models (DEMs)
130 obtained at different periods. Thus, a thorough validation of the capability of SfM-MVS surveys to
131 replace existing survey methods requires a detailed analysis of the precision of this approach at
132 the scale required for a particular application.

133

134 Errors in SfM-MVS surveys are related to a number of factors, including the camera used
135 (Micheletti et al., 2014), number and resolution of images acquired, distribution of perspectives in
136 those images (James and Robson, 2014), processing software (particularly the number of
137 parameters used in the camera model; James and Robson, 2012; Ouédraogo et al., 2014) and the
138 distribution and quality of ground control points used for georeferencing (James and Robson,
139 2012). However, although the source of error is variable, it appears that the range at which the
140 pictures are acquired is a particularly important factor in determining the resultant errors, with sub-
141 m range surveys (i.e. $<10^0$ mm/pixel photography) exhibiting sub-mm errors and km-range surveys

142 (i.e. $> 10^1$ mm/pixel) exhibiting m-scale errors. Clearly, the survey range achievable logistically is
143 controlled by the spatial coverage of the surveys.

144

145 Overall, SfM has substantial potential to revolutionise the acquisition and accessibility of high
146 resolution topographic data, potentially permitting the study of erosion rates over a range of spatial
147 scales with a single technique. With a nested survey design and three scales of enquiry, ranging
148 from experimental plots to experimental landscapes, this paper makes a substantial contribution to
149 the validation of this approach. The aim of this study is to provide a detailed examination of the
150 ability of SfM-MVS to represent topography and roughness and to detect reliably small topographic
151 changes in a complex badland setting. To achieve this, the most extensive and detailed repeat
152 TLS survey of an eroding badland conducted to date is used as a reference dataset.

153

154 Four specific objectives achieve this aim:

- 155 (1) To provide a robust validation of the capability of SfM-MVS as a high resolution topographic
156 survey technique through quantitative analysis of standard derived topographic data
157 products including (a) topography (DEMs); (b) sub-grid surface roughness; and (c)
158 distributed topographic changes (erosion and deposition, i.e. sediment budgets);
- 159 (2) To examine the effect of survey range and extent on the results of (1);
- 160 (3) To examine the effect of the type of validation dataset on the results of (1);
- 161 (4) To integrate these findings with those of existing SfM-MVS validation studies to elucidate
162 the scale-effects limiting the accuracy of SfM-MVS surveys.

163

164 The paper is structured as follows: the experimental badland is described in section 2. Field data
165 collection is described in section 3.1. The post-processing steps are then described in section 3.2.
166 Validation of topography is presented both for point-based total station data (section 4.2) and TLS-
167 based DEMs (section 4.3). The latter is then used as a benchmark dataset against which to test
168 the ability of SfM-MVS to represent sub-grid roughness (section 4.4) and topographic change
169 (section 4.5). Finally, a synthesis of these results with those of recent SfM-MVS validation studies
170 is presented in section 5.

171

172 **2. Study Area**

173

174 Eroding badlands provide an appropriate location validation of a topographic survey technique due
175 to the complexity of their surfaces (e.g. slopes, aspect, dissection) and the variability of surface
176 deformation rates (e.g. rill formation, head-cutting, deposition). A series of highly erodible badlands
177 located at the Upper River Cinca (Central Pyrenees, Iberian Peninsula, Ebro Basin) were chosen
178 for this study (Figure 1). The badlands are located at an average altitude of 600 m.a.s.l. and the
179 local relief can be more than 15 m. The site has a Continental climate with an annual rainfall
180 around 700 mm. Maximum rainfall is observed during spring and autumn. The average
181 temperature is 11 °C. Temperatures below freezing are often registered in winter when freeze-thaw
182 is a fundamental process controlling the erosion and transfer of sediment.

183

184 The selected badlands present steep slopes (near vertical in places) and a high degree of
185 dissection. The presence of vegetation is limited: isolated shrubs are observed in gentle slopes
186 while boxwoods and relatively young pines are present on low gradient upper surfaces (Figure 1C).
187 The badlands are composed of highly erodible Eocene marls and sandstones. A sequence of
188 marls with different degree of compactness is observed. Therefore, erosional processes are
189 hypothesized to be highly complex and spatially variable. The study is focused in three embedded
190 scales as can be seen in Figure 1: (i) plots (5 in total and between 8 and 30 m²) located within (ii) a
191 small catchment (4710 m²) (Figure 1C) which in turn is located within (iii) a larger landscape-scale
192 (~1 km²; Figure 1B).

193

194 The study landscape is rapidly eroding relative to other hillslopes in the area; however, the
195 magnitude of the topographic change observed is small in comparison with that reported in gravel
196 bed rivers or in areas subjected to landslides, for which morphometric sediment budgets are
197 typically calculated. Therefore, the relatively low magnitude of the surface change represents a
198 deliberately challenging test for SfM-MVS.

199

200 **3. Methods**

201

202 **3.1. Field Data Collection**

203

204 Two field campaigns were undertaken with an 11 month survey interval. The first survey took place
205 over the 27th and 28th June 2013. The second took place over the 27th and 28th May 2014. A
206 summary of the main methods used at each scale of enquiry is provided in Table 1. Two main data
207 sets were obtained: (a) a series of photographs to derive point clouds by means of SfM; and (b) a
208 series of validation data sets based on Terrestrial Laser Scanning and Total Station (TS) surveys.
209 Details of the methods applied to obtain the data are provided in the following sections.

210

211 *3.1.1. SfM-MVS image acquisition*

212

213 To quantify robustly the typical errors observed with SfM, a number of separate image sets were
214 acquired from different platforms and at different altitudes (Table 1). A number of sources of error
215 can be identified for SfM-MVS including the number of images used and their overlap, errors
216 associated with processing (software and algorithms), imaging geometry, the characteristics of the
217 camera used and the quality of the lens model. However, the focus herein is on the effect of survey
218 range (i.e. altitude from where the pictures are taken); a fundamental issue for assessing the
219 broader applicability of SfM in geomorphology since it determines indirectly the maximum
220 capability of survey coverage and data resolution (i.e. closer-range images cover smaller areas for
221 a given camera). The errors associated with range will determine the appropriate scales at which
222 SfM can be deployed to investigate scale-dependent processes and, consequently, address
223 geomorphological questions.

224

225 In 2013 two sets of ~350 images were taken (Table 1) at the small-catchment scale (Figure 1C).
226 The first was ground-based, utilising only oblique photographs taken from around the perimeter

227 and hillcrests of the badland. Ground-based surveys are referred to as 'Oblique' surveys in the
228 results. A Panasonic DMC-TZ65 (focal length 4 mm which is a 35-mm equivalent of 25 mm; 10
229 Mpx) was used in this campaign. The second sequence of pictures was taken aerially from a UAV;
230 a remote controlled hexacopter DJI F550. In this case, a Ricoh CX5 (focal length 5 mm which is a
231 35-mm equivalent of 28 mm; 10 Mpx) camera was suspended from underneath the UAV with a
232 vertical viewing angle. These two cameras are very similar; the key difference was that the Ricoh
233 camera had an intervalometer. The mean flying height was 47 m above ground. The camera was
234 set up to take a picture every 5 seconds (interval timer, auto shooting). This survey is referred to as
235 the 'UAV' survey in the results.

236

237 In 2014 a different set of images was obtained for each of the three study scales: plot, small-
238 catchment and landscape. Five plots were imaged from the ground at around 5 m range (between
239 25 and 33 oblique images taken by hand). The same Panasonic DMC-TZ65 was used for this
240 image set. Four independent sets of images were obtained at the small catchment scale (Table 1).
241 First, the oblique survey of 2013 was repeated taking imagery along exactly the same route and
242 using the same camera as in 2013. In addition, three aerial surveys were conducted at different
243 altitudes. Images were taken from on-board a piloted AutoGiro (or gyrocopter). Off-vertical images
244 were taken to avoid the doming effect described in James and Robson (2014). Flight paths were a
245 sequence of parallel flight strips (previously designed based on flight altitude and camera
246 specifications) spaced ~70 m apart, with ~3 additional perpendicular strips added to maximise the
247 coverage and overlap between pictures. Images in a flight strip were ~ 10 m apart. Target flying
248 heights of 50 m, 150 m and 250 m were designed for the three surveys; however, owing to the
249 topographic variability of the ground, each survey contained a range of viewing heights. Final mean
250 flying heights were 70 m (SD = 16 m), 170 m (SD = 25 m) and 270 m (SD = 19 m) respectively.
251 Finally, to obtain the images required for the landscape scale study, the two AutoGiro flights at 150
252 m and 250 m above the ground were extended to cover an area of around 1 km x 1 km (Figure
253 1B). The 50 m altitude AG survey resulted in 149 images of the small catchment while the 150 m
254 and 250 m altitude AG surveys of the 1 km² area resulted in 527 and 138 images respectively.
255 With the camera operator taking images manually, a heavier camera could be used than from the

256 UAV; however, previous camera intercomparison experiments (Thoeni et al., 2014; Micheletti et
257 al., 2014) show little difference between compact cameras and DSLRs. All images taken from the
258 AutoGiro were obtained by means of a Nikon D310 SLR (focal length 55 mm which is a 35-mm
259 equivalent of 25 mm; 14 Mpx). The improved image resolution of the Nikon was considered
260 necessary to support the 250 m altitude surveys and locate GCPs. These surveys are referred to
261 as 'AutoGiro' (AG) surveys in the results and the altitude of each is also stated to distinguish the
262 data sets (e.g. AG 250 m).

263

264 A primary control network based on 4 benchmarks was established. Coordinates were obtained by
265 means of a Leica Viva GS15 GNSS base station and post-processed using Rinex data from 5
266 stations of the Spanish National Geographic Institute (IGN) and the Spatial Data Infrastructure of
267 Aragon (SITAR). The data quality of the coordinates of the benchmarks (3d quality) was, on
268 average, 0.006 m, with a standard deviation of 0.0017 m. This primary network was used to
269 register all surveys conducted in 2013 and 2014 to the same coordinate system.

270

271 Three different secondary networks of Ground Control Points (GCPs) were set up in relation to the
272 scale of the study. Five 200 x 200 mm red targets with a central 50-mm diameter disk-mark were
273 used for the plot scale and surveyed by means of a Total Station (TS). For the small-catchment
274 scale, in both 2013 and 2014, a network of 30 GCPs was surveyed with a Leica Viva GS15 RTK-
275 GPS. In this case, black 1 m x 1 m targets with a yellow cross were laid in a grid over the full
276 catchment, similar to those used by Vericat et al. (2009) and Westoby et al. (2012). A local GPS
277 base was set up at one of the benchmarks transmitting corrections to the RTK-Rover system.
278 Small catchment GCPs were surveyed with 3d qualities between 0.009 and 0.014 m. Finally, at the
279 landscape scale, the 200 x 200 mm red targets were used. The size and colour of the targets were
280 chosen based on an experiment to determine the minimum target size that could be resolved using
281 the Nikon D3100 camera from 250 m above the ground. A total of 80 GCPs were placed
282 throughout the 1 km² badland area and surveyed with a Leica Viva GS15 RTK-GPS (3d qualities <
283 0.05 m).

284

285 *3.1.2. Validation Datasets*

286

287 Validation datasets were based on TLS and TS topographic surveys. A Leica ScanStation C10
288 TLS was used to provide high resolution topographic data across the field site in both 2013 and
289 2014. The C10 uses a 532-nm pulsed laser with stated precisions of 6 mm for position, 4 mm for
290 distance, and 60 μ rad for angles (one standard deviation; Leica Geosystems, 2011). The
291 maximum data acquisition rate is 50000 points per second while the maximum survey range is 300
292 m. Although the reported minimum point spacing is < 1 mm, the laser point spread function is 4
293 mm over a range of up to 50 m. The small catchment area was surveyed from 12 different stations
294 to minimise and eliminate gaps caused by occlusion. For consistency, survey markers were placed
295 at each station to ensure that the same locations were used for the TLS surveys in each year.
296 Plots were also surveyed and were positioned close to TLS stations. A target-based registration
297 was performed using a floating network of tripod-mounted Leica targets (i.e. 6" circular tilt and turn
298 blue/white targets). This floating network was registered using the primary control network
299 described above. The coordinates of the targets were obtained by means of a reflectorless Leica
300 TPS1200 Total Station. All TS surveys were performed by averaging 10 consecutive
301 measurements with standard deviations always < 0.004 mm. The mean absolute scan registration
302 errors were 3 mm and 2 mm in 2013 and 2014 respectively. All topographic data were
303 georeferenced to a geographic coordinate system (ED50 UTM31N) using the primary control
304 network.

305

306 The 2014 TLS dataset is used to validate SfM-MVS surveys, conducted concurrently. In addition,
307 as an independent dataset to provide an additional validation, 515 points within the small
308 catchment and 215 across the landscape-scale area were also surveyed with the reflectorless TS.
309 Errors on the TS surveys were in the sub-centimetre range.

310

311 *3.1.3. Validation metrics*

312

313 Differences between SfM-derived topographic data and the validation datasets were investigated
314 using the following metrics: (i) mean error (ME); (ii) mean absolute error (MAE); (iii) root mean
315 squared error (RMSE); and (iv) standard deviation of error (SD).

316

317 **3.2. Post-Processing**

318

319 *3.2.1. Obtaining SfM and TLS-based point clouds*

320

321 Photographs were inspected manually and any blurred images were deleted. The remaining
322 photographs were imported into Agisoft Photoscan Professional 1.0.4. This software package
323 identifies keypoints using an algorithm based on the Scale Invariant Feature Transform (SIFT)
324 object recognition system outlined in Lowe (2004). Once the SfM process was complete, estimated
325 camera positions were inspected for misalignment and any misaligned images were removed.
326 Such images typically resulted from insufficient overlap with other photographs, from objects that
327 were not static during the image acquisition (e.g. vegetation, moving shadows), or from
328 approximations in the keypoint matching process. GCPs were then identified in the image set and
329 their GPS coordinates were imported. A linear similarity transformation was performed to scale and
330 georeference the point clouds and the transformation was then optimised; a process where camera
331 parameters and 3D points are adjusted to minimize the sum of the reprojection error and the
332 georeferencing error (Agisoft, 2012; Javernick et al., 2014). A MVS dense reconstruction was then
333 performed to produce the final SfM-MVS point clouds.

334

335 TLS point clouds obtained from the 12 stations were registered using Leica Cyclone 8.0. Both TLS
336 and SfM point clouds were cropped to include only the area of interest. Specifically, at the plot
337 scale, surveyed areas were limited to mostly bare soil, but any small shrubs were removed
338 manually. At the small catchment scale, large trees and shrubs were also removed from the point
339 clouds manually. In addition, a mosaicked orthophoto of the small catchment was derived from the
340 AutoGiro flight at 50 m altitude. This orthophoto was extracted by means of Agisoft Photoscan
341 Professional 1.0.4 after scaling and georeferencing. From this orthophoto (Figure 1C), polygons

342 were defined manually to mask out areas of vegetation which were excluded from analysis. At the
343 landscape scale, no such data cleaning took place as the TS validation was limited to bare areas
344 and, consequently, was unaffected by vegetation.

345 346 *3.2.2. Extracting ground surface and sub-grid topographic statistics*

347
348 The open-source topographic point cloud analysis toolkit (ToPCAT) was used to unify point
349 densities, extract ground-elevations and, consequently create DEMs from georeferenced 3d point
350 clouds. Brasington et al. (2012) and Rychkov et al. (2012) give a full description of this intelligent
351 decimation method and provide several examples of its application. While developed originally for
352 use with TLS data, it has been used with SfM-MVS datasets previously (Javernick et al., 2014;
353 Smith et al., 2014). ToPCAT was run to extract sub-grid topographic statistics at a 0.1 x 0.1 m
354 resolution in case of the plot and small catchment scales. Several statistics (mean elevation,
355 minimum elevation, maximum elevation, etc.) of the point clouds were obtained within each 0.1 x
356 0.1 m grid cell. Owing to the large area under investigation, the landscape-scale point clouds were
357 post-processed at 1 x 1 m resolution. In each case, the mean elevation of each grid cell was used
358 to generate a DEM.

359
360 Additional sub-grid scale statistics were also calculated using ToPCAT. For each cell, a
361 neighbourhood triangular tessellation based on mean elevation in each cell was used to construct
362 the local surface and detrend all points within the central grid cell (see Brasington et al., 2012). The
363 detrended standard deviation of elevations σ_d was then calculated in each cell. Given the
364 proliferation of use of σ_d as a roughness metric across the Earth Sciences (Smith, 2014), σ_d is an
365 appropriate choice of roughness metric for this study.

366 367 *3.2.3. Comparing DEMs and assessing a minimum Level of Detection (minLoD)*

368
369 DEMs of the small-catchment were compared to investigate erosion and sedimentation patterns,
370 and assess the net topographic change during the 11 months between surveys (as a proxy of the

371 sediment yield). Three independent estimates were calculated: (i) differencing TLS-based 2013
372 and 2014 DEMs; (ii) differencing oblique, ground-based SfM DEMs from 2013 and 2014; and (iii)
373 differencing SfM-based DEMs from the lowest aerial surveys (50 m flying altitude, see Table 1). To
374 calculate topographic changes between the two survey periods the old DEM was subtracted from
375 the new DEM to create a DEM of Difference (DoD) where negative values indicate a lowering of
376 topography (erosion) and positive values represent sedimentation. The significance of these
377 changes will be controlled by the errors and topographic uncertainties in each DEM. In the case of
378 this study, following the approach described by Brasington et al. (2000), a threshold minimum level
379 of detection was applied to distinguish between real topographic change and artefacts arising from
380 errors/uncertainties in the two DEMs (see also the more recent studies of Brasington et al., 2003;
381 Wheaton et al., 2010; Vericat et al., 2014). The minimum level of detection for real topographic
382 change (i.e. minLoD), was calculated as:

383

$$\text{minLoD} = t[\varepsilon_{DEM1}^2 + \varepsilon_{DEM2}^2]^{0.5}$$

384

385 where t is the critical t value for a given confidence interval and ε_{DEMi} the errors associated to the
386 new ($i = 1$) and old ($i = 2$) DEMs. Using the 90% confidence interval, $t = 1.65$. For each DEM the
387 sub-grid roughness value σ_d was applied to represent ε_{DEMi} as the sub-grid topographic variability
388 in the point cloud may be the largest source of uncertainty in the ground estimate. This technique
389 yields a spatially distributed threshold minimum level of detection based upon local topographic
390 roughness where small changes can be resolved more reliably on smooth surfaces than rough
391 surfaces. Observed changes below the minLoD were filtered out of each DoD and considered
392 unreliable.

393

394 **4. Results**

395

396 Results are divided into 5 sections: section 4.1 outlines the errors involved in registering and
397 georeferencing TLS and SfM-based datasets. Validation of both 2014 TLS and SfM-derived

398 topographic models (DEMs) with point-based measurements acquired through a TS survey is
399 presented in section 4.2. The TS point measurements are considered to represent the true ground
400 elevation. The validation is performed for the 2014 datasets over the three study scales to assess
401 the role of survey range on survey quality. In section 4.3, TLS and SfM-based DEMs obtained in
402 2014 are compared at plot and small-catchment scales. In this case the TLS model is considered
403 to represent the true ground surface estimate. The sub-grid scale topographic variability (i.e.
404 roughness) of TLS and each SfM-based point cloud obtained for the 2014 datasets at the plot and
405 small-catchment scales are compared in section 4.4. Finally, a demonstration of the change
406 detection capabilities of TLS and SfM at the small-catchment scale is presented in section 4.5
407 through differencing of the DEMs obtained in each year.

408

409 *4.1. Registration and georeferencing of point clouds*

410

411 In both 2013 and 2014, a total of 12 TLS scans were merged to create the full topographic model
412 at the small catchment scale using a target-based registration as explained above. Average
413 registration errors were 3 mm (2013) and 2 mm (2014) (Table 2). The georeferencing error of the
414 targets was < 2.2 mm. Both TLS point clouds contained over 300 Mn points resulting in an average
415 point density of >6.7 points per cm².

416

417 SfM surveys at the small-catchment scale typically employed around 20 GCPs. Reported 3d errors
418 range from 0.06 m to 0.21 m. The relatively high errors reported in the oblique (i.e. ground-based)
419 2014 survey reflect poor matches in the upper catchment, which was excluded from analysis owing
420 to a low point density and presence of unreliable mismatched imagery. Excluding GCPs from the
421 upper catchment reduces this error to 0.109 m. Relatively high georeferencing errors were also
422 reported in the higher altitude AutoGiro (AG) surveys; however, for these surveys additional targets
423 distributed over the 1 km² landscape-scale were used for georeferencing. Using only GCPs over
424 the catchment-scale reduces this 3d error. At the plot scale, much lower 3d errors were reported.
425 In this case 5 targets were used to georeference each plot survey with one target in each vertex of

426 the plot and one extra GCP for redundancy. Such a perimeter-distribution was one of the optimal
427 distributions observed by Vericat et al. (2009) when georeferencing aerial imagery.

428

429 The ability to georeference such surveys accurately is a fundamental aspect of an examination of
430 SfM to produce reliable change detection estimates; however, it has the potential to affect greatly
431 the comparison of topographic models in section 4.5 (see Micheletti et al., 2014). As such,
432 topographic data products were produced for each survey to check for any systematic
433 misalignment against the TLS datasets that would dominate results. Aspect and flow accumulation
434 rasters were compared and no systematic georeferencing problems were observed (with a 0.1 m
435 grid size).

436

437 4.2. *SfM and TLS validation based on Total Station Surveys*

438

439 External validation of both TLS and SfM-based surveys obtained in 2014 is provided by 515 TS
440 survey points within the small-catchment, and an additional 215 points distributed over the
441 landscape scale area. The plot scale SfM surveys (gridded at 0.1 x 0.1 m) were validated against
442 TS point-based surveys (Table 3). No TS validation points were located within Plot 5. Plot-scale
443 MAE values were in some cases an order of magnitude lower than those observed for the results
444 from the aerial surveys (i.e. AG) and in all but one case, lower than the reported errors for the TLS
445 survey (Table 2). This close fit is also reflected in the RMSE values (see Table 3; Figure 3A).

446

447 The distributions of errors for each small-catchment scale survey are displayed in Figure 2 and the
448 errors for all surveys at each scale are summarised in Table 3 and Figure 3A. At the small
449 catchment scale, the MAE between the gridded TLS DEM and the TS survey points was 0.03 m. In
450 comparison, the reported MAE for the SfM surveys increased with survey altitude ranging from
451 0.07 m (AG50 m) to 0.18 m (AG250 m). The oblique survey demonstrated a higher MAE than the
452 lowest aerial survey with a large number of points surveyed as being considerably lower than the
453 validation dataset (Figure3A). From visual inspection of the oblique SfM DEM, a patch where

454 images were matched incorrectly can be observed (also seen in Figure 4A). Other error metrics
455 follow a similar pattern (Table 3).

456

457 Finally, the 1 m resolution AG150 m and AG250 m landscape-scale DEMs were validated against
458 all 730 TS survey observations. Errors are increased substantially; while this increase may reflect
459 greater unreliability of the SfM surveys outside of the small catchment, it also reflects the greater
460 grid size used to produce the DEM. This issue is discussed further in section 5, and highlights the
461 need for a robust validation of SfM surveys against co-incident TLS-derived point clouds.

462

463 4.3. *SfM validation based on TLS Digital Elevation Models*

464

465 Differences between each SfM-based DEM and the DEMs produced from the TLS datasets are
466 summarised in Table 4 and Figure 3b. Differences between SfM and TLS-based DEMs (i.e.
467 $DoD_{SfM-TLS}$) at the plot scale were very small, with generally sub-centimetre MAE. RMSE values
468 between the cells of the plot scale data are all <0.02 m. These values are an order of magnitude
469 lower than those found at the small catchment-scale (Table 4). Again, the lowest altitude (~ 50 m)
470 SfM aerial survey showed the lowest errors when compared against the concurrent TLS data (MAE
471 = 0.055 m; RMSE = 0.080 m). All error metrics increased with the altitude at which pictures were
472 taken. Finally, the oblique ground-based SfM survey exhibited intermediate error metrics (Table 4).
473 Notably, the UAV survey in 2013 exhibits much greater errors (MAE = 0.218 m, RMSE = 0.308 m)
474 than the 50 m survey which was at a similar height and indicates a clear systematic error with this
475 SfM model (Figure 4E).

476

477 In common with the TS validation (section 4.2), the distribution of errors for the Oblique SfM survey
478 (Figure 5a) reveals a large area where the SfM DEM was lower than the TLS DEM in the stretching
479 of positive errors. Examination of the spatial pattern of these differences (Figure 4A) identifies
480 several areas of strong positive errors (i.e. SfM DEM is lower than the TLS DEM) mostly in the
481 upper part of the catchment, but also with clear patches in the centre of the study area. The lowest
482 altitude SfM aerial survey also underestimates terrain height over most of the catchment (Figure

483 4B), but this difference is relatively minor (see histogram). The survey overestimates the height of
484 some thalwegs in the catchment, suggesting that the model is least reliable here.

485

486 The models obtained with pictures taken from the AutoGiro at 150 m and 250 m altitude
487 overestimate the terrain height across much of the study area (Figure 4C–D; Table 4). Examination
488 of the spatial distribution of errors (Figure 4C–D) highlights clearly a strong spatial pattern that
489 appears related to the topographic variability, particularly in the lower parts of the study catchment.
490 A profile taken over this area of pronounced topographic variability (i.e. high local relief) clarifies
491 the nature of these errors (Figure 5).

492

493 While at first, the patterns in Figure 4D appear to resemble georeferencing errors in a zone of
494 steeply sloping terrain, Figure 5 demonstrates that the models are well aligned. The AG50 m DEM
495 corresponds closely with the TLS survey, as is also the case for the oblique survey, though clear
496 areas of underestimated terrain height can be seen in the latter (e.g. at around 4 m on the profile).
497 The higher SfM-based data are not able to represent fully the range of elevations, underestimating
498 ridge elevations and overestimating thalweg elevations (despite an estimated pixel size of the
499 images at around 0.025 m at the highest flying altitude). The increased variability in mean elevation
500 in each grid cell with flying height is also pronounced (e.g. at 15 m in Figure 5). Such a loss of
501 precision is investigated in section 4.4.

502

503 4.4. *Differences in sub-grid topographic variability*

504

505 An increasing number of studies are utilising the sub-grid variability of topography, or roughness, to
506 infer process or as error terms in the case of change detection (as demonstrated in section 4.5).
507 Thus, it is instructive to compare the topographic variability within each grid cell, specifically the
508 detrended standard deviation taken as a metric of roughness. Increased sub-grid topographic
509 variability will reflect either real surface roughness or the survey precision; the two components are
510 combined in a sub-grid roughness metric (on a flat surface, sub-grid roughness would reflect
511 instrument precision alone). The assumption here is that where real surface roughness has been

512 captured by the higher precision instrument (i.e. the TLS) higher roughness values obtained with
513 different survey methods broadly (though not directly) indicate survey precision. The distribution of
514 roughness values in each survey is summarised in Table 5 along with summary statistics of cell-
515 by-cell differences between TLS and SfM-based surveys at the plot and small-catchment scales.
516 The spatial and statistical distributions of small catchment scale roughness values is displayed in
517 Figure 6A-D and Figure 6E-H while cell-by-cell differences between each SfM-based survey and
518 the TLS survey are presented in Figure 6I-K.

519

520 At the plot scale, sub-grid roughness in the TLS and SfM surveys are comparable. SfM surveys
521 more frequently exhibit smaller roughness values overall which may indicate higher precision of the
522 data set (or may alternatively reflect smoothing as part of the MVS algorithm). Indeed, the
523 distribution of plot-scale TLS roughness contains a small number of cells with high roughness
524 values which are not observed with SfM and could indicate the presence of 'mixed pixels'.

525

526 At the small-catchment scale, both the mean and standard deviation of sub-grid roughness in TLS
527 2014 and AG50 m surveys are comparable and only marginally higher in the oblique SfM survey.
528 Figure 6 demonstrates that the distributions of these values are similar. The spatial patterns of
529 roughness in Figure 6A-D indicates that the TLS and AG50 m SfM surveys are picking out similar
530 patterns, while the oblique survey exhibits additional patches of high roughness values. These high
531 roughness patches are broadly co-incident with the areas of mean elevation underestimation (Figure
532 4A) in the oblique survey, and are a consequence of mismatched imagery creating two surfaces at
533 the same location at different elevations, increasing the range of elevations (and thus the sub-grid
534 roughness) while lowering the mean elevation value used to derive the DEM. Despite being
535 acquired from a similar survey range to the AG50m data, the 2013 UAV data is much rougher than
536 the concurrent TLS data.

537

538 Figure 6D shows that the distribution of sub-grid roughness is clearly different for the higher
539 altitude SfM aerial surveys with much higher values reported (Table 5). It should be noted that only
540 grid cells with >3 survey points were included in the roughness analysis. This criterion limited the

541 number of cells included from the AG150 m and AG250 m surveys. Nevertheless, it is clear from
542 Figure 6D that the populated roughness values are much higher than observed by the TLS and so
543 are likely to be dominated by a reduction in precision of the SfM point cloud even at 150 m altitude,
544 particularly in the topographic lows, as seen in Figure 5. With only 102 sufficiently populated cells
545 for roughness analysis, the distributions of roughness for the AG250 m SfM survey are not
546 presented in Figure 5.

547

548 Cell-by-cell comparisons (Figure 6I-K) show considerable scatter at lower roughness values for
549 both TLS and SfM-based surveys, suggesting that no agreement exists between the TLS and SfM
550 data sets. The lack of agreement may reflect the uncertainty of the data sets which is relevant at
551 such small sub-grid scales. Where higher sub-grid roughness is observed (~ 0.2 m) agreement can
552 be seen, though this breaks down with increasing altitude.

553

554 4.5. *Topographic change detection*

555

556 The ability of SfM-MVS surveys to detect topographic change is compared against TLS-based
557 results (i.e. $\text{DoD}_{\text{TLS2014-TLS2013}}$). While relatively large in comparison with other hillslope areas, the
558 typical topographic changes observed over 11 months in a rapidly eroding badland are moderate in
559 comparison with more dynamic higher-energy systems (e.g. gravel-bed rivers) to which this
560 morphometric method is more often applied (e.g. Wheaton et al., 2013).

561

562 For TLS data, the number of cells above the minLoD is relatively low indicating that most
563 topographic changes between surveys are in the range of the uncertainty of the surveys. The final
564 DoDs created from the TLS data demonstrate relatively small areas of detectable topographic
565 change focused in the thalwegs and flow lines of the small catchment (Figure 7A). This extensive
566 TLS-derived morphometric sediment budget covers an area over 100 times larger than that
567 presented previously by Vericat et al. (2014). Volumetrically, erosion was twice than deposition,
568 with a catchment average topographic change of -1.44 mm a^{-1} (Table 6). As expected, much of this

569 change is dominated by relatively small topographic differences between the two models,
570 particularly in areas of deposition, which tend to be less pronounced but more widespread.

571

572 The magnitude of the measured topographic change increases when SfM-based surveys are used
573 to estimate the morphometric sediment budget. While the overall catchment average topographic
574 change calculated from ground-based SfM might at first appear to be reasonably accurate (-2.19
575 mm a⁻¹, Table 6), examination of the volumes of estimated erosion and deposition reveals that both
576 figures are largely overestimating the real changes, resulting from insufficient accuracy. Similar
577 overestimates are evident for the aerial surveys, which is to be expected given errors reported in
578 the earlier topographic validation.

579

580 There is little relation between the TLS-derived DoD and the SfM-derived DoDs with considerable
581 reconstruction error observable throughout the study area. Clear patterns of systematic error can
582 be seen through the catchment. Quantitative comparison of the DoD derived from oblique ground
583 based imagery (Figure 7B) with the DoD derived from TLS surveys reveals a ME of -38.97 mm, a
584 MAE of 158.28 mm, an RMSE of 301.93 mm and a SDE of 299.41 mm. In comparison, the DoD
585 derived from the aerial image at 50 m above the ground (Figure 7C) demonstrated much lower
586 error metrics of ME = 2.51 mm, MAE = 134.54 mm, RMSE = 194.35 mm and SDE = 192.72 mm.
587 Comparison of Figures 7C and 4E identified the 2013 UAV survey as the source of this error. For
588 both datasets, these errors are too large to resolve annual topographic changes associated with
589 badlands at this scale, though two datasets of the same quality as the AG50m imagery would
590 enhance the ability of aerial imagery to resolve changes of <0.1 m.

591

592 **5. Discussion**

593

594 As a survey method, SfM-MVS can be implemented easily across a particularly wide range of
595 scales (see Figure 8). This capability offers the potential for relatively standardised measurements
596 of topography over a range of spatial and temporal scales. The validation study presented herein,

597 aimed to clarify typical errors expected from SfM-MVS surveys, by conducting multiple nested
598 surveys of the same area at a number of scales and over a number of platforms. Repeat TLS
599 surveys covering a catchment of over 4000 m² and the derived spatially-distributed morphometric
600 sediment budget offered an ideal and unique data product with which to validate both plot scale
601 and small catchment SfM surveys. This was supplemented further with total station surveys for
602 independent validation.

603

604 5.1. *Quality of SfM-based topographic surveys: scale dependence*

605

606

607 At the plot scale (here ~10 m²), sub-centimetre mean absolute differences between SfM-MVS
608 DEMs and TLS-derived DEMs are observed. In some cases, the detectable differences are
609 sufficiently small that there is no reason to necessarily prefer the TLS survey as the reference
610 dataset owing to: (i) the increased point density of the SfM-MVS point clouds over these plots; (ii)
611 the generally lower sub-grid roughness (i.e. inferred higher precision) of SfM-MVS data sets and;
612 (iii) the greater range of perspectives offered by SfM-MVS (causing fewer shadows). This finding is
613 in line with that of James and Robson (2012) who observed sub-millimetre errors when surveying a
614 hand sample from an even shorter range. Given the high resolution of topographic data achievable
615 at the plot scale with individual clasts being clearly observable, SfM-MVS is well capable of
616 detecting topographic changes and, sediment budgets, at the plot or even slope scale, and is likely
617 to be an improvement on many existing methods. Errors are well within those of the TLS sediment
618 budget presented in Figure 7A. The visual nature of the method even indicates that the movement
619 of individual clasts could be tracked in three-dimensions, permitting new inferences in the study of
620 sediment transport connectivity (e.g. virtual travel velocity). Tuffen et al. (2013) applied such an
621 approach to estimate the velocity of lava flows. Further work is required to demonstrate this
622 convincingly.

623

624 Scaling up SfM-MVS using oblique ground-based imagery to small catchment scales (~0.5 ha in
625 this example) becomes problematic, especially in a complex, heavily dissected environment as

626 surveyed here. In some areas, the closer range yielded a dense point cloud and a close fit to the
627 TLS-reference dataset (see profiles in Figure 5); however, the keypoint matching and camera pose
628 estimation proved unreliable in parts of the survey area. While image pose estimation was
629 examined visually before implementing the dense cloud reconstruction process, relatively small
630 mismatches proved undetectable. Moreover, many images were rejected by the software and were
631 not included in the reconstruction, resulting in a large part of the upper catchment where more
632 vegetation is present (see Figure 1C) being excluded from oblique surveys. Matching ground-
633 based imagery over relatively large scales is a demanding task for SfM software. Yet, mismatched
634 patches are particularly problematic as these issues are not apparent during the field survey, and
635 only arise during post-processing. The results herein suggest that, beyond plot sizes of $\sim 100 \text{ m}^2$,
636 there is a preference for aerial imagery for SfM-based point cloud generation.

637

638 Aside from large volumetric changes as seen with gully network expansion (e.g. d'Oleire-Oltmanns
639 et al., 2012; Frankl et al., 2015), results herein suggest that SfM-MVS is only suitable as a method
640 of monitoring soil erosion from ranges of $< 50 \text{ m}$ and possibly $< 10 \text{ m}$. This would restrict
641 applications to relatively small areas ($< 1 \text{ ha}$) as has been demonstrated by Eltner et al. (2014). Yet,
642 errors observed even at the landscape scale are likely to be similar if not smaller than existing
643 morphometrically-derived sediment yield estimates covering the largest areas which were
644 estimated using DEMs created from historical aerial imagery (Ciccacci et al., 2008). Using an
645 AutoGiro (or gyrocopter) as an aerial platform has advantages over UAV platforms allowing
646 coverage over larger areas in a single survey, with longer flight times and the flexibility and stability
647 that comes with hand-held shooting (permitting slightly oblique convergent photography).
648 Comparison of the UAV and AutoGiro data acquired at the same altitude demonstrates this clearly,
649 as UAV data exhibit a MAE four-times greater than the AutoGiro study. This result provides the first
650 empirical confirmation of the modelling findings of James and Robson (2014) that off-vertical
651 imagery in convergent pairs (taken for the AutoGiro survey) coupled with distributed ground control
652 can reduce doming effects arising from vertical image sets (taken for the UAV survey) and
653 inaccurate camera models. Further quality improvements can be made as camera technology

654 develops; for example, full-frame FX sensors are now available for DSLRs which provide finer
655 detail and capture larger image areas.

656

657 As reported in Vericat et al. (2014) in the case of sub-humid badlands, morphometric sediment
658 budgets also require differentiation between topographic changes caused by erosion/deposition
659 and surface shrinking/swelling which requires additional datasets (e.g. deep-anchored ground
660 control points combined with trail cameras). Also, the masking out of observed changes that are
661 below the minimum level of detection (and deemed unreliable) can potentially underestimate
662 topographic change. However, as such changes are, by definition, minimal, this effect would not
663 introduce a large bias in estimated sediment yield.

664

665 The potential cost and time savings achievable using SfM-MVS in place of other high-resolution
666 survey methods (e.g. TLS or airborne LiDAR) are noteworthy (see Castillo et al., 2012). There was
667 little difference in survey time required for each camera platform (all ~ 10-15 minutes) and while
668 UAV purchase costs are the greatest expense (~£1,000) this was balanced by the cost of the
669 gyrocopter hire (~£150). Greater errors from larger survey ranges are likely to be acceptable for
670 other applications (e.g. terrain analysis) or for monitoring change on more dynamic systems (e.g.
671 gravel bed rivers). From 50 m survey range, changes of ~ 0.1 m will be detectable. Surface models
672 derived from 150 m elevation imagery (e.g. the TIN of Figure 1B) are certainly comparable to those
673 derived from airborne LiDAR. For the first time, this study has shown that the spatial distribution of
674 sub-grid roughness can be reproduced with SfM from 50 m survey range meaning that the survey
675 precision is similar to that of TLS, although systematic errors may be present in the data. Further
676 developments using camera phones and freely available online processing software (e.g. 123D
677 Catch) (Micheletti et al., 2014) increase the accessibility of SfM-MVS as a survey method and
678 indicate serious potential for widespread utilisation of the technique in the Geosciences and
679 beyond.

680

681 The TLS-derived morphometric sediment budget displayed in Figure 7A covers a much larger area
682 than previous data sets presented in eroding badlands. Such a dataset is extremely valuable for

683 the development of improved understandings of sediment connectivity (see Bracken et al., 2014).
684 Further work is required to understand the topographic and meteorological controls on this erosion.
685 Embedded event-scale repeat SfM surveys at the plot or slope scale can add value to such annual
686 sediment budgets owing to the reduction in survey time and resources required to undertake such
687 work regularly. In this manner, SfM can add value to longer-term morphometric monitoring with
688 more conventional means.

689

690 5.2. *Synthesis of SfM-validation: key findings and issues*

691

692 This study contributes to the emerging body of literature that aims to validate SfM robustly in that it
693 has increased substantially the amount of available validation data points to date. Multiple SfM
694 surveys from a range of survey heights and over a wide range of scales are validated with both
695 point-based total-station data and through a comparison of SfM and TLS DEMs (gridded data). In
696 each case the same software was used; however, a range of alternative SfM programs are
697 available and used in existing literature (e.g. Mic Mac, Visual SfM). Combining the findings of this
698 study with other reported validation studies yields important insights into the overall accuracy
699 achievable with SfM-MVS. While several studies report mean error (e.g. Fonstad et al., 2013;
700 Woodget et al., 2014), RMSE is commonly cited as a metric of surface quality, while MAE provides
701 an indication of non-directional elevation errors and provides a natural and comparable measure of
702 model performance (Willmott and Matsuura, 2005). In total, 50 SfM validation points have been
703 compiled.

704

705 Figure 9 plots both RMSE and MAE against survey range both for data sets presented in this
706 paper and existing studies that report each validation metric. Data points are broadly separated
707 into: (i) those that compare SfM-derived rasters (i.e. DEMs) with point topographic data (e.g. from
708 RTK-dGPS or Total Stations) ('point-to-raster'); (ii) those that compare SfM-DEMs with equivalent
709 raster-based data products derived from another survey technique such as TLS ('raster to raster');
710 and (iii) those that compare two point clouds directly ('point to point'). As might be expected, RMSE
711 at a given range decreases from (i) to (iii) (Figure 9A). Comparison of points with rasters is also

712 dependent on raster grid size; this effect can be seen directly in Figure 3A as the error metrics for
713 the AG150 m and AG250 m surveys increased between the small-catchment (0.1 x 0.1 m DEM)
714 and landscape scales (1 x 1 m DEM) which were derived from the same point cloud. Direct
715 comparison of two DEMs or two point clouds seem to be the fairest tests of SfM as comparable
716 data-products are being evaluated. However, applications of SfM data typically derive DEMs as a
717 final processing step, thus it could be argued that a raster-based comparison is most
718 representative of real errors in final data products.

719

720 A linear degradation in precision with survey range is expected theoretically, is well established for
721 traditional stereo photogrammetry and has been observed previously for SfM (James and Robson,
722 2012). However, the majority of existing validation studies report RMSE and not SD.
723 With a greater synthesis of data points, over a wide-range of terrain types, a power-law relating
724 RMSE and survey range provides the best fit to the data between survey ranges of <1 m and 1000
725 m (Figure 9A). The exponent of this relationship is 0.88 which is close to linear ($R^2 = 0.80$, $n = 43$).
726 Combining all SfM validation points, a median ratio of RMSE : survey range of 1:639 is observed,
727 which is very similar to the ratio of 1:625 reported by Micheletti et al. (2014). Since RMSE reflects
728 overall model accuracy and not precision, the ratio is well below the 1:1000 ratio between precision
729 and range reported by James and Robson (2012). RMSE reflects more than the expected linear
730 degradation in precision; although a linear relationship between RMSE and survey range might be
731 also expected, the summary in Figure 9A reflects a number of factors that seem to limit the
732 practically-achievable accuracy of SfM. Camera platform, camera sensor, weather, georeferencing
733 method, validation method, number of images and their geometry, distribution of GCPs, terrain
734 type and processing software will all influence the final model quality to some extent and may be
735 responsible for the observed non-linear trend. Certainly, survey range is not the only variable to be
736 altered between the points in Figure 9A which compiles results from a wide range of studies. While
737 Figure 9A gives a useful indication of the relationship between RMSE and survey range, there is a
738 clear need for a systematic validation of SfM to determine the effect of each of these factors on
739 data quality.

740

741 MAE is reported less frequently; Figure 9B compiles 28 reported values. Again, raster-based
742 comparisons yield a lower error metric at a given range. Again a power law best fits the data ($R^2 =$
743 0.69) with a lower exponent of 0.57 . Using just the raster-based validation data ($n = 8$) increases
744 the exponent to 0.78 and improves fit substantially ($R^2 = 0.97$) (dashed line in Figure 9B).

745

746 From Figure 9A and considering both the RMSE : range ratio of 1:639 and degree of scatter
747 around the trend line, at 10 m range, around 10–15 mm errors can be achieved which would be
748 suitable for the majority of applications. Inspection poles provide ideal viewing angles at that range
749 and could replace the need for UAVs over the small catchment scale presented here. Such
750 inspection poles allow remote triggering of elevated cameras and achieve a compromise between
751 the close-range imagery available from oblique ground-based surveys, and the more reliable
752 surfaces generated from airborne surveys. Over larger areas (i.e. the landscape-scale surveys
753 presented here) a larger range is required (>100 m) for a manageable survey; this increases
754 anticipated errors by an order of magnitude. Thus, synthesis of extant literature suggests that, for
755 soil erosion applications, SfM should only be applied where survey ranges ~ 10 m can be
756 achieved.

757

758 **6. Summary and Conclusions**

759

760 Structure-from-Motion with Multi-View Stereo can be used to generate high resolution topographic
761 data products at a wide range of scales. For the first time, this study presents a robust validation of
762 SfM using multi-scale nested surveys and a distributed morphometric sediment budget over an
763 area >4000 m² derived using TLS. Validation reveals that data sets of a sufficient quality for soil
764 erosion monitoring and comparable with TLS can be obtained at the plot or hillslope scale. With a
765 0.1×0.1 m grid size, sub-grid roughness parameters similar to those from TLS can be derived
766 even from ranges of ~ 70 m. However, the suitability of using SfM for topographic change detection
767 at this scale is limited to rapidly changing landforms and environments (e.g. gravel bed rivers). For
768 larger areas of more complex topography, aerial images from piloted gyrocopters are preferable for

769 reliable image matching, but with increasing survey height, surface precision decreases. Sub-
770 centimetre errors are achievable at ~10 m range as might be provided by a camera inspection
771 pole. Errors increase approximately linearly with survey range and ratios of RMSE : survey range
772 of 1:639 are observed. Despite these errors, landscape-scale DEMs can be derived rapidly and at
773 minimal expense and are likely to have a considerable impact of the future trajectory of
774 geomorphology as a discipline.

775

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784

785 **References**

786

787 Agisoft, 2012. Agisoft PhotoScan User Manual: Professional Edition, Version 0.9.0. Available from:
788 <http://www.agisoft.ru/products/photoscan/professional>

789

790 Avendaño C, Sanz ME, Cobo R. 2000. State of the art of reservoir sedimentation management in
791 Spain. *Proceedings of the International Workshop and Symposium on Reservoir Sedimentation*
792 *Management*, Tokyo, Japan, pp. 27–35.

793

794 Batalla RJ, Vericat D. 2011. An appraisal of the contemporary sediment yield in the Ebro Basin.
795 *Journal of Soils and Sediments* **11**: 1070–1081.

796

797 Boardman J. 2006. Soil erosion science: reflections on the limitations of current approaches.
798 *Catena* **68**: 73–86.
799

800 Boix-Fayos C, Martinez-Mena M, Arnau-Rosalen E, Calvo-Cases A, Castillo V, Albaladejo J. 2006.
801 Measuring soil erosion by field plots: understanding the sources of variation. *Earth-Science*
802 *Reviews* **78**: 267–285.
803

804 Bracken LJ, Turnbull L, Wainwright J, Bogaart P. 2014. Sediment connectivity: a framework for
805 understanding sediment transfer at multiple scales. *Earth Surface Processes & Landforms* doi:
806 10.1002/esp.3635
807

808 Brasington J, Rumsby BT, McVey RA. 2000. Monitoring and modelling morphological change in a
809 braided gravel-bed river using high resolution GPS-based survey. *Earth Surface Processes and*
810 *Landforms* **25**: 973–990.
811

812 Brasington J, Langham J, Rumsby B. 2003. Methodological sensitivity of morphometric estimates
813 of coarse fluvial sediment transport. *Geomorphology* **53**: 299–316.
814

815 Brasington J, Vericat D, Rychkov I. 2012. Modeling river bed morphology, roughness, and surface
816 sedimentology using high resolution terrestrial laser scanning. *Water Resources Research* **48**: 1–
817 18.
818

819 Bretar F, Chauve A, Bailly J-S, Mallet C, Jacome A. 2009. Terrain surfaces and 3-D landcover
820 classification from small footprint full-waveform lidar data: application to badlands. *Hydrol. Earth*
821 *Syst. Sci.* **13**: 1531–1544.
822

823 Bryan R, Yair A. 1982. Perspectives on studies of badland geomorphology. In *Badland*
824 *Geomorphology & Piping*, Bryan R, Yair A. (eds.). Geo Books: Cambridge; 1–12.
825

826 Buendia C, Gibbins CN, Vericat D, Batalla RJ. 2013. Reach and catchment-scale influences on
827 invertebrate assemblages in a river with naturally high fine sediment loads. *Limnol. Ecol. Manag.*
828 *Inland Waters* **43**: 362–370.

829

830 Cantón Y, Domingo F, Solé-Benet A, Puigdefábregas J. 2001. Hydrological and erosion response
831 of a badlands system in semiarid SE Spain. *J. Hydrol.* **252**: 65–84.

832

833 Castillo C, Pérez R, James MR, Quinton NJ, Taguas EV, Gómez JA. 2012. Comparing the
834 accuracy of several field methods for measuring gully erosion. *Soil Science Society of America*
835 *Journal* **76**: 1319-1332. doi: 10.2136/sssaj2011.0390

836

837 Ciccacci S, Galiano M, Roma MA, Salvatore MC. 2008. Morphological analysis and erosion rate
838 evaluation in badlands of Radicofani area (southern Tuscany – Italy). *Catena* **74**: 87–97.

839

840 Clarke ML, Rendell HL. 2006. Process-form relationships in Southern Italian badlands: Erosion
841 rates and implications for landform evolution. *Earth Surface Processes and Landforms* **31**: 15–29.

842

843 Della Seta M, Del Monte M, Fredi P, Lupia-Palmieni E. 2009. Space-time variability of denudation
844 rates at the catchment and hillslope scales on the Tyrrhenian side of Central Italy. *Geomorphology*
845 **107**: 161–177.

846

847 Descroix L, Claude JC, 2002. Spatial and temporal factors of erosion by water of black marls in the
848 badlands of the French southern Alps. *Hydrol. Sci. J.* **47**: 227–242.

849

850 d'Oleire-Oltmanns S, Marzloff I, Peter KD, Ries JB. 2012. Unmanned Aerial Vehicle (UAV) for
851 monitoring soil erosion in Morocco. *Remote Sensing* **4**: 3390–3416.

852

853 de Vente J, Poesen J, Verstraeten G. 2005. The application of semi-quantitative methods and
854 reservoir sedimentation rates for the prediction of basin sediment yield in Spain. *Journal of*
855 *Hydrology* **305**: 63–86.

856

857 Eltner A, Baumgart P, Maas H-G, Faust D. 2014. Multi-temporal UAV data for automatic
858 measurement of rill and interrill erosion on loess soil. *Earth Surface Processes and Landforms* doi:
859 10.1002/esp.3673.

860

861 Faulkner H. 2008. Connectivity as a crucial determinant of badland morphology and evolution.
862 *Geomorphology* **100**: 91–103.

863

864 Favalli M, Fornaciai A, Isola I, Tarquini S, Nannipieri L. 2012. Multiview 3D reconstruction in
865 geosciences. *Computers & Geosciences* **44**: 168-176.

866

867 Fonstad MA, Dietrich JT, Courville BC, Jensen JL, Carbonneau PE. 2013. Topographic structure
868 from motion: a new development in photogrammetric measurement. *Earth Surface Processes and*
869 *Landforms* **38**: 421–430.

870

871 Francke T. 2009. *Measurement and modelling of water and sediment fluxes in mesoscale dryland*
872 *catchments*. Ph.D. Thesis Universität Potsdam, Germany.

873

874 Frankl A, Stal C, Abraha A, Kyssen J, Rieke-Zapp D, De Wulf A, Poesen J. 2015. Detailed
875 recording of gully morphology in 3D through image-based modelling. *Catena* **127**: 92-101.

876

877 Furukawa Y, Ponce J. 2010. Accurate, dense and robust multiview stereopsis. *IEEE Transactions*
878 *on Pattern Analysis and Machine Intelligence* **32**: 1362–1376.

879

880 García-Ruiz JM, Regüés D, Alvera B, Lana-Renault N, Serrano-Muela P, Nadal-Romero E, Navas
881 A, Latron J, Martí-Bono C, Arnáez J. 2008. Flood generation and sediment transport in

882 experimental catchments affected by land use changes in the central Pyrenees. *J. Hydrol.* **356**:
883 245–260.

884

885 Godfrey AE, Everitt BL, Martín Duque JF. 2008. Episodic sediment delivery and landscape
886 connectivity in the Mancos Shale badlands and Fremont River system, Utah, USA.
887 *Geomorphology* **122**: 242–251.

888

889 Harwin S, Lucieer A. 2012. Assessing the accuracy of georeferenced point clouds produced via
890 multi-view stereopsis from unmanned aerial vehicle (UAV) imagery. *Remote Sensing* **4**: 1573-
891 1599.

892

893 James MR, Robson S. 2012. Straightforward reconstruction of 3D surfaces and topography with a
894 camera: accuracy and geoscience application. *Journal of Geophysical Research: Earth Surface*
895 **117**: F03017, doi: 10.1029/2011JF002289.

896

897 James MR, Robson S. 2014. Mitigating systematic error in topographic models derived from UAV
898 and ground-based image networks. *Earth Surface Processes and Landforms* **39**: 1413–1420.

899

900 James MR, Quinton JN. 2013. Ultra-rapid topographic surveying for complex environments: the
901 hand-held mobile laser scanner (HMLS). *Earth Surface Processes and Landforms* **39**: 138–142.

902

903 James MR, Varley N. 2012. Identification of structural controls in an active lava dome with high
904 resolution DEMs: Volcán de Colima, Mexico. *Geophysical Research Letters* **39**: L22303. doi:
905 10.1029/2012GL054245

906

907 Javernick L, Brasington J, Caruso B. 2014. Modelling the topography of shallow braided rivers
908 using Structure-from-Motion photogrammetry. *Geomorphology*
909 doi:10.1016/j.geomorph.2014.01.006

910

911 Kirkby MJ, Jones RJA, Irvine B, Gobin A, Govers G, Cerdan O, Van Rompaey AJJ, Le Bissonnais
912 Y, Daroussin J, King D, Montanarella L, Grimm M, Vieillefont V, Puigdefabregas J, Boer M,
913 Kosmas C, Yassoglou N, Tsara M, Mantel S, Van Lynden GJ, Huting J. 2004. Pan-European Soil
914 Erosion Risk Assessment: The PESERA Map, Version 1 October 2003. Explanation of Special
915 Publication Ispra 2004 No.73 (S.P.I.04.73). *European Soil Bureau Research Report No.16*, EUR
916 21176, 18pp. and 1 map in ISO B1 format. Office for Official Publications of the European
917 Communities, Luxembourg

918

919 Kuhn NJ, Yair A. 2004. Spatial distribution of surface conditions and runoff generation in small arid
920 watersheds, Zin Valley Badlands, Israel. *Geomorphology* **57**: 183–200.

921

922 Lázaro R, Cantón Y, Solé-Benet A, Bevan J, Alexander R, Sancho LG, Puigdefábregas J. 2008.
923 The influence of competition between lichen colonization and erosion on the evolution of soil
924 surfaces in the Tabernas badlands (SE Spain) and its landscape effects. *Geomorphology* **102**:
925 252–266.

926

927 Leica Geosystems. 2011. Leica ScanStation C10. Available from http://hds.leica-geosystems.com/downloads123/hds/hds/ScanStation%20C10/brochuresdatasheet/Leica_ScanStation_C10_DS_en.pdf [06 September 2012].

928
929

930

931 Lopez-Saez J, Corona C, Stoffel M, Rovéra G, Astrade L, Berger F. 2011. Mapping of erosion
932 rates in marly badlands based on a coupling of anatomical changes in exposed roots with slope
933 maps derived from LiDAR data. *Earth Surface Processes and Landforms* **36**: 1162–1171.

934

935 López-Tarazón JA, Batalla RJ, Vericat D, Francke T. 2012. The sediment budget of a highly
936 dynamic mesoscale catchment: The River Isábena. *Geomorphology* **138**: 15–28.

937

938 Lowe DG. 2004. Distinctive image features from scale-invariant keypoints. *International Journal of*
939 *Computer Vision* **60**: 91-110.

940

941 Lucieer A, de Jong SM, Turner D. 2014. Mapping landslide displacements using Structure from
942 Motion (SfM) and image correlation of multi-temporal UAV photography. *Progress in Physical
943 Geography* **38**: 97–116.

944

945 Mancini F, Dubbini M, Gattelli M, Stecchi F, Fabbri S, Gabbianelli G. 2013. Using unmanned aerial
946 vehicles (UAV) for high-resolution reconstruction of topography: The structure from motion
947 approach on coastal environments. *Remote Sensing* **5**: 6880-6898.

948

949 Mathys N, Brochot S, Meunier M, Richard D. 2003. Erosion quantification in the small marly
950 experimental catchments of Draix (Alpes de Haute Provence, France). Calibration of the ETC
951 rainfall-runoff erosion model. *Catena* **50**: 527–548.

952

953 Micheletti N, Chandler JH, Lane SN. 2014. Investigating the geomorphological potential of freely
954 available and accessible Structure-from-Motion photogrammetry using a smartphone. *Earth
955 Surface Processes and Landforms* doi: 10.1002/esp.3648

956

957 Nadal-Romero E, Martínez-Murillo JF, Vanmaercke M, Poesen J. 2011. Scale-dependency of
958 sediment yield from badland areas in Mediterranean environments. *Progress in Physical
959 Geography* **35**: 297–332.

960

961 Nadal-Romero E, Martínez-Murillo JF, Vanmaercke M, Poesen J. 2014. Corrigendum to “Scale-
962 dependency of sediment yield from badland areas in Mediterranean environments”. *Progress in
963 Physical Geography* **38**: 381–386.

964

965 Oúedraogo MM, Degré A, Debouche C, Lisein J. 2014. The evaluation of unmanned aerial
966 systems-based photogrammetry and terrestrial laser scanning to generate DEMs of agricultural
967 watersheds. *Geomorphology* doi: 10.1016/j.geomorph.2014.02.016.

968

969 Poesen J, Hooke JM. 1997. Erosion, flooding and channel management in Mediterranean
970 Environments of southern Europe. *Progress in Physical Geography* **21**: 157–199.
971

972 Ružić I, Marović I, Benac Č, Ilić S. 2014. Coastal cliff geometry derived from structure-from-motion
973 photogrammetry at Stara Baška, Krk Island, Croatia. *Geo-Marine Letters* **34**: 555-565.
974

975 Rychkov I, Brasington J, Vericat D. 2012. Computational and methodological aspects of terrestrial
976 surface analysis based on point clouds. *Computers and Geosciences* **42**: 64–70.
977

978 Sirvent J, Desir G, Gutiérrez M, Sancho C, Benito G. 1997. Erosion rates in badland areas
979 recorded by collectors, erosion pins and profilometer techniques (Ebro Basin, NE-Spain).
980 *Geomorphology* **18**: 61–75.
981

982 Smith MW. 2014. Roughness in the Earth Sciences. *Earth-Science Reviews* **136**: 202–225.
983

984 Smith MW, Carrivick JL, Hooke J, Kirkby MJ. 2014. Reconstructing Flash Flood Magnitudes Using
985 ‘Structure-from-Motion’: a rapid assessment tool. *Journal of Hydrology* **519**: 1914–1927.
986

987 Solé-Benet A, Calvo A, Cerdà A, Lázaro R, Pini R, Barbero J. 1997. Influence of microrelief
988 patterns and plant cover on runoff related processes in badlands from Tabernas (SE Spain).
989 *Catena* **31**: 23–38.
990

991 Snavely N, Seitz SN, Szeliski R. 2008. Modeling the world from internet photo collections.
992 *International Journal of Computer Vision* **80**: 189-210.
993

994 Stumpf A, Malet JP, Allemand P, Pierrot-Deseilligny M, Skupinski G. 2015. Ground-based multi-
995 view photogrammetry for the monitoring of landslide deformation and erosion. *Geomorphology*
996 **231**: 130-145.
997

998 Thoeni K, Giacomini A, Murtagh R, Kniest E. 2014. A comparison of multi-view 3D reconstruction
999 of a rock wall using several cameras and a laser scanner. In: *Proceedings of ISPRS Technical*
1000 *Commission V Symposium*, Riva del Garda, Italy, pp. 23-25.

1001

1002 Thommeret N, Bailly JS, Puech C. 2010. Robust extraction of thalwegs network from DTM:
1003 application on badlands. *Hydrol. Earth Syst. Sci.* **7**: 879–905.

1004

1005 Tonkin TN, Midgley NG, Graham DJ, Labadz JC. 2014. The potential of small unmanned aircraft
1006 systems and structure-from-motion for topographic surveys: A test of emerging integrated
1007 approaches at Cwm Idwal, North Wales. *Geomorphology* doi: 10.1016/j.geomorph.2014.07.021.

1008

1009 Triggs B, McLauchlan PF, Hartley RI, Fitzgibbon AW. 2000. Bundle adjustment – a modern
1010 synthesis. In Triggs, B., Zisserman, A., Szeliski, R. (eds). *Vision Algorithms '99*, LNCS 1883, 298–
1011 372. Springer-Verlag: Berlin Heidelberg.

1012

1013 Tuffen H, James MR, Castro JM, Schipper CI. 2013. Exceptional mobility of an advancing rhyolitic
1014 obsidian flow at Cordon Caulle volcano in Chile. *Nature Communications* **4**: DOI:
1015 10.1038/ncomms3709

1016

1017 Vericat D, Brasington J, Wheaton J, Cowie M. 2009. Accuracy assessment of aerial photographs
1018 acquired using lighter-than-air blimps: low cost tools for mapping river corridors. *River Research*
1019 *and Applications* **25**: 985-1000.

1020

1021 Vericat D, Smith MW, Brasington J. 2014. Patterns of topographic change in sub-humid badlands
1022 determined by high resolution multi-temporal topographic surveys. *Catena* **120**: 164–176.

1023

1024 Westoby MJ, Brasington J, Glasser NF, Hambrey MJ, Reynolds JM. 2012. 'Structure-from-Motion'
1025 photogrammetry: a low-cost, effective tool for geoscience applications. *Geomorphology* **179**:
1026 300–314.

1027

1028 Wheaton JM, Brasington J, Darby SE, Sear DA. 2010. Accounting for uncertainty in DEMs from
1029 repeat topographic surveys: improved sediment budgets. *Earth Surface Processes and Landforms*
1030 **35**: 136–156.

1031

1032 Wheaton JM, Brasington J, Darby SE, Karsprak A, Sear D, Vericat D. 2013. Morphodynamic
1033 signatures of braiding mechanisms as expressed through change in sediment storage in a gravel-
1034 bed river. *Journal of Geophysical Research: Earth Surface* **118**: 758-779.

1035

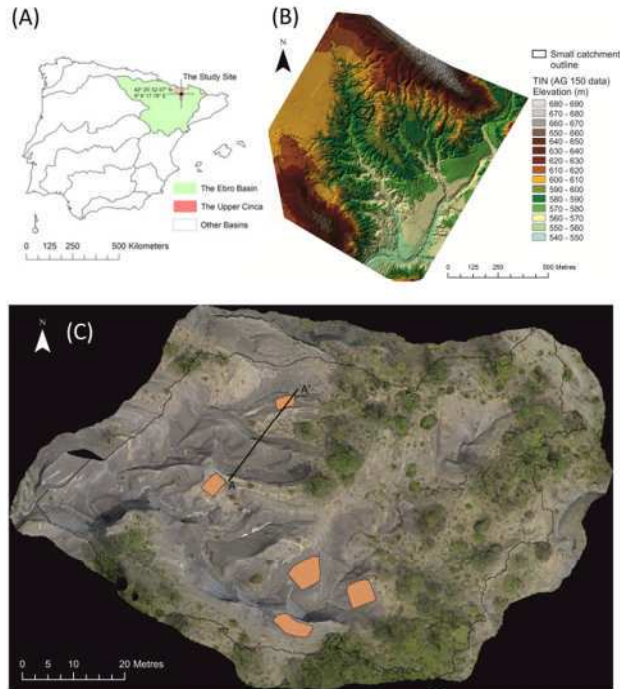
1036 Willmott CJ, Matsuura K. 2005. Advantages of the mean absolute error (MAE) over the root mean
1037 square error (RMSE) in assessing average model performance. *Climate Research* **30**: 79–82.

1038

1039 Woodget AS, Carbonneau PE, Visser F, Maddock IP. 2014. Quantifying submerged fluvial
1040 topography using hyperspatial resolution UAS imagery and structure from motion photogrammetry.
1041 *Earth Surface Processes and Landforms*. doi: 10.1002/esp.3613.

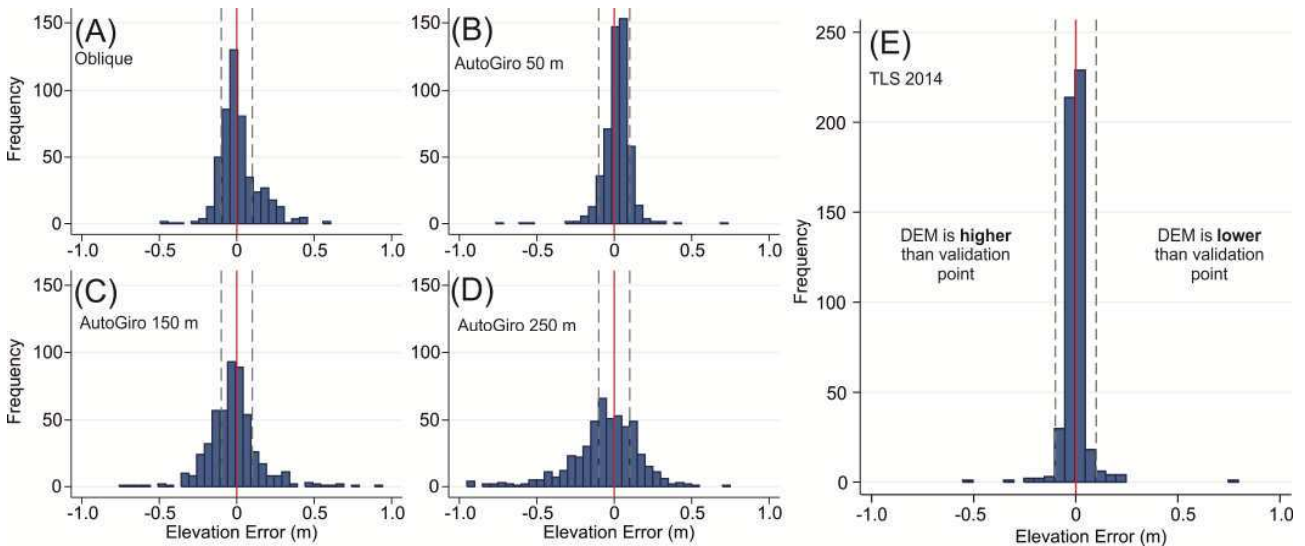
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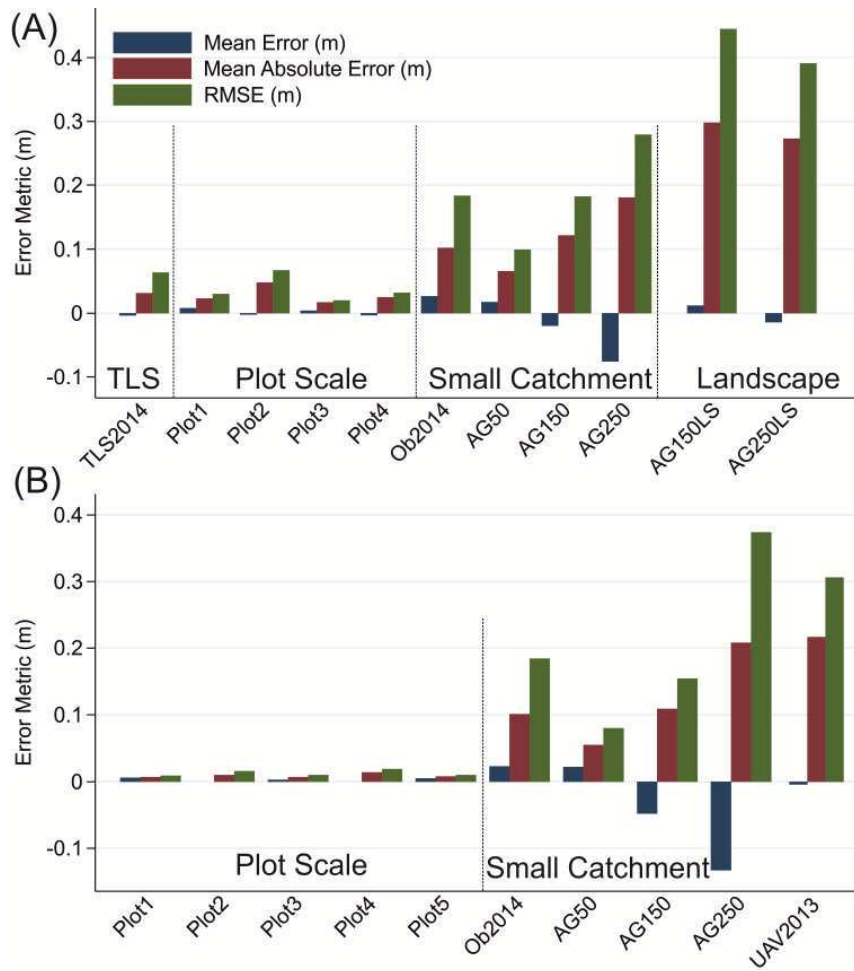
1044
 1045 **Figure 1.** (A) Location of study site in the Upper River Cinca (Central Pyrenees, Iberian Peninsula,
 1046 Ebro Basin); (B) topographic model of the landscape-scale (1 km²) study area derived from SfM;
 1047 (C) orthophoto of the small-catchment (4710 m²) which is the main focus of this paper. Plot
 1048 outlines (< 30 m²) and the location of the profile AA' in Figure 5 are shown in (C).

1049



1050
 1051 **Figure 2.** Distribution of errors in the total station validation of SfM-MVS surveys (A–D) and the
 1052 TLS 2014 survey (E) at the small catchment scale. Dashed lines indicate ± 0.1 m.

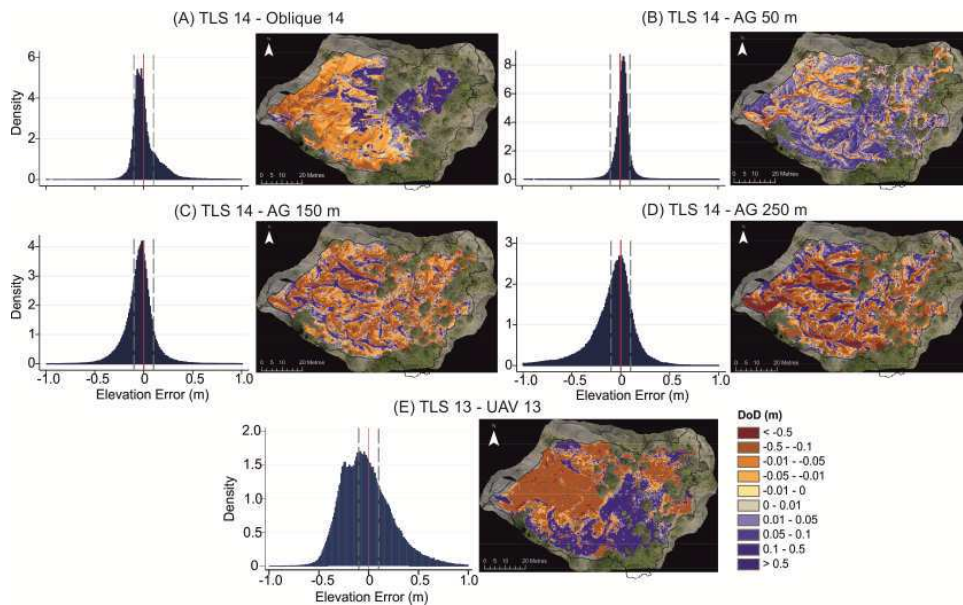
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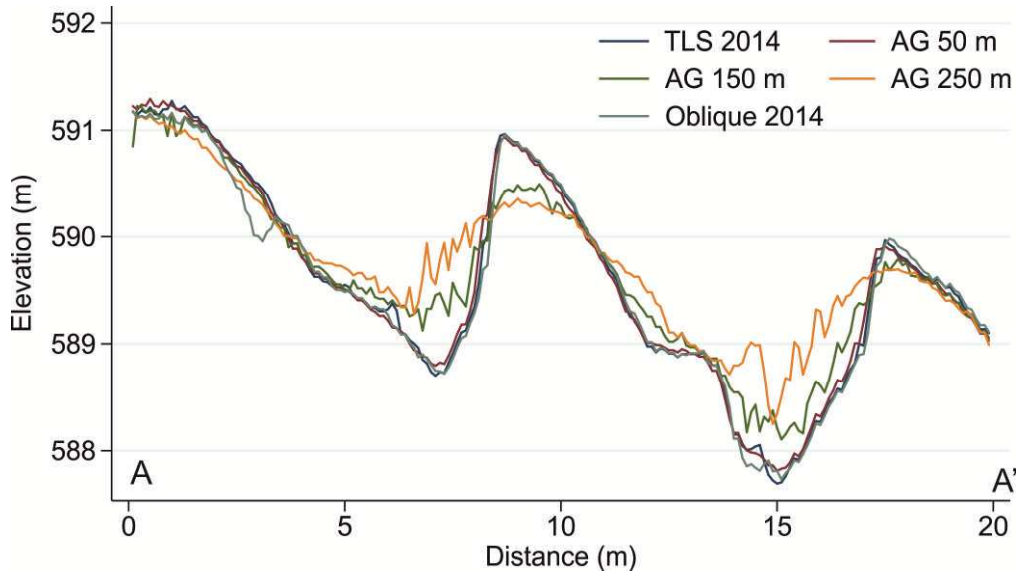
1055 **Figure 3.** Summary of errors in topographic validation at three different scales using (A) total
 1056 station data; and (B) using TLS data.

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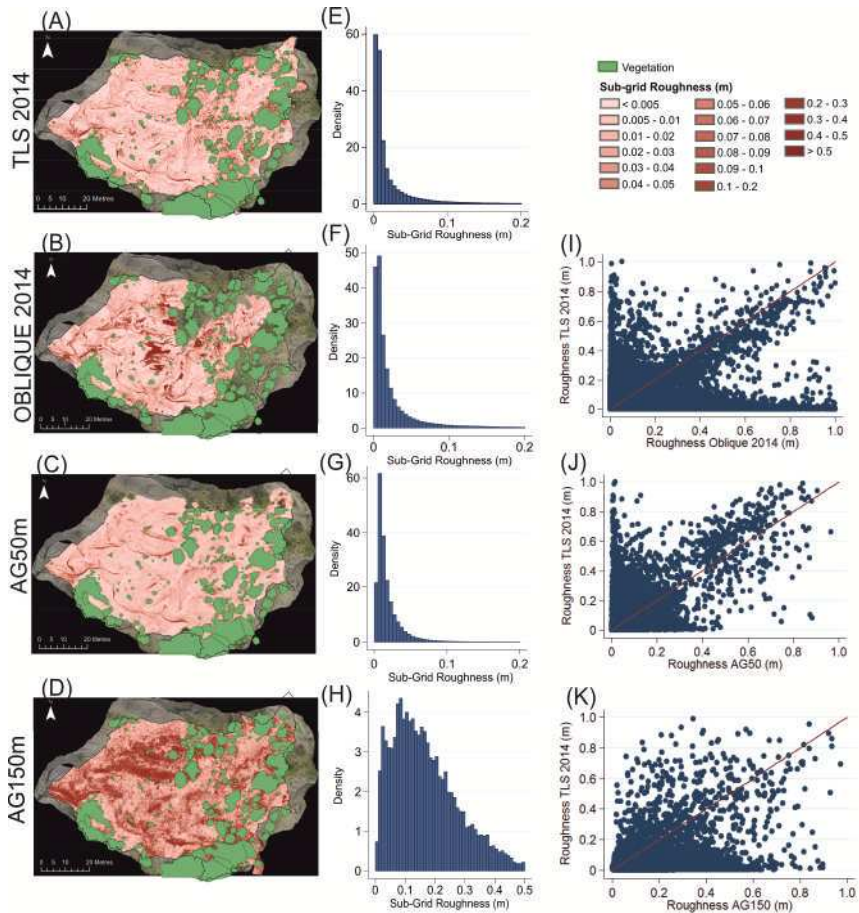
1059 **Figure 4.** Distribution of errors in the TLS validation of SfM-MVS surveys and the spatial pattern of
 1060 the errors across the small catchment (TLS survey – SfM surveys). Dashed lines indicate ± 0.1 m.



1062

1063 **Figure 5.** Profiles comparing the TLS DEM with each small catchment-scale SfM DEM. For the
 1064 location of the cross-section, see Figure 1C.

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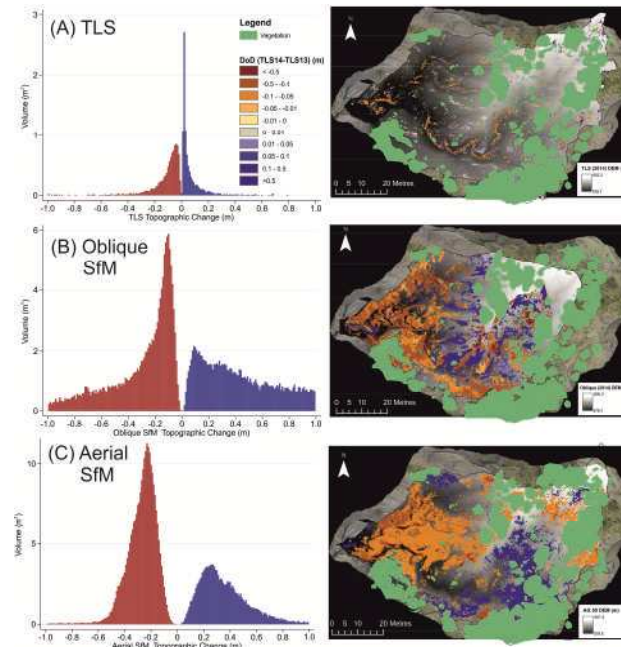


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1067 **Figure 6.** Spatial (A-D) and statistical (E-H) distributions of sub-grid roughness for the TLS (2014)
 1068 survey (A, E); oblique ground-based SfM survey (B, F); the 50 m altitude aerial SfM survey (C, G);

1069 and the 150 m altitude aerial SfM survey (D, H). Note: the x-axis range of the distribution of (H) has
 1070 been limited to aid comparison. Cell-by-cell comparison between SfM-derived sub-grid roughness
 1071 and TLS data (I-K).

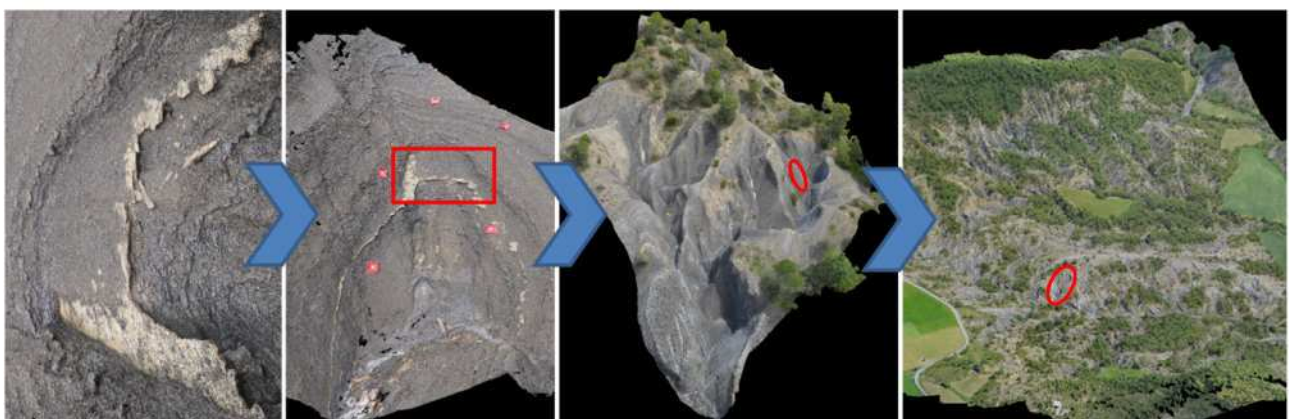
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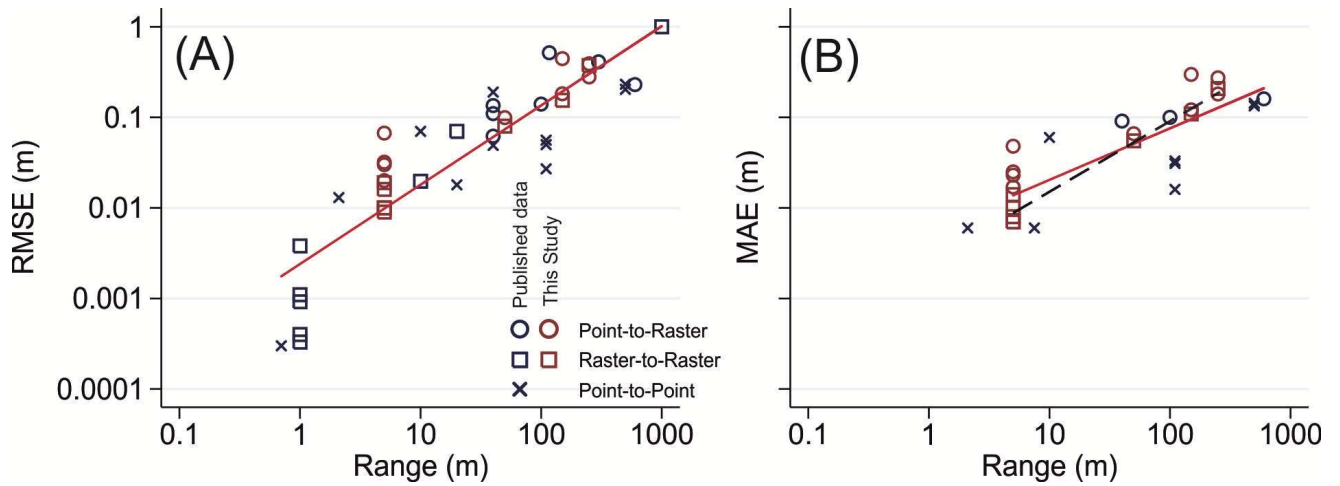
1074 **Figure 7.** DEMs of Difference (DoDs) at the small catchment scale alongside a summary
 1075 distribution of estimated volumetric changes associated with different degrees of topographic
 1076 change for (a) TLS data; (b) oblique ground-based SfM surveys (showing only absolute changes
 1077 <math>< 1</math> m); (c) aerial SfM surveys (AG50 and the UAV data in 2013).

1078



1079

1080 **Figure 8.** SfM-derived photorendered point clouds of the study badlands over a variety of scales
 1081 (left to right): from plot (~ 0.0001 ha) to slope (~ 0.01 ha), to small catchment (~ 1 ha) to landscape
 1082 (~ 100 ha).



1084

1085 **Figure 9.** Synthesis of existing SfM validation studies (navy) with data points generated in this
 1086 study (maroon) examining the effect of survey range against (A) RMSE and (B) MAE. Dashed line
 1087 in (B) summarises only raster-based validation data. Data extracted from: Favalli et al. (2012),
 1088 Harwin and Lucieer (2012), James and Robson (2012), Mancini et al. (2013), James and Quinton
 1089 (2014), Javernick et al. (2014), Lucieer et al. (2014), Micheletti et al. (2014), Ouédraogo et al.
 1090 (2014), Ruzic et al. (2014), Smith et al. (2014), Thoeni et al. (2014), Tonkin et al. (2014), Stumpf et
 1091 al. (2015), subaerial data from Woodget et al. (2014) and an unpublished result by the authors on
 1092 ice surface plots.

1093

1094 **Tables**

1095

1096 **Table 1.** Overview of field data obtained at each study scale. Note that plot and landscape scale
 1097 surveys were not conducted in 2013.

1098

	Plot Scale	Small Catchment Scale	Landscape Scale
2013 survey	-	- SfM: ground-based oblique photography - SfM: aerial photography from a UAV (50 m altitude) - TLS	-
2014 survey	- SfM: ground-based oblique photography - Terrestrial Laser Scanning (TLS) - Total Station (TS)	- SfM: ground-based oblique photography - SfM: aerial photography from a manned AutoGiro (50 m altitude) - SfM: AutoGiro at 150 m altitude - SfM: AutoGiro at 250 m altitude - TLS - TS	- SfM: AutoGiro at 150 m altitude - SfM: AutoGiro at 250 m altitude - TS

1099

1100

1101 **Table 2.** Summary of registration (i.e. MAE of targets) and georeferencing errors (i.e. RMSE on
 1102 control points) for 2013 and 2014 surveys. For the landscape-scale surveys (AG150m and
 1103 AG250m) values in parentheses indicate errors using GCPs over sub-catchment area only. For the
 1104 Oblique 2014 survey, values in parentheses indicate errors using GCPs in the lower catchment
 1105 only.

1106

TLS-based Surveys				
Survey	Year	Points	Registration Error (m)	Georeferencing Error (m)
TLS 2013	2013	351 Mn	0.003	0.002
TLS 2014	2014	317 Mn	0.002	0.002
SfM-MVS-based Surveys				
Survey	Year	Points	GCPs	Georeferencing Error (m)
Oblique 2013	2013	30.3 Mn	20	0.062
UAV 2013	2013	9.6 Mn	16	0.100
Oblique 2014	2014	99.4 Mn	21 (15)	0.210 (0.109)
AG50 m 2014	2014	2.4 Mn	29	0.086
AG150 m 2014	2014	717,000	110 (29)	0.100 (0.070)
AG250 m 2014	2014	313,000	75 (29)	0.150 (0.092)
Plots (5) 2014	2014	3.6–20 Mn	5	<0.01

1107

1108

1109 **Table 3.** Summary of errors in the total station (TS) validation of SFM-MVS surveys and the TLS
 1110 2014 survey at three different scales. Note: no TS validation points overlapped with Plot 5.
 1111

Survey	Validation points	ME (m)	MAE (m)	SDE (m)	RMSE (m)
Plot Scale (0.1 x 0.1 m grid)					
Plot 1	9	0.008	0.023	0.031	0.030
Plot 2	18	-0.002	0.048	0.069	0.067
Plot 3	12	0.004	0.017	0.020	0.020
Plot 4	36	-0.003	0.025	0.032	0.032
Small Catchment Scale (0.1 x 0.1 m grid)					
TLS 2014	515	-0.003	0.031	0.063	0.064
Oblique 2014	504	0.027	0.102	0.181	0.183
AG50 m	515	0.018	0.066	0.098	0.099
AG150 m	515	-0.020	0.121	0.181	0.182
AG250 m	515	-0.076	0.181	0.269	0.279
Landscape Scale (1 x 1 m grid)					
AG150 m	730	0.012	0.298	0.446	0.445
AG250 m	730	-0.014	0.273	0.391	0.391

1112

1113

1114

1115 **Table 4.** Summary of errors in the validation of SfM-MVS surveys with the TLS surveys at the plot
1116 and small-catchment scales (comparison of gridded data).

1117

Survey	Validation points	ME (m)	MAE (m)	SDE (m)	RMSE (m)
Plot Scale (0.1 x 0.1 m grid)					
Plot 1	808	0.006	0.007	0.007	0.009
Plot 2	2829	0.000	0.010	0.016	0.016
Plot 3	2238	0.003	0.007	0.010	0.010
Plot 4	2040	0.000	0.014	0.019	0.019
Plot 5	1149	0.005	0.008	0.009	0.010
Small Catchment Scale (0.1 x 0.1 m grid)					
Oblique 2014	277,000	0.023	0.101	0.183	0.184
AG50 m	333,000	0.022	0.055	0.077	0.080
AG150 m	327,000	-0.048	0.109	0.146	0.154
AG250 m	328,000	-0.133	0.208	0.349	0.374
UAV (2013)	331,293	-0.004	0.218	0.308	0.308

1118

1119

1120

1121 **Table 5.** Summary of: (i) sub-grid roughness statistics and (ii) cell-by-cell differences between TLS
 1122 and SfM sub-grid roughness for each plot and small catchment scale survey.

1123

Survey	Summary of sub-grid roughness (mm)			Summary of Sub-grid Roughness Differences (TLS – SfM) (mm)			
	<i>n</i>	Mean	SD	ME	MAE	RMSE	SDE
Plot 1							
TLS	1017	9.08	10.50	1.22	4.37	10.11	10.04
SfM	1017	7.85	6.21				
Plot 2							
TLS	2830	18.35	33.22	3.23	11.35	32.60	32.44
SfM	2830	15.12	16.78				
Plot 3							
TLS	2816	5.82	4.50	-0.53	2.70	4.48	4.45
SfM	2816	6.35	5.12				
Plot 4							
TLS	2442	11.60	20.60	2.10	7.94	21.11	21.01
SfM	2442	9.50	6.40				
Plot 5							
TLS	2047	8.82	12.67	-3.85	7.74	14.05	13.51
SfM	2047	12.67	12.54				
Small Catchment							
TLS (2013)	582591	30.84	92.92	-			
UAV (2013)	332269	104.07	111.87	-73.34	96.24	145.23	162.49
TLS (2014)	324940	21.76	47.37	-			
Oblique (2014)	264528	38.98	98.35	-19.18	34.28	101.17	99.33
AG50 m	241103	19.90	31.73	2.81	18.95	38.98	38.88
AG150 m	13100	176.46	126.36	-133.64	148.14	189.41	134.23
AG250 m	102	181.73	159.74	-141.39	163.99	227.41	179.03

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1127 **Table 6.** Sediment budgets at the small catchment scale derived from TLS data, ground-based
1128 oblique SfM surveys and repeat aerial SfM surveys (at ~ 50 m altitude).

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Survey	Total Erosion (m³)	Total Deposition (m³)	Net (m³)	Catchment Average Topographic Change (mm a⁻¹)
TLS	-12.63	6.40	-6.24	-1.44
Oblique SfM	-153.62	144.16	-9.46	-2.19
Aerial SfM (50 m)	-258.72	136.35	-122.37	-28.34

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