February 27, 2018

Daniele GIORDAN
Handling Editor
Special issue “*The use of remotely piloted aircraft systems (RPAS) in monitoring applications and management of natural hazards*”

Dear Daniele GIORDAN,

We have revised our manuscript according to the remarks and suggestions of the two referees. A point-by-point explanation of our responses can be found below, followed by an automatically computed marked-up manuscript version.

We warmly thank the reviewers for their comments and remarks, which helped us a lot to improve the manuscript. The reviewers asked us for a major revision of the manuscript with, in particular, 1) a better positioning of the objectives of the article to more clearly state its novelty and the new insights it provided, 2) a more in-depth evaluation of the quality of the gully network derived from the kite DEM and 3) a better structure and writing of the whole paper.

This led us to: 1) rewrite the abstract and the introduction to clarify our objectives, 2) compare our calculations with ground-truth data - the addition of these new data was made by the two new co-authors of the paper, 3) discuss these new results. In order to add this new material without significantly increasing the length of the paper, the existing parts of the discussion and the first subsections of the methods have been shortened by removing points of lesser importance. Finally, the entire manuscript has been carefully reviewed to refine our writing in a clear, concise and well-structured manner. The manuscript has also undergone a new certified language check, which was carried out by a native English speaker with skills in Earth Sciences.

We hope that the genuinely improved form and substance of the revised manuscript would meet the requirements for publication in NHESS.

Denis FEURER
(on behalf of the author team)

AMERICAN JOURNAL EXPERTS

EDITORIAL CERTIFICATE

This document certifies that the manuscript listed below was edited for proper English language, grammar, punctuation, spelling, and overall style by one or more of the highly qualified native English speaking editors at American Journal Experts.

Manuscript title:

Using kites for 3-D mapping of gullies at decimetric resolution over several square kilometres: a case study on the Kamech catchment, Tunisia

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For the sake of readability, *the reviewers' remarks* are in italics and highlighted in yellow. Our answers are in black with normal formatting and *the excerpts of the revised manuscript* are shown in italics and grey.

Answer to Report #1 submitted on 25 Sep 2017 by Reviewer #3

General comments:

Although this is a potentially interesting contribution to SfM methodologies and gully delineation using kite platforms, there are many things to improve in the aims, structure and writing. I attached a more detailed review on the pdf file.

We would like to thank the reviewer for his constructive and supportive remarks. We endeavoured to answer all these demands to produce an earnestly revised version of the manuscript.

- Aims: to me the objective of this manuscript has not been well defined. In too many occasions, the authors assume that they are making a more novel contribution than they might be making. Kite photogrammetry is quite an old approach, and its potencial (see title) has been well established, similarly also to SfM and gully delineation. The authors should try to rethink and justify which part of this work provides new insights and provides a meaningful contribution.

Gully delineation at the scale of the square kilometres with kites is actually new. This was achieved thanks to a novel workflow. We acknowledge that the novelty of our work does not lie in a remarkable innovation at a particular point in the workflow, but in a series of small innovations which, put together, demonstrated that the use of kites can make it possible to achieve methodological objectives and, as a direct consequence, thematic objectives, both being not yet explored at the square-kilometre scale. We completely rewrote the abstract and the introduction to make this positioning as clear as possible. We also changed the title as follows: "*Using kites for 3-D mapping of gullies at decimetre resolution over several square kilometres: a case study on the Kamech catchment, Tunisia*".

The objective of the paper has been more carefully defined with the following sentence in the abstract: "*The goal of this study is to investigate the ability of low-tech kite aerial photography to obtain decimetre DEMs that permit 3-D descriptions of active gullying in cultivated areas of several square kilometres.*"

In the introduction, it has been rewritten as follows: "*the aim of this study is to test the ability of low-tech kite aerial photography to obtain high-resolution DEMs that permit 3-D descriptions of active gullying in cultivated areas of several square kilometres*."

I found the references quite incomplete sometimes, especially regarding gully detection algorithms. Why are you offering a new method? Please review more critically previous works and the need for a new method.

A more in-depth review of the existing literature on gully detection algorithms was added in the revised introduction. Then, our method is grounded on two considerations:

- First, to the best of our knowledge, no algorithm for extracting channel-like features and/or gullies are truly automated, with the remarkable exception of Passalacqua et al. (2010), which we unsuccessfully tried to use on our DEM. According to our analysis, this is not due to a gap in the theory but to the fact that the delineation of the boundaries of the gullies is unclear and site dependent. This is true for the transverse delimitation of the gullies. For instance, Castillo et al., 2014, note that no study assesses where the gully 'begins' in the transverse direction. This is also true for the delimitation of the gully heads when these are small (on the order of the metre), which is a case met in our study. Orlandini et al. (2011) also noted that there are issues in automatically mapping channel heads for features of less than 1 m wide. These reasons led us to propose a semi-automatic gully mapping method. Especially, it relies on delimiting gully heads manually on a shaded view of the DEM. This positioning was explained, in the section titled "*Gully detection*" of the material and methods, which was significantly revised.

- Second, DEM sizes continue to grow. Sizes of the gigapixel order and probably even more will become the norm in the future. The processing of such huge datasets raises issues. For example, Castillo et al. (2014) could not process their most detailed DTM in full resolution. This is why we proposed an algorithm based on convolution with a Gaussian kernel, itself based on Fourier transforms. The benefits of this algorithm are explained in detail in the following sentence (Material and methods, sub-section Gully detection): "*This method has two advantages. The first relates to computation time: with the Fourier transforms, the algorithm has a computational complexity of O(n.log(n)), with n being the total number of pixels of the DEM. Sliding window algorithms have a computational complexity of O(n.m), with m being the window size in pixels. Hence, convolution with the Fourier transform is faster than filtering with sliding windows except for very small windows. Above all, the processing time with convolution is independent of the kernel size.*"
This positioning is discussed accordingly in the discussion (sub-section Gully network map and 3-D gully morphology).

In addition, please specify clearly what are the objectives and develop the methods accordingly.
- Structure and writing: This is my main concern. The objectives are not clearly defined, the actual perfomed experiments ill-explained and frequently methods, introduction and results are mixed up.
To me this careless writing has been irritating.
As said, the introduction was completely rewritten, with a better statement of the objectives, which were redefined in the new introduction with the following sentences: "*Thus, the aim of this study is to test the ability of low-tech kite aerial photography to obtain high-resolution DEMs that permit 3-D descriptions of active gullying in cultivated areas of several square kilometres. This goal jointly requires (i) determining and assessing the conditions that allow the use of a simple kite to acquire a suitable photogrammetric dataset on a relatively large area and (ii) obtaining a 3-D map of gullies and assessing the relevance of this map for erosion studies.*"
The structure of the article was also clarified ; methods were developed accordingly to the better-focused objectives and the material and methods section has the following subsections: "*1. Study site; 2. Conditions for the use*

of a kite as a photogrammetric platform; 3. Photogrammetric acquisition; 4. DEM computation; 5. Gully detection; 6. Validation".

The tone of the language is also very informal many times, it seems to be written for a report rather than for a scientific journal.
The tone of the language was checked and the wording changed where necessary. Qualitative adjectives were replaced with figures wherever possible. Several informal sentences were discarded. The minor paragraphs of the methods were moved to a newly created Appendix.

I also believe (not native english speaker) that the writing needs a major revision and I doubt this work has been edited by a proffesional english reviewer.
English correction was performed by an organization that certifies the work done. Prior to the English check, the writing has been improved throughout the entire manuscript.

I recommend major revision to give the authors an opportunity to build a better focused manuscript after undegoing major improvements to achieve the standards of a journal like HESS.
We definitively and certainly have appreciated the work of the reviewers. We thank them for having given us the opportunity to propose a revised version. We did significant rewriting efforts so that all the remarks of reviewer #3 and reviewer #4 have been taken into account. We hope that the revised version will be of highest interest to the readers of NHESS.

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In-text questions and remarks: We only reported here remarks or questions that called for answers or comments. Other remarks were formulated for words or sentences that needed linguistic check or that needed to be moved/removed. These corrections were done and marked in the revised text but were not repeated hereafter for the sake of readability.

Page 1
Note 1 (p.1, title)
I think the photogrammetric potential of this technique has been proved long ago in literature.
There was a misunderstanding due to the previous wording of the title and the previous writing of abstract and introduction. The new proposed title is: "*Using kites for 3-D mapping of gullies at decimetre resolution over several square kilometres: a case study on the Kamech catchment, Tunisia*". Before our study, to our best knowledge, there was no example of kite acquisition for 3-D mapping on several square kilometres. There was also no study which would have assessed the capacity of 3-D DEMs acquired by kite to characterise gully erosion at the scale of the entire gully network. The closest published work is the one of Marzolff and Poesen (2009) who used kites and balloons to monitor 2 gullies. Their article indeed demonstrated the potential of kites for gully monitoring, but there was still a need to prove that this technique could be used at the scale of a full gully network, which often spans over several square

kilometres, as stated by Jinze and Qingmei, 1981 (*reference added*). Our work proved that this significant step can be passed through and hence proposed a new workflow for further gully erosion studies at these scales.

It sounds as if this the first application of the technique for those scales. Is that so?

Yes it is.

It is important that the title fits the content and main topic of the manuscript.

The title was changed.

Page 1

Note 2 (p.1, abstract)

Please, follow also in the abstract the classic structure: intro, meth, res and disc.

The abstract was rewritten according to this advice.

Page 1

Note 4 (p.1, l.1)

quasi sound very vague together with the strong 'exhaustive'. Can really these words go together?

Note 5 (p.1, l.4)

Such detailed explanation should not be in an abstract.

These words and sentences were removed.

Page 2

Note 1 (p.2, l.5)

References supporting this

The whole introduction was rewritten and this assertion was not kept.

Note 2 (p.2, l.6)

Please provide references. This work is really scarce on references to photogrammetric studies on gully erosion

Rewriting of introduction was accompanied with the insertion of numerous references to gully erosion mapping and photogrammetric studies. For the particular point raised by the reviewer, we made references to the works Castillo et al. (2014), Marzolff and Poesen (2009) and the reviews and book of Smith et al. (2016), Eltner et al. (2016), Mosbrucker et al. (2017) and Carrivick et al. (2016).

Note 3 (p.2, l.8)

Clarify the meaning of plurimetric.

The wording pluri-metric is no more used in the rewritten introduction. It related to gullies width. The same wording was corrected to "*pluri-metre width*" in the test site presentation.

Note 4 (p.2, l.9)

References to provide examples.

This assertion was not kept in the rewritten introduction.

Note 5 (p.2, l.13)

What is 'small' for the authors?

The expression “small gullies” was removed. The more general expression “gully erosion” was kept throughout the introduction.

Note 6 (p.2, l.17)

I would try to express these ideas in a more objective way. There is also a breadth of papers on ephemeral gully erosion (maybe this is what the authors want to convey with small) which have not been referenced.

The wording chosen in the previous version was not adequate and may have leaded to misunderstandings. We endeavoured to use the most clear, objective and unambiguous writing at all places in the revised version, including in the introduction, where reviewer #3 raised issues of this kind. This sentence does not appear any more in the revised introduction.

We also added in the revised introduction a focused but comprehensive review of papers aiming at automatically mapping gullies from high-resolution DEMs.

Note 7 (p.2, l.23)

Again, please cite papers reconstructiing gully networks both with terrestrial and aerial aquisition in hourly time spans.

Our aim, now clarified in the revised introduction, was not to contribute with a brand new algorithm. The idea we wanted to present instead was to highlight the need for cost-effective methods allowing for the reconstruction of gully networks, which is the aim of our work. As said above, rewritten introduction, abstract and title aimed at making this goal more clear. In the revised abstract, this is reflected by the following sentence: “*The goal of this study is to investigate the ability of low-tech kite aerial photography to obtain decimetre DEMs that permit 3-D descriptions of active gullying in cultivated areas of several square kilometres.*”

Note 8 (p.2, l.26-27)

This is very general. There are gully watersheds with areas spanning across several orders of magnitude (0.1 - 10000 ha, see literature).

So, what does it mean 'typical'?

The order of magnitude of the square kilometre for a watershed that includes gullies has a rationale. It is related to the “elementary watershed” defined by Jinze and Qingmei (1981): *“By elementary watershed is meant areas under study with similar types of soil erosion characteristics, of drainage area under 1.0 km2, including all three elements of landforms which are hillslope, gully slopes and gully, which forms a complete watershed. Such a watershed is regarded as the sediment source.”* This was indicated in the revised introduction with the following sentence: ”*Soil losses caused by erosion are a major hazard in agricultural areas. Management of this risk requires a good understanding of various erosion forms and the quantification of eroded volumes over areas of several square kilometres, which is the scale of the elementary watershed as defined by Jinze and Qingmei (1981).*”

Jinze, M., & Qingmei, M. (1981). Sediment delivery ratio as used in the computation of watershed sediment yield. Journal of Hydrology (New Zealand), 27-38

Page 3

Note 3 (p.3, l.13)

Please, provide examples.

This was clarified in the revised introduction with the following sentences: "*(...) SfM-based methods can be deployed with consumer-grade cameras and even smartphones (e.g., Micheletti 2015). As image data acquisition is now possible with less constraints, the field of 3-D modelling has opened to a wide range of applications from worldwide modelling of cities and landscapes (Snavely et al., 2006, 2008) to the geosciences (Fonstad et al., 2013; Westoby et al., 2012).*"

Note 4 (p.3, l.14)

Examples.

Note 5 (p.3, l.14)

Provide company and country.

Note 6 (p.3, l.15)

I think the prize is lower for academic use.

Note 7 (p.3, l.16)

References

Note 8 (p.3, l.19)

Which algorithm is this?

Sentences that included references to specific SfM software do not appear any more in the revised introduction. The MicMac algorithm used in our study is described in the methods. This description begins with the following sentences: "*Kite images were processed with MicMac open-source software (Pierrot-Deseilligny and Paparoditis, 2006). This software implements a bundle block adjustment and a hierarchical, true multi-view dense matching algorithm that is also used by the French Institut Géographique National for producing 3-D cartography. MicMac hierarchically computes multi-view dense matching from coarse grids to the full resolution by gradually refining the results at successive scales.*"

Note 9 (p.3, l.31)

References

Note 11 (p.3, l.32)

Is this not the scale you are working with? Has not been the potential of the technique already demonstrated?

This is indeed the scale we are working at, which had not been yet covered by kites for 3-D topographic acquisition. The revised version of the introduction more clearly states this point with the following sentences which appear after a literature review : "*(...) there are yet no studies showing the use of kites for 3-D topography acquisition suitable for gully erosion mapping at the headwater catchment scale, i.e., over areas of several square kilometres. Indeed, kites suffer from several limitations, of which flight control is the most challenging, as noted by Verhoeven (2009). Some authors have given indications for ensuring proper data acquisition with kites: Bryson et al. (2013) used graduated lines to control flight altitude, and Aber et al. (2010) dedicated a chapter section to the principles and methods of kite aerial photography. However, the kite's ability to follow a predefined flight plan that enables 3-D coverage of several square kilometres has not yet been proven.*"

Page 4
Note 1 (p.4, l.1)
Sometimes the writing is too specific (Why focusing on Aber et al.?) and then later too broad with no references to support the sentence (...most commonly found...). To me, the writing is confusing and many times too informal. Try also to organize the text in paragraphs holding homogeneous ideas. Here, the authors mix that there is little information on kites in literature and then they start to enumerate the advantages of using kites. In addition, this paragraph is far too long.

Aber et al. (2010) was a major contribution in the field of small-format aerial photography. Kite aerial photography even has a dedicated section in the chapter dealing with platforms used for small-format aerial photography. We hence changed the sentence referring to this work. This is showed above in the answer to the previous remark of the reviewer.

Next, the literature review on the use of kite for photogrammetry was detailed in a dedicated paragraph of the revised introduction (together with a significant reduction of the whole introduction). The paragraph of kite literature review is now as follows: "*In various fields in the geosciences, kites have indeed already been used with photogrammetric techniques for applications requiring 3-D mapping. Oh and Green (2003) used kite imagery to compute a 3-D model of an urban area. Wundram and Loeffler (2008) compared a DEM computed from kite aerial imagery to a ground survey and classified vegetation in mountainous areas with favourable results. Smith et al. (2009) also demonstrated the potential of kite aerial photography for DEM production over small areas (i.e., less than 1 ha) using off-the-shelf cameras and professional photogrammetry software. More recently, 3-D modelling from kite imagery was performed with SfM software by a small number of authors. Dandois and Ellis (2010) have compared this technique (called "Ecosynth" by the authors) to LiDAR data for deriving elevation data and canopy height models. Bryson et al. (2013, 2016) performed centimetre 3-D mapping of vegetation in coastal areas and mapped coastal changes. Wigmore and Mark (2017) assessed the accuracy of SfM DEMs acquired with kites in comparison to LiDAR data in mountainous areas, where conditions limit the use of RPAS. More specifically, in the field of gully erosion, the potential of small-format cameras aboard kites and other platforms has been established by Marzolff and Poesen (2009) and Marzolff et al. (2011), who realised the 3-D monitoring of several individual gullies in southern Spain.*"

Note 2 (p.4, l.7)
Too Informal
Note 3 (p.4, l.15)
Start a new paragraph with limitations
Note 5 (p.4, l.26)
I was expecting here your objectives, but start discussing on methodologies.

These issues were addressed with a complete rewriting of the introduction.

Note 6 (p.4, l.28)
Interill and rill erosion also?

No. Our work focuses on gully erosion only. The wording "*erosion features and erosion processes*" was deleted and the wording "*gully erosion*" was systematically used throughout the whole revised introduction to make it more clear.

Page 5
Note 3 (p.5, l.26)
Several-meters wide gullies? Size is very general (length, width, depth)?
The missing word "*wide*" was added.

Note 5 (p.5, l.30)
No information on rainfall, soils...
Information was added.

Page 6, Note 1 (p.6, l.5)
This experiment has not been mentioned in the objectives of the manuscript.
The numerical experiment and the field experiment are now in separate subsections, both in the material and methods and in the results sections. They are announced in the introduction more clearly with the following sentence: "*(...) we first expose and verify the conditions required to allow the use of a kite for photogrammetric acquisition over several square kilometres with numerical and field experiments.*"

Page 7
Note 1 (p.7, l.3)
Which conditions?
This information was clarified in the text with the following words: "*The two delta kites performed a total of five flights with wind conditions ranging from Beaufort 3 to Beaufort 7 and with line lengths ranging from 150 to 700 m.*"

Note 2 (p.7, l.8)
No information is provided on these simulations. Equations, software?
These simulations were performed with a finite-element model using equations of aerodynamic forces on the kite line through an ad-hoc Matlab code. The new section 2.2 and the new table 2 now describe in more details these simulations. Sentences describing equations and software are the following: "*The model used was an ad hoc finite element model written in MATLAB. The line was sampled in sections of one metre. The aerodynamics of the line were taken into account with the equation $F = \frac{1}{2} A \rho V^2 C_x$, where F is the drag force in N, A is the projected surface area in m^2, ρ is the air bulk density in $kg.m^{-3}$, V is the wind speed in $m.s^{-1}$, and C_x is the dimensionless drag coefficient.*"

Page 8
Note 1 (p.8, Table 1.)
Does the manuscript need this table?
This information was asked for by reviewer #2. We moved this table in a newly created Appendix section.

Note 3 (p.8, l.21-22)
This is results or discussion, not methods. Too informal writing.
Page 9
Note 1 (p.9, l.1-3)
this is not methods. This sounds more like a blog than a scientific manuscript.
This information was asked for by reviewer #2. This being said, we agree with reviewer #3 that the proposed writing may have appeared as too informal. We proposed a new wording of these sentences, which have been moved to the Appendix, as follows: "*It is worth noting that flying large kites, especially in strong winds, can raise security issues. Aside from Aber et al. (2010), these facts are still barely reported in the scientific literature. The problems we faced appeared only under conditions of strong winds. These problems include small burns on hands, arms or clothes when the line is moving too fast or when the winder is temporarily out of control during a wind gust. This problem may also occur when the kite shows erratic movement in strongest winds when the operator is walking upwind. To avoid such problems, the following safety measures can be adopted: (i) ensuring physical protection of the operator with leather gloves and covering clothes and ensuring the security of other people by keeping the downwind zone free of any lightweight and large equipment; (ii) keeping in mind that danger - and necessary expertise - grows with wind strength, a clever decision may be not to fly if conditions are not met; (iii) securing the flying gear (attaching it with hooks, for instance); (iv) keeping attention on the equipment and the surrounding people.*"

Note 2 (p.9, l.6-7)
Please, specify kite and wind conditions combinations.
Kite and wind conditions combinations were detailed on the revised Figure 7.

Note 4 (p.9, l.12)
I don not understand this. Also try to be more concise. Would have not been better to report directly the points valid for GCPs?
These sentences were rewritten as follows: "*(...) 8 points (cross marks on Figure 1-c) that were clearly visible in the kite images were used as GCPs. Their position was measured with a Topcon GR-3 RTK DGPS with a theoretical altimetric and planimetric accuracy of 1.5 cm. These GCPs were used as spatial reference in the photogrammetric processing.*"

Note 5 (p.9, l.15)
Again conciseness. Why not giving the real accuracy in just one sentence?
We simplified this sentence by only indicating the commercial accuracy given by Topcon, the provider of the GPS used in this study. The corresponding sentence is the one presented in answer to Note 4 above.

Note 6 (p.9, l.18)
How many? Sometimes it is almost tiring to find such a confusing structure in the methodology. Specify in the methods that there were 2 objectives: a) flights for the angle assessment; b) flights for DEM reconstruction. Reorganize sections. Refer to Table 2 earlier in the methods.
The subsections of the material and methods section were clarified as requested. We hope this reorganisation made more clear the two consecutive

and inseparable steps of our approach: securing acquisition of precise imagery covering several square kilometres and then, acquiring images for DEM construction and gully mapping. Table 2 is now referred to only at the appropriate place.

Page 10
Note 1 (p.10, Table 2.)
How many?
Five flights; this information was better stated in the manuscript. Besides, as noted by reviewer #4, this table suffered from a lack of conciseness and clarity. The original table was simplified. It now focuses on the characteristics of the photogrammetric flights, and was placed in the subsection "*2.3 Photogrammetric acquisition*". Table caption was changed into: "*Flight conditions and characteristics of the photogrammetric survey.*"

Note 5 (p.10, l.10)
Please, provide your actual methodology, not the possible alternatives.
Note 6 (p.10, l.15)
Why including this if this not your case?
The corresponding sentences were deleted.

Page 11
Note 5 (p.11, l.7)
Why this is not in Table 2?
This approach was actually not used in our workflow. The corresponding sentences were deleted from the methods.

Note 8 (p.11, l.16)
Which criteria, value?
This part of the methods was revised according to the remarks of reviewer #4. These informations are now in the following sentences: "*For the delimitation of the channel network, the fully automated algorithm proposed by Passalacqua et al. (2010) was tested at first (results not reported here). With this algorithm, the automated localisation of gully heads detected by high positive plan curvatures presented flaws. We observed that different threshold values - including the proposed default value - resulted either in an excessive number of missing gully heads or in categorising many anthropogenic depressions, such as village streets or spaces between trees in orchards, as gully heads. As noted by Orlandini et al. (2011), the automatic detection of channel heads is indeed most problematic for small-scale features such as some of the features targeted by our work.*"

Page 12
Note 1 (p.12, l.2)
It sounds like results or discussion? Very confusing.
The choices made for the methods used in the article result from a close scrutiny of the existing literature and in particular the only – to the best of our knowledge – algorithm of channel-like features extraction that does not require the tuning of any parameter or threshold (see answer general comments and to Note 8 above). The tests we made with this algorithm led us to the choice of

manually digitizing gully heads. This choice is hence presented in the methods section. We proposed a different writing of these sentences in the revised version to eliminate the potential sources of confusion. This part of the revised text (including the sentences already shown above), is as follows: "*For the delimitation of the channel network, the fully automated algorithm proposed by Passalacqua et al. (2010) was tested at first (results not reported here). With this algorithm, the automated localisation of gully heads detected by high positive plan curvatures presented flaws. We observed that different threshold values - including the proposed default value - resulted either in an excessive number of missing gully heads or in categorising many anthropogenic depressions, such as village streets or spaces between trees in orchards, as gully heads. As noted by Orlandini et al. (2011), the automatic detection of channel heads is indeed most problematic for small-scale features such as some of the features targeted by our work.*
Thus, gully heads were digitized from a shaded view of the DEM with the same type of expertise as one would use in the field. This approach was used by Höfle et al. (2013) to produce their validation dataset."

Note 2 (p.12, l.11)
Why 25 cm?
This was clarified as follows: "*The threshold was chosen as slightly larger than the pixel size considering that lower differences in elevation would probably be noise. Features that did not show depths greater to 25 cm were hence discarded.*"

Page 13
Note 2 (p.13, Figure 4)
Where are the gullies? Explain better.
"detected gullies" changed to "*profiles of the detected gullies.*"

Note 3 (p.13, l.1)
Reasons why
Rewritten as follows: "*The cleaning consisted of pruning out patches with volumes less than one cubic metre. This value allowed us to eliminate small-scale noise while keeping each detail of the gullies, even when they were made of discontinuous patches.*"

Note 4 (p.13, l.6)
A figure with plan views of the detected gullies might be useful. See Castillo et al. (2014) on the Normalized Topographic method for an example.
We agree with the reviewer that plan views were useful in the case of Castillo et al. (2014) and added references to their work in this section, in particular in the starting sentence of the revised "*2.5 Gully detection*" section: "*Similar to Castillo et al. (2014), a gully is considered in this study as a morphological object with a marked depression that is in the immediate proximity of a channel, the latter being determined by another algorithm.*"
However, we would like the reviewer to consider that Castillo et al. (2014) algorithm relies on mathematical morphology in 2D, for which plan views are indeed adapted. Contrarily, our algorithm relies on calculations of volumes and

elevation differences, which explains our choice of illustrating these steps in section views.

Note 5 (p.13, l.11-13)
This should have been already explained in methods, not here.
The results shown in Figure 5 are actual results of our simulations, which confirmed our empirical observations. The sentence was reworded to make this more clear: "*This figure revealed the following three findings: (i) with light and thin lines, the kite line is almost straight, and the flying angle is maximal; (ii) when the kite is flown in sufficiently strong wind, wind speed variations cause only small effective flight angle variations; and (iii) the latter observation is all the more true when the kite line is thin and light. These conclusions corroborate the field observations, which made us choose a thin and light line for photogrammetric acquisitions.*"

Page 14
Note 1 (p.14, Figure 5.)
The simulation approach has not been properly explained.
This was corrected in the methods with a dedicated and named section "Simulations of kite flights".

Note 2 (p.14, Figure 5.)
What does 'ideal' mean?
The wording '*perfect theoretical line*' has been used instead. The definition of what a perfect theoretical line is was kept in the Figure caption. It was repeated in the added Table 1 related to paragraph "*Simulations of kite flights*" of the section "*2.2 Conditions for the use of a kite as a photogrammetric platform*". In the text, the perfect line was defined as follows: "*a perfect theoretical material with negligible weight and diameter*".

Note 3 (p.14, Figure 6.)
Is this field work, is it a simulation? Is it theoretical since there no points on it?
It is a simulation. This was clarified by the use of the wordings "*numerical experiment*" and "*numerical simulations*" as opposed to the wording "*field experiment*".

Note 4 (p.14, l.4)
Should not this and the previous section merged in a single one: flight angle?
With a clarified structure of the methods section as advised by the reviewer, the structure of the results section was also clarified. The two first subsections of the results section are now "*3.1 Simulated line characteristics*", which presents the results of our simulations and "*3.2 Observed kite flight angles*", which presents the results of our field experiments with kites.

Page 15 Note 1 (p.15, l.8)
I don't think this needs a section
The section was deleted from the results section. The paragraph was shortened and moved to the discussion section.

Page 16 Note 1 (p.16, Figure 8.)
Headcuts?
“hard cuts” was changed to “*areas of high curvature*”.

Page 20
Note 2 (p.20, l.21)
Please, reduce the conclusions, too long.
Conclusions were rewritten in order to be very much shorter as requested.

Page 20
Note 3 (p.20, l.23)
References to this concept.
The sentence does not appear any more in the revised conclusion but a reference to the Radjou et al. (2015) book was added in introduction in the following sentence: “*(...), kites can hence be at the root of dependable and low-tech solutions relying on the principles of so-called ‘frugal innovation’, which can simply be defined by "doing more with less" (Radjou et al., 2015).*”

Note 5 (p.20, l.29)
meaning of downlink?
The sentence does not appear any more in the revised conclusion but this wording, which appeared in the methods section, was modified to : “(...) *a radio link between the camera and the operator.*”

Answer to report #2 submitted on 06 Oct 2017 by Reviewer #4

General Comments:

This manuscript explores the potential for using kites as aerial platforms to generate digital elevation models (DEM) using structure from motion. The authors subsequently attempt to detect gully heads and channels based on a DEM analysis. The main focus of this manuscript appears to be on the technique of image acquisition, with a lesser focus on the structure from motion DEM generation and the gully analysis.

Generally, I think this manuscript details an interesting study. The process of using a kite to collect photos is interesting, and the authors have clearly thought through some of the important details to make this type of research successful.

The application of gully head/channel analysis comes across as an after-thought though, and it is not clear how well their approach achieves the mapping. If extracting gullies were the main goal of the paper, I would expect a stronger analysis of their results shown in Figure 8. Currently, they spend very little time analyzing the gully extraction results.

We would like to thank reviewer #4 for his encouraging remarks and his advices. A better balance between methods and thematic applications have been made. The remarks of the reviewer helped us to clarify the objectives of the study and the positioning of the paper has been better focused. We hence completely rewrote the abstract and introduction to make this more clear.

We also followed the advice of the reviewer for a much more detailed presentation of the algorithm and a more in-depth analysis of the results. The methods section have hence been balanced, with paragraphs summarized, moved, or deleted. The overall structure has also been improved. More importantly, we were joined by two new co-authors who provided independent field reference. Thus, the results of the algorithm could have been quantitatively assessed as requested. This new dataset is described in the methods section, the associated results constitute a new subsection in the revised results section and our results are discussed relatively to the existing literature.

These changes led us to shorten the existing material in the methods and the discussion sections. At many places, the existing material was summarized or shortened and carefully rewritten. It was then completed by the new material requested by the reviewer. Hence, we hope that the revised manuscript would answer the demands of the reviewer and meet the requirements for publication in NHESS.

How much of the area identified as a gully channel was a false-positive?

With the gully mapping method having been improved following the remarks of the reviewer, and by comparing the results to the independent ground survey, the amount of false positive was estimated to 8% (in length) of the gully channel. This information is given in more details in the dedicated subsection of the results. We also estimated false positives (26%) and the overall accuracy (percentage of matches, 74%). This global result is announced in the abstract with the following sentence: “(...) *we showed that high-resolution topographic data permit both the detection and characterisation of an entire gully system* *with a high level of detail and an overall accuracy of 74% compared to an independent field survey.*"

To my eye, in Figure 8 everything that is a road or a building is mapped as a gully channel.

We changed the definition of a gully. The sentence introducing this new definition is: "*Compared to Castillo et al. (2014), a gully is considered in this study as a morphological object with a marked depression that is in the immediate proximity of a channel, the latter being determined by another algorithm.*" (section 2.5: Gully detection). The algorithm was changed accordingly. The gully map is obtained by intersecting a map of gully candidates with a map of areas located at less than 15 m from the hydrological network downstream the gully heads. This has been explained in the revised section "*2.5 Gully detection*" and with a new Figure that gives a detailed description of the algorithm ("***Figure 3.*** *Flowchart of the method used to map gullies from the kite DEM. The letters associated with each step are referenced in the text describing the method in section 2.5*").

I would encourage the authors to quantitatively show how much of the area that is mapped as a gully is actually a gully. Now how much of figure 8 that is mapped as a gully is something else?

This comparison has been done with the results of the improved algorithm. It is illustrated in a new figure (***Figure 9***) and assessed in a new table (***Table 4***) in the revised version of the manuscript.

Moreover, they state in the abstract that they are going to map gully heads, but I did not see any data indicating this was done.

This sentence was removed from the whole paper. A more accurate and more in-depth description of the gully mapping method, which was improved following the advices of the reviewer, has been given in the revised section 2.5. The wording "automatic" was changed to "*semi-automatic*", given that gully heads were digitized manually. This choice was made considering the fact that, from the literature and from our own experience, detection of channel heads is most problematic for small features (e.g Orlandini et al., 2011) and gully heads detection is the main source of false positive and false negative.

As it is currently presented, this is really a "methods" paper, and I think if the authors wanted to stop there, they would be making a fine contribution to a journal that is focused on methods. But they have come very close to making a useful contribution to researchers interested in gullies, so I would encourage the authors to dig more deeply into this.

We balanced the paper with that aim, with more focus on gullies mapping, along with some details in the other methods having been summarized. More importantly, the analysis of our results against a new dataset of field measurements were carried out.

Try to go beyond just highlighting the areas that are incised. Try to identify the gully heads. See if you can add some criteria like slope or drainage area to filter out roads and buildings where there are no gullies.

We added a criteria to filter out these artefacts as advised. However, the issue of automatically identifying gully heads - although of great interest, we totally agree with the reviewer on that - is beyond the scope of our study. This is justified in the following paragraph of the discussion: "*The detection of gullies in DEMs faces the difficulty of determining an unambiguous and generic definition of what a gully is. Castillo et al. (2014) indicated that to their knowledge, no one has yet assessed where gullies 'begin' in the transverse direction. Conversely, Evans and Lindsay (2010) stated that "gully edges are the critical features for gully mapping". Baruch and Filin (2011) noted that the assumptions usually used in channel-like extraction techniques do not apply to the environment of alluvial fans in which they hence propose an ad hoc gully mapping method. In brief, due to the variety of gully shapes and the fuzzy definition of their extent, each gully mapping algorithm in the literature so far requires the manual tuning of parameters and/or thresholds and is preferably applied to specific landscape types*."

The DEM differencing using the Gaussian filter approach is interesting, but it isn't really a breakthrough that merits publication. If the authors added a few more steps to really show that they can identify gullies, I think it would make this paper much more useful to the many researchers who study gullies.

We agree with the fact that approaches with filtering do exist for gully and channel-like features mapping. We also agree that some more steps were needed. Thus, we added them, following in that the remarks of the reviewer. However, we would like the reviewer to consider the two following points:

- First, the novelty brought by our work does not rely on the sole gully mapping algorithm: to the best of our knowledge, our study is both the first case of a full 3-D mapping workflow on several square kilometres by kites, and the first demonstration that a kite-based DEM allowed for 3-D description of gullies at the scale of an entire channel network. This fact has been clarified in the sentences describing the goal of our study in the abstract, and by the following sentences in the revised introduction: "*However, there are yet no studies showing the use of kites for 3-D topography acquisition suitable for gully erosion mapping at the headwater catchment scale, i.e., over areas of several square kilometres. (...) Thus, the aim of this study is to test the ability of low-tech kite aerial photography to obtain high-resolution DEMs that permit 3-D descriptions of active gullying in cultivated areas of several square kilometres.*"
- Second, our method brings several improvements, even on the filtering approach. Indeed previous works were based on sliding windows approaches that suffer from severe limits linked to their computational complexity. This has been clarified in the methods with the following sentences : "*To delimit depressions, most recent studies use sliding windows. For example, Castillo et al. (2014) use a sliding "normalized elevation" kernel. We chose another approach: we convolved the DEM with a Gaussian kernel by computing the inverse Fourier transform of the pointwise product of the Fourier transforms of the DEM and the Gaussian kernel. This method has two advantages. The first relates to computation*

time: with the Fourier transforms, the algorithm has a computational complexity of O(n.log(n)), with n being the total number of pixels of the DEM. Sliding window algorithms have a computational complexity of O(n.m), with m being the window size in pixels. Hence, convolution with Fourier transforms is faster than filtering with sliding windows except for very small windows. Above all, the processing time with convolution is independent of the kernel size. The second advantage is as follows: convolution by a Gaussian kernel simulates diffusive processes. Hence, the DEM after convolution represents the hypothetical future shape of the ground surface after the processes involved in linear erosion have stopped and the processes leading to the healing of the gullies have begun."

I am including many line-by-line comments in the attached pdf.

Again we would like to thank the reviewer for his remarks, which helped us to improve the manuscript. Each remark or question of the reviewer was taken into account and answered in the revised version of the manuscript. Some remarks/questions/typos only required a short answer/correction (words or sentences that needed linguistic check or that needed to be moved or removed, for instance) and have not been reported hereafter. We answer below to all the other remarks, which needed a detailed explanation or argumentation. Paging and note numbers refer to the .pdf file of reviewer #4's review.

Page 3, Note 2 (p.3, l.32)
This may be true today. But in a few years it will not be true, so I suggest focusing less on these types of statements.
The sentence does not appear any more in the revised introduction.

Page 6, Note 1 (p.6, l.6)
What is the accuracy/precision?
This was added: "*This data logger had a given accuracy of 3 meters.*"

Page 7, Note 1 (p.7, l.15)
You already said this.
The sentence has been deleted.

Page 8, Note 1 (p.8, Table 1.)
Consider calling this column: Characteristic or metric. Currently, the column does not just describe the "flight type".
The table was summarized with a focus given on the photogrammetric flights only. Information about the flights that aimed at characterising the kite behaviour was moved into the text with the following sentences: "*In this study, two delta kites, one with an area of 4 m^2 and another with an area of 10 m^2, were used. (...) The two delta kites performed a total of five flights with wind conditions ranging from Beaufort 3 to Beaufort 7 and with line lengths ranging from 150 to 700 m.*"

Page 10, Note 2 (p.10, l.4)
1. How did you define a "zone"
2. What threshold do you use, and why?
3. How did you remove the residual noise manually?

The gully delineation method has been refined, described with more details and the corresponding paragraph has been almost totally rewritten. In addition, the revised manuscript includes a new figure (***Figure 3***) which illustrates the gully mapping algorithm.

Page 11, Note 1 (p.11, Figure 4)
What do each of the 5 lines denote?

Each of the 5 lines are associated with a wind speed ranging from 3m/s to 11m/s in increments of 2m/s. The following words were added to the Figure caption: "*Simulations were performed with five wind speeds from 3 m.s^{-1} to 11 m.s^{-1} in steps of 2 m.s^{-1}*".

In addition and as requested by reviewer #3, this information was detailed in the methods section with a dedicated paragraph and a new table (***Table 1***).

Page 11, Note 1 (p.1, Figure 6.)
You should probably identify the different wind speeds in the plot.

This was done and the following words were added to the caption of the figure: "*Wind conditions (in italics) are expressed in the Beaufort scale.*"

Page 12, Note 2 (p.12, l.15)
It sounds like you were mainly limited by the software. You should mention this.

Actually we were not limited by the software and were able to do all the computations we needed. However, in certain cases prohibitive computation times or prohibitive memory needs can indeed be met. This is especially the case for some gully-mapping algorithms executed on large DEMs (e.g., Castillo et al. (2014) were unable to process their largest DEM at full resolution). Following the advice of the reviewer, this issue was mentioned in the revised manuscript. In the methods section, it results in the following sentences: "(...) *we convolved the DEM with a Gaussian kernel by computing the inverse Fourier transform of the pointwise product of the Fourier transforms of the DEM and the Gaussian kernel. This method has two advantages. The first relates to computation time: with the Fourier transforms, the algorithm has a computational complexity of O(n.log(n)), with n being the total number of pixels of the DEM. Sliding window algorithms have a computational complexity of O(n.m), with m being the window size in pixels. Hence, convolution with Fourier transforms is faster than filtering with sliding windows except for very small windows. Above all, the processing time with convolution is independent of the kernel size.*".

This is discussed as follows in the discussion: "*(...) multi-scale analysis [...] was [...] seen by Passalacqua et al. (2015) as a future research direction for high-resolution topography analysis. For future work in this direction, our algorithm has the advantage of being based on Fourier transforms instead of sliding windows, which makes the computation time independent of the characteristic size of the kernel and hence opens the door to multi-scale filtering with controlled computation times. Computing time is indeed one issue for DEM* *processing; Castillo et al. (2014) have been, for instance, unable to process the full resolution of their largest DEM.*"

Page 13, Note 6 (p.13, l.3)
What do you mean by plot here?

The word "plot" was designating a field of cultivated land. These sentences were revised as follows: "*The assessment showed that the kite DEM planimetric and altimetric resolutions allow for the visual detection of numerous landscape features, including most man-made structures (roads, tracks, buildings) and gully heads that were identified in the field (e.g., subfigures 8-a and 8-b). The plot locations and limits were also clearly depicted (subfigure 8-a). Indeed, the boundaries between two separate adjacent plots are not exposed to tillage erosion and finally form small humps that are visible in the DEM.*"

Page 15
Note 2 (p.15, l.30)
How do you calculate your ground sampling distance?

This value is the spatial resolution given by the authors. Our wording may have not been adequate. Sentence changed to "*Wundram and Loeffler (2008) achieved a +0.13 m mean error, 0.36 m standard deviation of the error and 0.75 m maximal error on a 0.25 m resolution DEM (one thousand validation points).*"

Note 3 (p.15, l.35)
Is this your error between the DEM and validation points? If so, make that more clear.

This is indeed the error between the DEM and validation points given by El Maaoui et al. (2015). The sentence was rewritten to make it more clear : "*A quality check with 176 independent validation points resulted in a mean error of +0.04 m and a standard deviation of 0.07 m.*"

Page 16
Note 2 (p.16, l.16)
What type of multiscale information are you referring to?

For example, using different kernel sizes for smoothing the DEM, which would result in modelling different times of diffusion processes. The revised sentences (already mentioned in the answer to Note 2, Page 12 above) are as follows: "*A possible workaround would be the use of multi-scale analysis, which was still seen by Passalacqua et al. (2015) as a future research direction for high-resolution topography analysis. For future work in this direction, our algorithm has the advantage of being based on Fourier transforms instead of sliding windows, which makes the computation time independent of the characteristic size of the kernel and hence opens the door to multi-scale filtering with controlled computation times.*"

Note 3 (p.16, l.25)
Add some references here.
Note 4 (p.16, l.33)
What is the first step?
Note 5 (p.16, l.34)
support this with references.

Discussion has been thoroughly revised and our results were discussed relative to the methods of gully mapping of the literature. As a result these sentences do not appear any more in the revised discussion.

Marked-up version of the manuscript

For the sake of readability, the following colour code was used :

olive	paragraphs and sections that were totally rewritten
~~red~~	deleted or moved (source)
blue	added or moved (destination)

~~Potential of kite-borne photogrammetry~~ Using kites for ~~decimetric and kilometre square 3D~~ 3-D mapping of gullies at decimetre resolution over several square kilometres: ~~an application for automatic gully detection~~a case study on the Kamech catchment, Tunisia

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Abstract. Monitoring agricultural areas threatened by soil erosion often requires decimetre topographic information over areas of several square kilometres. Airborne LiDAR and remotely piloted aircraft system (RPAS) imagery have the ability to provide repeated decimetre digital elevation models (DEM) covering these extents, which is unrealistic with ground surveys. However, various factors hamper the dissemination of these technologies in a wide range of situations, including local regulations for RPAS and the cost for airborne laser systems and medium-format RPAS imagery. The goal of this study is to investigate the ability of low-tech kite aerial photography to obtain decimetre DEMs that permit 3-D descriptions of active gullying in cultivated areas of several square kilometres. To this end, we developed and assessed a two-step workflow. First, we used both heuristic experimental approaches in field along with numerical simulations to determine the conditions that make it possible and effective a photogrammetric flight over several square kilometres with a kite and a consumer grade camera. Second, we mapped and characterised the entire gully system of a test catchment in 3-D. We showed numerically and experimentally that using a thin and light line for the kite is key for making it possible the complete 3-D coverage over several square kilometres. We thus obtained a decimetre resolution DEM covering 3.18 km^2 with a mean error and standard deviation of the error in elevation of +7 cm and 22 cm respectively. With this dataset, we showed that high-resolution topographic data permit both the detection and characterisation of an entire gully system with a high level of detail and an overall accuracy of 74 % compared to an independent field survey. Kite aerial photography with simple but appropriate equipment is hence an alternative tool that has been proven to be valuable for surveying gullies with sub-metric details in a square-kilometre-scale catchment. This case study suggests that access to high-resolution topographic data at these scales can be given to the community, which may help facilitate a better understanding of gullying processes in a broader spectrum of conditions.

1 Introduction

Soil losses caused by erosion are a major hazard in agricultural areas. Management of this risk requires a good understanding of various erosion forms and the quantification of eroded volumes over areas of several square kilometres, which is the scale of the elementary watershed as defined by Jinze and Qingmei (1981). As noted by Van Westen (2013), topography is one of the major factors in most hazards and the generation of DEMs plays a central role in their analysis. This is all the more true for gully erosion, considering that differencing DEMs theoretically allow for a direct estimation of eroded volumes. It is therefore appropriate to develop methods for generating detailed descriptions of landforms threatened by gully erosion at a limited cost. Cost-effective approaches are of great interest for monitoring at several spatial and temporal scales.

Before the advent of RPAS, developments in remote sensing technology had already brought very high-resolution topographic data to the earth sciences community. Among these data, airborne LiDAR constituted a breakthrough, allowing for the characterisation of terrain surfaces with metre-size details. Such dense topographic data are of major importance for the description of hydrological-oriented geomorphological features (Vaze et al., 2010). These even allowed for the development of the first algorithms for automatic gully detection. Evans and Lindsay (2010) used a 2 m LiDAR DEM to detect gullies as zones with high curvature and low altitude relative to the average surrounding elevation computed within a moving window. With a LiDAR dataset with a point density of 4 points/m^2, Baruch and Filin (2011) performed curvature analyses to detect gully candidates in segments and then connect them into a complete network. Höfle et al. (2013) proposed a method adapted to gullies of cushion peatlands using terrestrial LiDAR. In their work, gullies were delineated as polygons by detecting breaklines in the LiDAR DEM, and then artificial dams were manually positioned on the DEM, and finally, the formed sinks were filled. Occlusion effects due to the steep slopes of gully banks and the low altitude point of view were noted by the authors. Most recently, Noto et al. (2017) used fuzzy logic on several topographic indices computed on a 1 m LiDAR DEM and combined it with image information and morphological operators to map gullies.

Although LiDAR technology has been developed for use aboard RPAS and has proven its potential in gully detection over large areas, this technology remains costly, which compromises its widespread use as an everyday monitoring tool. Structure from motion (SfM) and multi-view stereo algorithms, recent developments in photogrammetry, represent new sources of very high-resolution topographic data with a limited cost and have high potential in the geosciences as noted by Westoby et al. (2012) and Fonstad et al. (2013). In the specific field of gully erosion mapping and in line with LiDAR-based gully mapping approaches, Castillo et al. (2014) proposed an automated algorithm tested on three DEMS of different types and scales - SfM DEMs computed from ground and aerial images and a coarser and more classical DEM provided by the Spanish geographic institute - and demonstrated the potential of SfM DEMs for gully erosion studies. For interested readers, in-depth details on SfM algorithms and their use in geosciences can be found in the reviews of Smith et al. (2016), Eltner et al. (2016), Mosbrucker et al. (2017) and the book of Carrivick et al. (2016).

The advent of SfM in the geosciences has made it possible to implement cost-effective solutions that can take advantage of developments previously achieved with LiDAR data for landforms mapping applications. Indeed, SfM-based methods can be deployed with consumer-grade cameras and even smartphones (e.g., Micheletti 2015). As image data acquisition is now possible with less constraints, the field of 3-D modelling has opened to a wide range of applications from worldwide modelling of cities and landscapes (Snavely et al., 2006, 2008) to the geosciences (Fonstad et al., 2013; Westoby et al., 2012). In combination with small-format RPAS, its potential for 3-D mapping is huge, as reviewed by Nex and Remondino (2014). However, covering several square kilometres with RPAS still requires costly fixed-wing or medium-format multi-rotor unmanned aircraft. Furthermore, the use of more affordable small-format rotary wing RPAS, which have shorter flight times, is limited in strong wind conditions. Finally, local regulations may hamper or even prohibit the use of autonomous aircraft in many places around the world. According to Colomina and Molina (2014), this is the main restriction on the widespread use of these powerful and versatile technologies.

For all these reasons, kites, which have been used for more than a century for aerial image acquisition, have been enjoying renewed interest (Duffy and Anderson, 2016) for several years. In combination with most recent 3-D image processing algorithms, kites can hence be at the root of dependable and low-tech solutions relying on the principles of so-called 'frugal innovation', which can simply be defined by "*doing more with less*" (Radjou et al., 2015). In various fields in the geosciences, kites have indeed already been used with photogrammetric techniques for applications requiring 3-D mapping. Oh and Green (2003) used kite imagery to compute a 3-D model of an urban area. Wundram and Loeffler (2008) compared a DEM computed from kite aerial imagery to a ground survey and classified vegetation in mountainous areas with favourable results. Smith et al. (2009) also demonstrated the potential of kite aerial photography for DEM production ver small areas (i.e., less than 1 ha) using off-the-shelf cameras and professional photogrammetry software. More recently, 3-D modelling from kite imagery was performed with SfM software by a small number of authors. Dandois and Ellis (2010) have compared this technique (called "*Ecosynth*" by the authors) to LiDAR data for deriving elevation data and canopy height models. Bryson et al. (2013, 2016) performed centimetre 3-D mapping of vegetation in coastal areas and mapped coastal changes. Wigmore and Mark (2017) assessed the accuracy of SfM DEMs acquired with kites in comparison to LiDAR data in mountainous areas, where conditions limit the use of RPAS. More specifically, in the field of gully erosion, the potential of small-format cameras aboard kites and other platforms has been established by Marzolff and Poesen (2009) and Marzolff et al. (2011), who realised the 3-D monitoring of several individual gullies in southern Spain.

However, there are yet no studies showing the use of kites for 3-D topography acquisition suitable for gully erosion mapping at the headwater catchment scale, i.e., over areas of several square kilometres. Indeed, kites suffer from several limitations, of which flight control is the most challenging, as noted by Verhoeven (2009). Some authors have given indications for ensuring proper data acquisition with kites: Bryson et al. (2013) used graduated lines to control flight altitude, and Aber et al. (2010) dedicated a chapter section to the principles and methods of kite aerial photography. However, the kite's ability to follow a predefined flight plan that enables 3-D coverage of several square kilometres has not yet been proven.

Thus, the aim of this study is to test the ability of low-tech kite aerial photography to obtain high-resolution DEMs that permit 3-D descriptions of active gullying in cultivated areas of several square kilometres. This goal jointly requires (i) determining and assessing the conditions that allow the use of a simple kite to acquire a suitable photogrammetric dataset on a relatively large area and (ii) obtaining a 3-D map of gullies and assessing the relevance of this map for erosion studies.

To achieve this goal, we first expose and verify the conditions required to allow the use of a kite for photogrammetric acquisition over several square kilometres with numerical and field experiments. We then present a case study of image acquisition and processing on the Kamech catchment, located in northern Tunisia. Next, we propose a semi-automatic method for mapping gullies from the kite DEM. Finally we compared our results with independent ground surveys to assess the quality of the 3-D mapping of gullies and to exhibit the potential of kite decimetre DEMs to study gully erosion.

2 Material and methods

2.1 Study site

The study site is the Kamech ~~watershed,~~ catchment, ~~Tunisia (Figure 1-b), which is a small experimental watershed of 2.63 km^2,~~ located ~~on~~in Cap Bon, a peninsula in ~~the North East of~~ northeastern Tunisia (Figure 1-a).

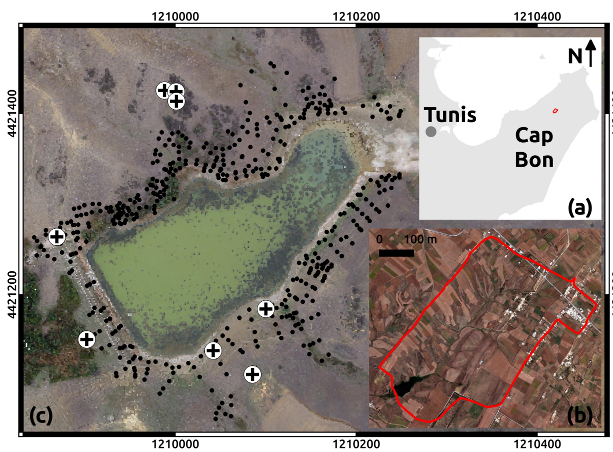

Figure 1. Location of the Kamech test site and available ground-truth data used in the SfM process. (a) Location of the Cap Bon peninsula, in ~~the north east of~~northeastern Tunisia; Kamech is marked in red. (b) Close-up of the Kamech catchment, 2.63 km^2, delineated in red;~~scale is given by the black scale bar; the~~ its oulet is an artificial lake ~~is,~~ visible in the south-east of the catchment. (c) Close-up of the available ground-truth data around the lake; scale is given by the external graduations (projection UTM, EPSG:32632); the dam is the linear feature visible on the southeast side of the lake~~; the dam outlet is at the northern extremity of the dam, near the most eastern cross~~. The ground-truth dataset is composed of ground control points (GCPs, crosses), which are used to give spatial references to the image dataset, and validation points (black dots), which are used to independently validate the DEM computed from the image dataset.

Kamech is one of the two catchments of the OMERE long-term hydro-meteorological research observatory (http://www.obs-omere.org). ~~D~~A detailed description of the Kamech catchment can be found in Mekki (2003), Mekki et al. (2006), and Raclot and Albergel (2006). More than 70% of the catchment area is ploughed and cultivated with rainfed crops. The climate is between semi-arid and sub-humid with a mean inter-annual rainfall of 650 mm and a long dry summer season from May to October. ~~E~~The elevation ranges between 80 and ~~100 m~~160 m. ~~Slopes~~The slope can locally exceed 45 degrees ~~and the landscape is crossed by several hundred decimetric to pluri-metric size gullies. In 1994, a reservoir of 140,000 m^3 was built at the outlet of the watershed (Figure 1-c). The reservoir is monitored since 1994 as part of a research agreement between the Direction for Soil and Water Conservation at the Tunisian ministry of agriculture (DG ACTA/CES, Tunisia) and the French Institute of Research for Development (IRD) and is one of the two sites of the research observatory OMERE (http://www.obs-omere.org)~~. The sub-stratum ~~of this test site~~ is mainly composed of ~~intercalations of~~ marl and clay ~~zones and~~ intercalated with sandstone layers. These layers have ~~a global south-east~~ an average southeast dip of approximately 30 degrees corresponding to the global anticline of Cape Bon. The right~~-~~ bank ~~side~~of the catchment shows a natural slope ~~globally~~ generally parallel to this dip and ~~presents~~ mainly presents marly layers. Hence, most gullies of the area have developed on this side. Sandstone ~~bar~~ outcrops ~~can be seen~~ are visible on the left~~-~~ bank ~~side~~ of the catchment (Figure 1~~-c~~-b). The soils have a sandy-loam texture with depths ranging from zero to more than 2 metres depending on the location within the catchment and local topography. The drainage network is composed of several kilometres of wadi and gully sections with decimetre to pluri-metre widths. The network drains intermittent flow discharge into a reservoir of 140,000 m^3 built in 1994 that silts up at an annual rate of 15 t.ha^{-1} because of water erosion (Inoubli et al., 2017). The gullies are permanent, and the gully heads are located at the edge of the agricultural fields. There is no significant ephemeral gully in the sense of Vandaele et al. (1996) or Nachtergaele and Poesen (1999). ~~Quantitative monitoring of erosion on this site is mainly focused on individual gullies considered as representative of the general active processes and has been done with classical topographic methods (see Khalili et al., 2013,for detailed results).~~

2.2 ~~Kite-based image acquisition method~~Conditions for the use of a kite as a photogrammetric platform

~~The image acquisition protocol lies~~ To ensure photogrammetric image acquisition of several square kilometres, the method is based on the following hypothesis: with a very stable kite as a payload carrier, ~~embarked~~ the position of the camera remains stationary ~~in relation~~ relative to the kite operator.

~~As a consequence, the "flight plan" is a simple~~ With this hypothesis, the flight path (i.e., the kite coordinates) is then a translation of the operator's ~~movement.~~course. Moreover, to use the simplest and most reliable apparatus, image acquisition is automatically triggered at a pre-set time interval. ~~Hence t~~The ~~"~~flight plan~~"~~ can hence be prepared prior to the survey itself and followed on the ground~~,~~ without any ~~necessity of having~~need for remote control of the platform ~~n~~ or a ~~down~~radio link ~~giving information about the carrier position~~ between the camera and the operator. ~~The operator only needs to know flight angle and kite line length (Figure 2). Flight altitude is controlled by line length. The line is hence graduated every 10 m on the first 100 m and then every 50 m with a simple colour/thickness coding system. A comparable approach is used by Bryson et al. (2013), with fewer constraints on the acquisition protocol due to the low altitudes. In the case of the method described in this paper, whose aim is to seamlessly acquire images on kilometre square wide areas, flight angle stability had to be carefully investigated and its mean value properly estimated.Evaluation of the average flight angle and its steadiness for each kite and for different operating conditions~~Thus, this hypothesis and the conditions ensuring its validity have to be carefully verified. This verification has been done with two complementary approaches, namely, field observations and numerical simulations, which are described in the two following subsections.

~~A steady flight angle~~**Empirical kite flight characterisation**

~~First~~In this study, two delta kites ~~(~~, one with an area of 4 m^2 ~~wing~~ and ~~one~~another with an area of 10 m^2~~wing)~~ were ~~flown~~used~~within different wind conditions and with different line lengths (see Table ??)~~. We used framed delta kites chosen among a large variety of kites because of their flight qualities (stability and high flight angles), easy assembly - with no need for adjustment in the field - and a reasonable payload capacity. A schematic representation and a close view of the equipment used for this study are shown in Figure 2.

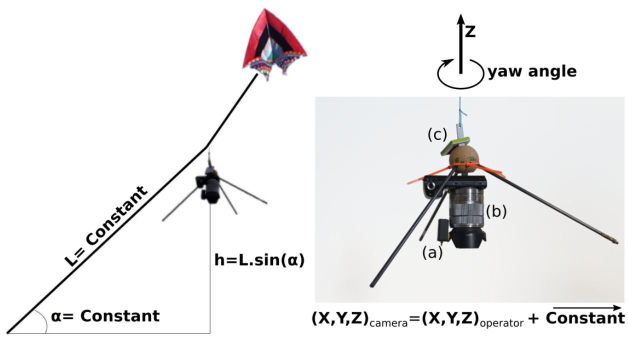

Figure 2. Left: schematic principle of kite image acquisition with a steady flight angle. Right: ~~T~~payload close-up, which consists of a tripod with ~~camera:~~ (a) ~~intervallometer;~~an automatic trigger (b) a camera~~;~~, and (c) a GPS logger. The yaw angle is the angle ~~of the camera~~ around the Z axis.

As shown, the camera was mounted under a protective tripod hanging from a long line forming a simple pendulum. This long pendulum smoothed out the potentially erratic movements of the kite. Finally, acting in the wind as a vane, the tripod allowed for a natural aerodynamic stabilisation of the yaw angle, which is the rotation angle around the vertical axis of the tripod (Figure 2-c).

The line used for all experimental setups was Cousin-Trestec TopLine Ultimate 16175, which is made of Dyneema®, a strong and light material. This line had a strength of 87 daN, a diameter of 0.8 mm and a weight of 0.39 g.m^{-1}. The two delta kites performed a total of five flights with wind conditions ranging from Beaufort 3 to Beaufort 7 and with line lengths ranging from 150 to 700 m. The use of the Beaufort scale was preferred in the field because it can be estimated from direct observation of land conditions (moving branches, raised dust,...) and does not require an anemometer. Camera and operator positions were simultaneously logged with a standalone QSTARZ BT1400S GPS data logger used with a 1 Hz acquisition rate (Figure 2-c). This data logger had a given accuracy of 3 metres. These logs ~~have then been~~ were used to compute effective kite flight angles~~.~~ from the pairs of camera and operator positions. Analysis of these flight angles was performed to verify the validity of our hypothesis and to empirically estimate the actual average flight angles. This information also ~~allowed us~~made it possible to check for the idealwind range in which the kite remains in a stable position, wing remained stable with a steady flight angle , and without and with neither shocks nor sudden movements during the flight.

Simulations of kite flights

Besides In addition to the collecting of the experimental data, numerical simulations of line shape and kite position have been done were performed for different wind conditions , (from 3 m.s^{-1} to 11 m.s^{-1} , which roughly corresponds to Beaufort winds from 3 to 7in increments of 2 m.s^{-1}) and for different line lengths (from 0 to 700 m). Use of Beaufort scale is preferred in the field as it can be estimated from direct observation of land conditions (moving branches, raised dust,...) and does not require any anemometer. The simulations compared two 300 m kite lines with two different materials: a Dyneema® line weighing 0.1 g.m^{-1} and a polyester line with a weight of 1 g. m^{-1}. For the sake of simplicity, simulations have been done with the same diameters for both lines The materials used for kite lines are of particular interest. Highly-resistant lines such as Dyneema® can be used in much smaller diameters than polyester of comparable strength, which results in less weight and aerodynamic drag. However, as the Dyneema® line is stronger than polyester, it is usually used with smaller diameters , which implies a lighter line and less drag on the line. For each line type, simulations compared the ideal case (no draft and lines with no weight , leading to the kite line being straight) with the more realistic scenario where the line is bowed by these two physical phenomenaPolyester, Dyneema® and a perfect theoretical material with negligible weight and diameter were numerically compared to each other. For all the simulations, the total load of therig load was 500 g, which is the actual load weight of the rig we used (shown in Figure 2). Effect of line length has also been assessed, both with these simulations and by experimentation. Empirical observation was carried out: using a thin and light line , notably, the line weight and draft should have a negligible impact on effective flight angle, even with long lines. Simulations were performed with the physical characteristics of the 10 m^2 delta wing, which weighs 2.7 kg.

The model used was an ad hoc finite element model written in MATLAB. The line was sampled in sections of one metre. The aerodynamics of the line were taken into account with the equation $F = \frac{1}{2} A \rho V^2 C_x$, where F is the drag force in N, A is the projected surface area in m^2, ρ is the air bulk density in kg.m^{-3}, V is the wind speed in m.s^{-1}, and C_x is the dimensionless drag coefficient. This equation was also used to calculate the wind forces on the kite as a function of wind strength. All the parameters used for the simulations are reported in Table 1. These numerical simulations aimed at assessing the impact of the kite line characteristics on the aforementioned hypothesis.

Robust and simple equipment

Criteria for choosing the material were cost, robustness, in-flight reliability and easy set up. The whole equipment is constituted by the platform itself, the rig attached below, a camera and a small GPS (Figure 2).

For the platform, framed delta kites were used.They have been chosen within a large variety of kites because of their flight qualities (stability and high flight angles), easy to mount - with no need for adjustment on the field - and fair payload.In this study, two delta kites, one of 4 m^2 and another one of 10 m^2 have been used. The line used for all experimental setups is a thin and light 90 kg Dyneema® line.

Table 1. Parameters used for the simulation of line shapes and flight angle

Parameter	Perfect line	Dyneema®	Polyester
Line diameter (mm)	0.01	0.8	2.5
Line weight (g/m)	0.01	0.39	3
Resistance (daN)	N/A	87	59
Pull angle (°)		60	
Total weight (kg)		2.7 (wing) + 0.5 (payload)	
Wing area (m^2)		10 ($A = 8.7$)	
Wing drag		$C_x = 0.15$	
Line drag		$C_x = 1$ (used for cylinders)	
Air density (kg/m3)		$\rho = 1.18$	
Line length (m)		[0,700]	
Wind speed (m/s)		$V \in \{3;5;7;9;11\}$	

~~The rig is a simple tripod hung down a long line forming a simple pendulum (Figure 2). The rig is fixed to the kite line some tens of metres apart from the kite itself so that the rig is less sensitive to kite movements. In addition, using a long line for the pendulum ensures low-frequency movements of the rig around the vertical position. Finally, acting in the wind as a vane, the tripod allowed for a natural aerodynamic stabilisation of the yaw angle, which is for the rotation angle around the vertical axis of the tripod (Figure 2). Even if not necessary for image processing - variable yaw angle can even be interesting for specific applications - stable yaw angle can however be interesting for manual images inspection after flight.~~

~~The camera was chosen as a compromise between weight, image quality and cost (see Table 6). A good compromise found at the time of the experiment was the Sony NEX-5N (Figure 2-b), which allowed us to take 16Mpix images with fixed focal and disabled image stabilizer. Fixed optics are indeed necessary to be able to properly and robustly estimate camera model during lens autocalibration performed in the SfM approach. A GentLED-Auto intervallometer has been used to automatically trigger the camera at given time intervals (Figure 2 -a)~~

2.3 ~~Field and image data~~Photogrammetric acquisition

Image acquisition was performed in September 2013 after the dry season, when vegetation cover was minimal. The equipment used for photogrammetric acquisition is shown in Figure 2 above.

~~Two autonomous QSTARZ BT1400S GPS loggers were used, one attached onto the camera (Figure 2-c) and the second on the kiteoperator. This positional information has been gathered in order to develop and refine the image acquisition protocol at first and then to check its operational application.~~The Dyneema® kite line was graduated every 10 m for the first 100 m and then every 50 m with a simple colour/thickness coding system with a comparable approach to that used by Bryson et al. (2013). Image acquisition was performed with the 10 m^2 kite. A maximum flight altitude of 500 m was chosen to acquire images with decimetre ground sampling distance. The corresponding line length was estimated with the worst case for the flying angle (50°)

and resulted in a maximum line length of 600 m. The targeted area was covered with parallel flight lines. These lines were oriented northeast-southwest along the global orientation of the catchment. The corresponding ground path was walked from the right bank towards the left bank. To simplify the field work, the operator remained at first on the same path near the right bank crest and unrolled different line lengths (150, 360 and then 600 m) so that the kite was positioned at the right downwind distance from the operator. Then, the operator continued to walk the rest of the ground path towards the right bank and covered the targeted area as planned.

Flying large kites, especially in strong winds, can raise security issues. The only problems we faced were under conditions of strong winds. It consisted in small burns on hands/arms or clothes when the line was going too fast, or having the winder temporarily slept out our hands during a wind gust. It also happened that kite went bad in strongest winds when not looking at it during several seconds and moving upwind. To avoid easily the main problems, the following security measures can be given: (i) protect yourself and other people: make sure the zone downwind any light and large equipment is always clear of any people as it is a dangerous zone; use gloves and more generally covering clothes; (ii) remember that danger and necessary skills grow with wind strength: a clever decision may be not to fly if conditions are not good; (iii) always secure flying gear (attach it with hooks for instance); (iv) keep looking at your equipment and at surrounding people. Images were taken with a Sony NEX-5N camera (Figure 2-b), which has a 16 Mpix 23.4x15.6 mm sensor. This camera was used with a fixed 18 mm focal length, and the image stabilizer was disabled, which are two important settings for the lens autocalibration step in SfM processing. This camera was chosen as the best compromise at the time of the experiment between weight, suitability for photogrammetric analysis and cost (see Table 6 in the Appendix). Automatic triggering was performed with a gentLED-Auto 05C intervalometer (Figure 2-a). A time interval of 5 seconds between each image was chosen to ensure sufficient overlap.

Four flights were done on this site during three days with various conditions of wind, and with either one of the two available kites, depending on wind conditions.

As a recurrent operation of the OMERE observatory, bathymetry and topography of the reservoir has been done a few weeks before image acquisition. From this dataset, eight points (cross marks on Figure 1)were visible in images and could therefore be used as Ground Control Points (GCPs). These GCPs were used to give spatial reference as an input to the photogrammetric image processing step described in the following section. Additionally, 469 points measured around the reservoir were used as independent validation points. Due to the fact that this dataset was not constituted with a view to validate a SfM DEM, some points of the original data set had to be removed: these points were located under or too close to trees and would have led to a bad estimation of DEM error. All these points including GCPs were measured with a Topcon GR-3 RTK DGPS with a given altimetric and planimetric accuracy of 1.5 cm. Further estimation of altimetric accuracy with the same instrument was however proven to be closer to 3 cm. Validation points were not used to compute the 3D model and were kept for independent quality assessment of the DEM.

Once the kite flight behaviour has been characterised - in particular effective flight angle - the last flights were used to obtain a quasi-complete coverage of the Kamech catchment, with a Complete coverage of the targeted area in the Kamech catchment was achieved within two flights of 3 hours each. A total of 752 images were used to cover an area of 3.18 km^2. The maximum flight altitude of 500 m leading led to a maximum estimated ground pixel size of 0.13 m . In total, 752 images have been used to cover an area of 318 ha (see Table 2 for a summary of all these data). However, the very The upstream part of the catchment could not be covered. Indeed, being crossed by a power lineis crossing the catchment in that place and we strictly avoided to have , we avoided having the kite line in close proximity to this power linenear it for safety reasons. As a result, a small area of the catchment was not covered by multi-view imagery. MHowever, more area downstream and outside the catchment - could bewas reached., which explains that the total covered area (318 ha) As a result, the dataset covered an area of 3.18 km^2, which exceeds the totalexceeded the area of the catchment itself (263ha2.63 km^2).

Table 2. Flight conditions -and characteristics of the photogrammetric surveywhen applicable - for kite characterisation and image acquisition flights.The first flights only aimed at characterising the kites behaviour so no images were acquired during these flights.

Flight type Kite characterisation Image acquisition Estimated Beaufort	3 to 7 4-5
Kite used	4 m^2 & 10 m^2 10 m^2
Line lengths (m)	150to 700 150, 360, 600
Flying heights (m)	120to 600 120, 300, 500
GCPs	-8
Validation points - 469 Focal length (mm)	-18
Sensor size (mm)	-23.4x15.6
Images used	-752
Max. pixel size (m)	-0.13
Total covered surface (km^2)	- 318 ha 3.18

Finally, 8 points (cross marks on Figure 1-c) that were clearly visible in the kite images were used as GCPs. Their position was measured with a Topcon GR-3 RTK DGPS with a theoretical altimetric and planimetric accuracy of 1.5 cm. These GCPs were used as spatial reference in the photogrammetric processing.

2.4 3D model productionDEM computation

Many photogrammetric software are available on the market, either commercial or open-source. We used the Kite images were processed with MicMac open-source solution Micmac (Pierrot-Deseilligny and Paparoditis, 2006). Micmac has already been described in the introduction in its broad lines. It implements the dense matching algorithm used by IGN to calculate their commercial 3D products. It is a software (Pierrot-Deseilligny and Paparoditis, 2006). This software implements a bundle block adjustment and a hierarchical, true multi-view algorithm. It is hierarchical in the sense that coarser grids are gradually refined by dividing by two the dense matching algorithm that is also used by the French Institut Géographique National for producing 3-D cartography. MicMac hierarchically computes multi-view dense matching from coarse grids to the full resolution by gradually refining the results at successive scales. The full resolution of the DEM at each step, until the user-defined final step (generally, full resolution) is reached. The DEM full resolution is the images mean ground resolution of the DEM is the average ground resolution of the images, which is estimated from the average flying height. This average flying height itself is estimated from the mean flight altitude and the average altitude of SIFT points . It is a true multi-view algorithm in the sense that all the images that can see the point being calculated key points computed with the SIFT algorithm (Lowe, 2004). All images covering the same point of interest are taken into account in the same bundle adjustment for the calculation of each point in the DEM. Thus, altimetric precision is of the order of magnitude of one pixel. This procedure results in an altimetric precision of one pixel on average. Of course, other kinds of software are available with algorithms of similar quality. For more information about the different SfM software available and their comparison with Micmac, the reader is invited, for instance, to consult the works of Stumpf et al. (2015), Jaud et al. (2016) or Smith et al. (2016).

The MicmacMicMac process (Table ??) is typical of SfM algorithms . Two characteristics of these algorithms have consequences on the planning of field work. The first characteristic is the memory limit of the calibration algorithm (a module called Tapas) . In this module, all SIFT points pairs previously recognized and matched are loaded in memory at the same time. As pointed by other authors, e.g Smith and Vericat (2015), this creates a bottleneck in resource capacity, especially in consumer-grade computers. Several workarounds are developed, from increasing computer power (e.g. using computer cluster) to algorithmic developments. These developments can have different directions : trying to merge results of computations done by chunks or decimating the set of SIFT points so that less memory would be necessary, for instance . Although some possibilities of reducing the number of SIFT point now exist, projects with more than one thousand images remain difficult to calibrate. (see Appendix) and is comparable with them (see for instance Stumpf et al., 2015 and Jaud et al., 2016).

After tThe SfM step (i.e. SIFT points recognition and matching + plus bundle calibration) is finished the completely automatic and followed by two manual stepsof the process were done. Firstly, we selected . First, the area for dense image matching and secondly, we pointed at the exact position of the GCPs. Then the project has was selected. Second, the GCP positions were manually digitized in the images to give the project a cartographic reference. and the dense matching can be launched.. The automatic dense image matching was finally run and resulted in a 0.20 m DEM. When GCPs are not available, the georeferencing of the project can be done with GPS data giving camera position at the time of image acquisition. The pipeline ends with the calculation of the DEM and the orthophotograph. The DEM is calculated by tiles so that the memory requirements fit with the computer capabilities. The computer we used was All image processing was performed on a laptop computer equipped with an Intel Core i7-3840QM CPU at 2.80 GHz and 32 Go of memoryGB of RAM.

Another characteristic of SfM processing has a direct implication in the specific case of our project. Our images have been acquired at a height of several hundred metres, leading to a rather poor 3D structure of the image block. When terrain height variability is low relatively to imaging distance a strong correlation between sensor altitude and focal length appears. The bundle calibration can fail at calibrating the intrinsic parameters of the camera, or fall into a false minimum. For this reason, it is always recommended to acquire a special set of images for the camera calibration. They can be taken from the ground if an adequate 3D scene is available, or by flying at low height over a well-defined relief such as buildings or natural geomorphic features. The calibration obtained separately can then be used in the bundle adjustment.

2.5 Gulliesy detection

As stated in introduction, our method for automatic gullies detection is a combination of existing methods. As said above, a gully is a portion of the hydrological network characterized by a sharp depression which is discordant with the smoothness of the surrounding topography. As others, we hence exploited the fact that erosion can be numerically detected by comparing the actual landscape to a landscape represented by a filtered digital elevation model. Gully border is then the limit between the zone with smooth topography and the steep slopes of the gully edges.Similar to Castillo et al. (2014), a gully is considered in this study as a morphological object with a marked depression that is in the immediate proximity of a channel, the latter being determined by another algorithm.

To delimit depressions, most recent studies use sliding windows. For example, Castillo et al. (2014) use a sliding "normalized elevation" kernel. We chose another approach: we convolved the DEM with a Gaussian kernel by computing the inverse Fourier transform of the pointwise product of the Fourier transforms of the DEM and the Gaussian kernel. This method has two advantages. The first relates to computation time: with the Fourier transforms, the algorithm has a computational complexity of $O(n.log(n))$, with n being the total number of pixels of the DEM. Sliding window algorithms have a computational complexity of $O(n.m)$, with m being the window size in pixels. Hence, convolution with Fourier transforms is faster than filtering with sliding windows, except for very small windows. Above all, the processing time with convolution is independent of the kernel size. The second advantage is as follows: convolution by a Gaussian kernel simulates diffusive processes. Hence the DEM after convolution represents the hypothetical future shape of the ground surface after the processes involved in linear erosion have stopped and the processes leading to the healing of the gullies have begun.

At first, we tested two-steps methods such as the one For the delimitation of the channel network, the fully automated algorithm proposed by Passalacqua et al. (2010) was tested at first (results not reported here). The two steps are (i)localisation of gully heads and (ii) network delineation from these heads. As said above, gully heads localisation is the part which presents most issues. Very broadly, a pixel is considered as a network head if it is concave and its concavity is beyond a threshold automatically calculated from the statistics of the entire landscape. The threshold can also be manually tuned. This automatic detection is most problematic for small-scale features (Orlandini et al., 2011) such as the ones targeted by our work. Indeed, when we executed the Passalacqua et al. (2010) algorithm, With this algorithm, the automated localisation of gully heads detected by high positive plan curvatures presented flaws. We observed that different threshold values - including the proposed default value - resulted either in missing several an excessive number of missing gully heads or in categorizing as gully heads categorising many anthropogenic depressions, such as streets in villages village streets or spaces between trees in orchards, as gully heads. As noted by Orlandini et al. (2011), the automatic detection of channel heads is indeed most problematic for small-scale features such as some of the features targeted by our work.

We then decided to digitize manually the gully heads on Thus, gully heads were digitized from a shaded view of the DEM , with the same kind type of expertise as one would use on in the field. The noticeable difference is that the entire digitalisation process This approach was used by Höfle et al. (2013) to produce their validation dataset. The entire digitization of the gully heads on the DEM was achieved in a few tens of minutes instead of hours or days that would have been necessary on the field. less than two hours. Once the gully heads were digitized the algorithm followsed the flowchart ofin Figure 3.

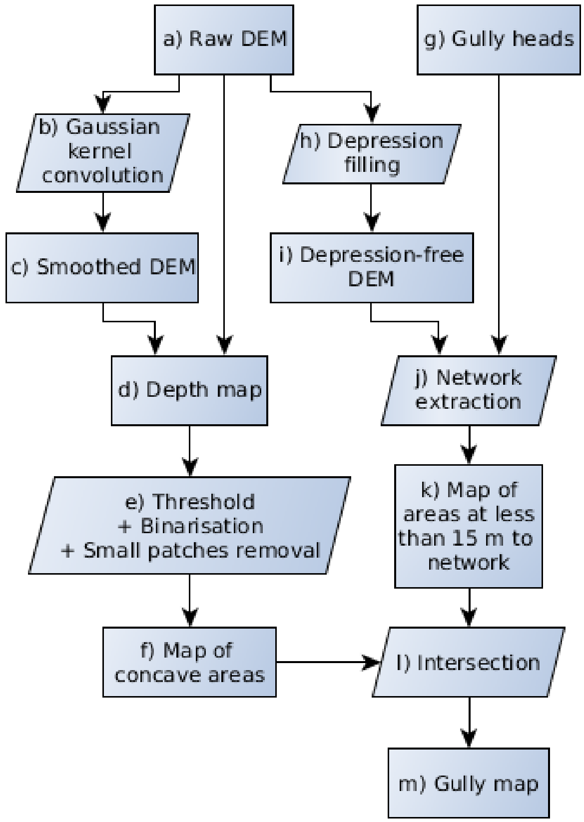

Figure 3. Flowchart of the method used to map gullies from the kite DEM. The letters associated with each step are referenced in the text describing the method in section 2.5

The raw DEM (a) was convoluted with a Gaussian ~~filter~~ kernel (b) ~~, resulting~~ of a standard deviation of 10 metres, which resulted in the smoothed DEM (c). ~~This smoothed DEM (e~~We chose this value so that twice the standard deviation of the kernel was equal to the width of the largest gullies to be detected (i.e., 20 m). The raw DEM (a) was subtracted ~~to the raw DEM~~ from the smoothed DEM (c) to create a depth map (d), which ~~therefore is the~~ was therefore the estimated depth of the natural surface below the smoothed surface. (e) ~~was a step of thresholding~~ consisted of applying a threshold to the depth map and cleaning ~~up~~ the result up~~(see Figure 4)~~. The threshold ~~consisted in discarding pixels that were not at least~~ was chosen as slightly larger than the pixel size considering that lower differences in elevation would probably be noise. Features that did not show depths greater to 25 cm ~~deep~~were hence discarded. The cleaning consisted ~~in discarding patches that were~~ of pruning out patches with volumes less than one cubic ~~meter in volume~~metre. This value allowed us to eliminate small-scale noise while keeping each detail of the gullies, even when they were made of discontinuous patches. Operation~~s~~(e) resulted in the (f) map. Steps (a) to (f) are illustrated with a section view in Figure 4.

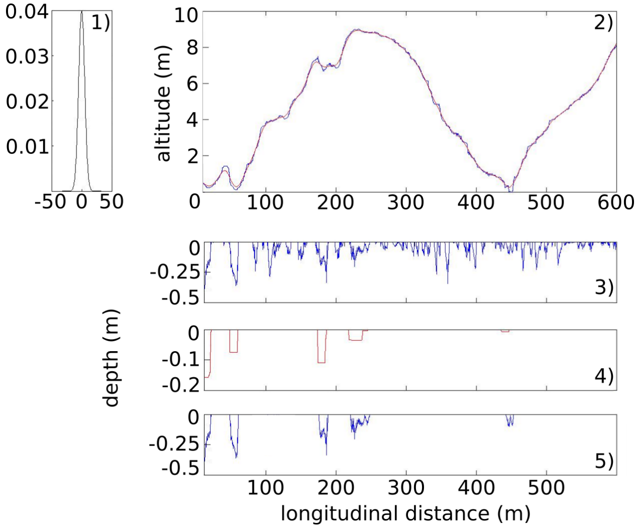

Figure 4. Principle of gully ~~contour~~ detection~~. Right~~: ~~the~~1) a Gaussian ~~filter~~kernel with a 10 m standard deviation~~. Left, from bottom to top:~~; 2) original (blue) and smoothed (red) topography; 3) raw negative differences between the original and smoothed topography; 4) detection of ~~possible~~the potential gullies~~ with a threshold on the volume of the element~~, then pruning out elements of less than one cubic metre; 5) profiles of the detected gullies.

~~The right side of the flow chart corresponds to~~ Steps (g) to (k) correspond to the extraction of the hydrological network. ~~As already described,~~ To map the hydrological network downstream of the previously digitized gully heads (g)~~were digitized manually. A~~ , a depression-free DEM (i) was generated from the raw DEM by filling gaps (h). The hydrological network (j) was generated by ~~descending the depression-free DEM~~ a steepest descent algorithm in (i) from gully heads ~~along the maxima descent. A~~ (g). Considering the typical width of the gullies at the test site, a binary map (k) of the areas located ~~at~~ less than 15 ~~meters of~~ metres from the network was computed. Intersecting the binary maps (f) and (k) resulted in the final gully map (m).

2.6 Validation

DEM quality

The kite DEM quality was evaluated on an independent validation dataset composed of 469 points (see Figure 1-c for their localisation) and the median error, mean error and standard deviation of error were used as evaluation criteria. This control dataset was surveyed with the same Topcon GR-3 RTK DGPS used for GCPs. These data came from a recurrent operation of bathymetry and topography of the reservoir performed a few weeks before image acquisition and from which points covered by vegetation were excluded.

A qualitative assessment was also performed with a visual inspection of the kite DEM at full resolution.

Gully map

The quality of the gully map derived from the kite DEM was also assessed with independent data. The gully map was compared to a gully network derived from a field survey and completed by the interpretation of a QuickBird image. The field survey was carried out between 2009 and 2012 on nearly 70% of the total gully and wadi network length of the Kamech catchment (Ben Slimane, 2013). Each gully and wadi was divided into sections whenever a branching (confluence) or a significant change in the cross-section size was identified. For each gully an upstream, middle and downstream position was recorded with a handheld Garmin eTrex GPS. The precise delineation of each section was photointerpreted on the orthorectified pansharpened QuickBird image using the upstream, middle and downstream GPS positions of the surveyed sections. Gully sections that were not described during the field survey were delineated on the orthorectified pansharpened QuickBird image only.

As in Thommeret et al. (2010), the field-mapped network was considered as a reference and two parameters were computed from the matching: "*the false negative* [under-detection], *which is the length of the reference not included in the extracted network domain, and the false positive* [over-detection], *which is the length of the extracted network not included in the reference domain.*" We also added a parameter that aimed to represent the overall accuracy and that was computed as the ratio of the total length of correctly mapped gullies to the total length of surveyed gullies.

Gully 3-D morphology

Finally, we tested the ability of the DEM to derive 3-D information that allows for gully morphology monitoring. This evaluation was based on a profile comparison of the kite DEM with a reference DEM derived from an intensive field topographic survey of a mid-size gully. This reference DEM was calculated on a 0.05 by 0.05 m grid from a very dense point dataset acquired in 2009 using a total station that had an (X,Y,Z) accuracy better than 0.01 m (Khalili et al., 2013). Standard statistics on the deviation between the kite DEM and the reference DEM were derived on an elevation profile of a path composed of a series of line segments.

3 Results

3.1 ~~Kite in-flight~~Simulated line characteristics

~~**Importance of kite line**~~

Figure 5 shows the results of kite line shape simulations with different wind speeds, line characteristics, and physical processes taken into account.

This figure ~~confirms three field observations~~revealed the following three findings: (i) with light and thin lines, the kite line is almost straight, and the flying angle is maximal; (ii) when the kite is flown ~~with~~ in sufficiently strong wind, wind speed variations cause~~s~~ only small effective flight angle variations; and (iii) the latter observation is all the more true when the kite line is thin and light. ~~In conclusion, using~~ These conclusions corroborate the field observations, which made us choose a thin

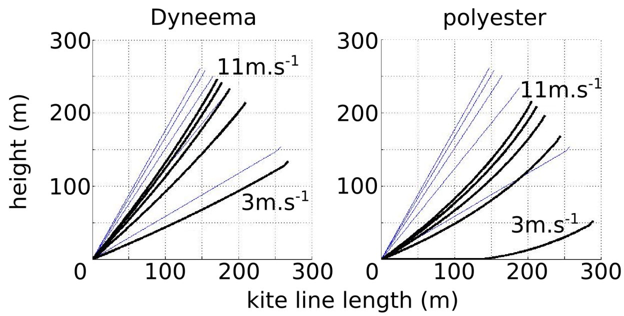

Figure 5. Comparison of the shapes of the 300 m lines (black bold) with ~~'ideal'~~perfect ones (thin grey) ~~ones~~ on a kite flown under different wind conditions and with different line materials. Simulations were performed with five wind speeds from 3 m.s^{-1} to 11 m.s^{-1} in steps of 2 m.s^{-1}. T~~otal~~he load of the rig (Figure 2 - right) for the simulation is 500 g. ~~'Ideal'~~Perfect lines (thin grey) ~~are~~were modelled ~~as weightless~~with negligible weight and ~~causing no~~ drag. Left: Dyneema® line (0.39 g.m^{-1}). Right: polyester line (3 g.m^{-1}).

and light line for photogrammetric acquisitions. Using a thin and light kite line~~,~~ - and ~~the~~a kite adapted to the actual wind conditions at the time of image acquisition ~~is mandatory~~ - is hence a key condition for obtaining a steady flight angle and hence the required stable position of the kite relative to the operator.

Figure 6 shows the simulated flight angle as a function of the line length for the Dyneema® line and polyester line. ~~Not~~

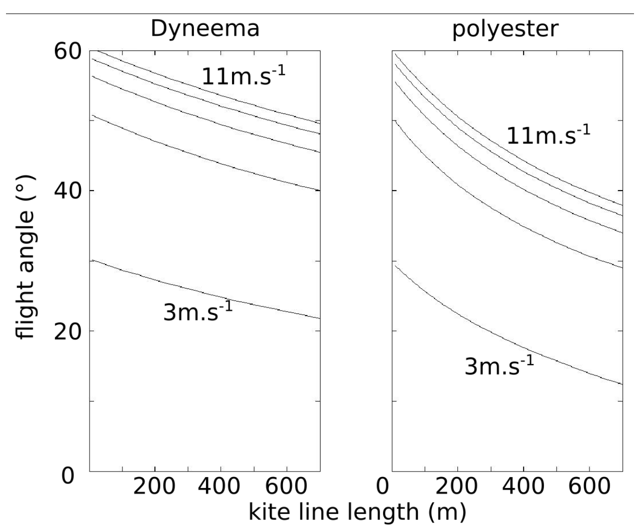

Figure 6. Simulation of the variation in flight angle with the line length for different winds and line materials. Simulations were performed with five wind speeds from 3 m.s^{-1} to 11 m.s^{-1} in steps of 2 m.s^{-1}. Left: Dyneema® line. Right: Polyester line

~~surprisingly, the figure shows~~ For both cases, the simulations showed that the flight angle ~~drops~~ dropped with increasing line length. The drop ~~is~~ was slight for the Dyneema® but critical for the polyester line ~~,~~ due to the stronger "banana shape" ~~line shape~~

~~effect observed in field and in~~ of the line observed in Figure 5. Hence, the use of thin and light kite lines such as Dyneema® lines allows for kite flights with a steady flight angle at a given line length (Figure 5) but also with various line lengths (Figure 6). This steady flight angle makes the line length the only factor for the variation of the kite position relatively to the operator. As a consequence, kite flights can effectively be planned and then properly realised. However, it is recommended to use a margin of security, considering the slight drop of flight angle for greatest line lengths. These findings were confirmed by the field experiments presented in the following section.

~~**Flight angle and windranges**~~

3.2 Observed kite flight angles

~~Empirical observation, confirmed by the simulation results showed above, led us to choose the thinnest and lightest Dyneema® line whose strength would secure the payload. Considering that the drag of the kites is always less than twenty kilograms even in strong winds (otherwise a smaller kite - with lower drag - is used) and that roughly one order of magnitude is requested as safety margin , we chose the closest available line strength which was 90 kg.~~

Figure 7 shows the measured effective flight ~~angle~~ angles for the two kites used with the Dyneema® line~~. Measured flight angles were summed up as min/max boxes for each flight.~~ for different line lengths and different wind conditions.

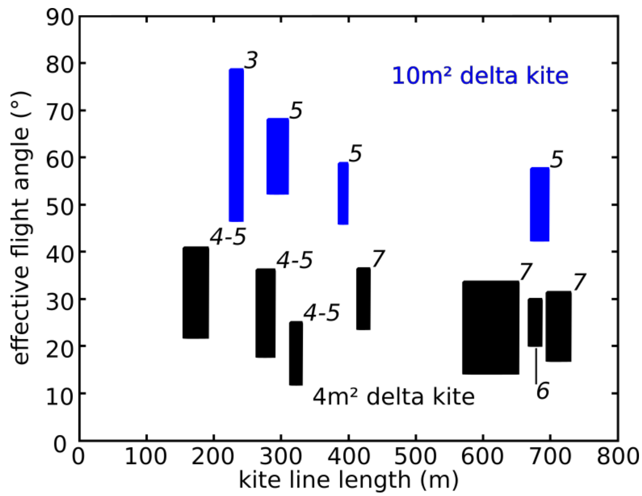

Figure 7. Observed flight angles for the two kites and various ~~conditions of~~ wind speed conditions and line lengths. Wind conditions (in italics) are expressed in the Beaufort scale. Measured flight angles were grouped in min/max boxes for each flight, blue boxes represent the behaviour of the 10 m^2 kite and black boxes represent the behaviour of the 4 m^2 kite.

~~This figure confirms what was anticipated after~~ This figure corroborates the simulation results shown Figure 6: during field experiments, the flight angle dropped slightly but significantly with ~~the line length, and this drop must~~ line length. This drop must hence be taken into account ~~for the preparation of the field work~~in preparation for image acquisition. We also ~~saw~~ noted that the smaller kite - which has a tail - flew at a significantly lower angle than the larger one. This figure also includes a flight These experiments also included a flight (the leftmost blue box in Figure 7) where the wind strength was insufficient to fly the 10 m^2 kite. Characteristics of this flight are represented by the leftmost blue box. This confirms that when the kite was not flown in the appropriate conditions, flight angles were far more variable. , which resulted in a wider range of flight angles and a greater variability of the camera position relative to the operator. This result confirms that even with a thin and light line, the kite must fly within the appropriate wind conditions so that the flight angle remains steady.

Flight duration

The autonomy of the various equipment takes into account the autonomy of batteries and the size of the memory, both for the camera and the GPS. These must be known prior to operating the entire system. It happened that our system was limited by the battery of the camera when the following settings were used: 64 Go memory card, triggering set to one image acquisition every five seconds, and GPS logging frequency set at 1 Hz. In these conditions we could do flights of three and a half hours, yielding potentially more than 2500 images. This amount of images corresponds to a significantly high computation time and need of memory for full resolution processing on a consumer-grade computer but gives an idea of the mapping potential of this equipment, which can be counted in gigapixels.

3.2 3D model

3.3 DEM quality

The whole processing chain was fed with 752 images for image orientation and dense matching. As explained above, Micmac determines automatically the optimal resolution of the orthophotograph and the DEM from the dataset characteristics (images configuration and resolutions). In our experiment, the DEM was calculated on a 11 cm grid (Figure 8). An orthophotograph was also calculated with a 11 cm pixel.

The independent set of 469 points located near the reservoir was used to compute altimetric error statistics. The following statistics have been retained: mean error, median of error, standard deviation of the error, and 90% confidence interval. They are

The quantitative assessment of the DEM quality is reported in Table 3.

Table 3. DEM altimetric error statistics

Mean (m)	+0.06
Median (m)	+0.07
Standard deviation (m)	0.22
90% confidence interval (m)	[-0.29 ; 0.81]
Sample size	469

The error statistics demonstrated good agreement between the kite DEM and the independent validation dataset. In particular, the mean error and median error felt were smaller than the pixel size and the standard deviation of the error was in the order of the pixel size. These figures show that the DEM acquired by kite constitutes a reliable model of the catchment topography.

~~A deep inspection of the shaded DEM alone~~ Moreover, a qualitative assessment of the kite DEM was carried out with a manual inspection of full-resolution DEM shaded views with three close-ups (Figure 8)~~and of some of its detailed views already showed that~~ . The assessment showed that the kite DEM planimetric and altimetric ~~resolution allowed~~ resolutions allow for the visual detection of numerous landscape features~~including all gully heads~~ , including most man-made structures (roads, tracks, buildings) and gully heads that were identified in the field (e.g. subfigures 8-a and 8-b). The ~~plots position~~ plot locations and limits were also clearly depicted (subfigure 8~~-b). Plot limits form humps. This is due to the fact that tillage erosion only affects the cultivated part of the plots ; none of two neighbouring farmers cultivate the limit between two plots. Consequently, limits between two~~ -a). Indeed, the boundaries between two separate adjacent plots are not exposed to tillage erosion and ~~consist in humps which~~ finally form small humps that are visible in the DEM. In the main thalweg (subfigure 8-c), marks of regressive erosion were visible~~. Finally, most of man-made structures were visible with topographic information at this scale : roads, tracks, buildings, plot limits.~~ , and headcut locations could easily be identified.~~ Full exploitation of such a rich topographic information goes beyond the scope of this article. The proposed gullies mapping method is only one example of its possible application in research.~~ The potential of the kite DEM for use in extensive gully mapping within an area of several square kilometres is quantitatively evaluated in the next section.

3.4 ~~Gullies mapping~~Assessment of 3-D gully modelling

An assessment of the gully network delineation was conducted at the scale of the whole channel network, and the 3-D restitution of the internal morphology of a gully was assessed at the scale of a single gully.

Figure 9 shows the final ~~gullies~~ gully map obtained by the proposed method superimposed on the shaded DEM~~. This map shows the potential of the proposed method for exhaustive gullies mapping within an area of several square kilometres. DEM inspection shows that the test site comprises different kind of gullies. Some gullies (in the area showed on subfigure 8-a) remain contained in greater ravines, which means that erosion has occurred at least at two distinct times; the inner gully is currently active, while the greater ravine, with its smooth shape, is the relict of ancient erosion. Some gully heads are located uphill of the larger ravines described here above, which denotes regressive erosion in the modern times (in the area showed on subfigure refDEM-b). Downhill the same gully, one can see that the gully bottom ends in a cultivated field, which is the main concern of current erosion for farmers. Finally, subfigure 8-c shows a step-pool feature in the main channel with vertical overhang, which indicates that erosion is also active in this part of the landscape.~~ and a map of the validation results. Statistics of the comparison between the network extracted from the DEM and the field reference network are presented in Table 4.

The analysis of the gully map and the statistics showed a very good agreement between the detected gullies and the field reference. The overall accuracy was 74%, with 8% of the gullies missed and 26% of the network length detected as gullies, whereas no gullies were surveyed in the field.

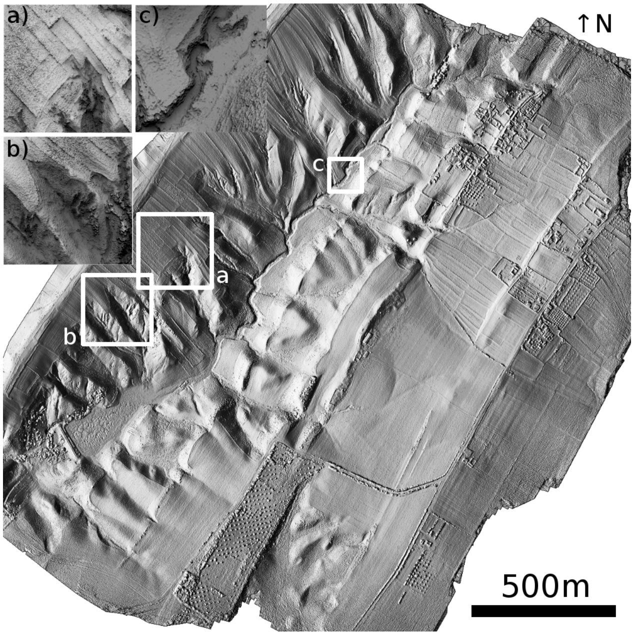

Figure 8. Shaded views of the computed DEM over the Kamech test site. The main view is a classical shading of the DEM computed with a unique illumination source located in the east. The three zoomed views are shaded views computed as the portion of visible sky at each point. This latter type of shading highlights local features such as steep slopes and hard cutsareas of high curvature: a) shows some cultivated plots with the plot borders easily visible and a gully head downstream of the plotsa gully head, b) shows a gully headsome cultivated plots with the plot borders easily visible and a gully head downstream of the plots, c) shows erosion which grows upstream - regressive erosion - in the main thalweg headcut, which is experiencing slow regressive erosion processes.

Table 4. Error statistics of the comparison at the scale of the channel network (Figure 9)

	Gullies length	
	total (m)	relative
Field reference	18,237	100%
Good fit	13,549	74%
False Positives (Over-detection)	1,513	8%
False Negatives (Under-detection)	4,688	26%

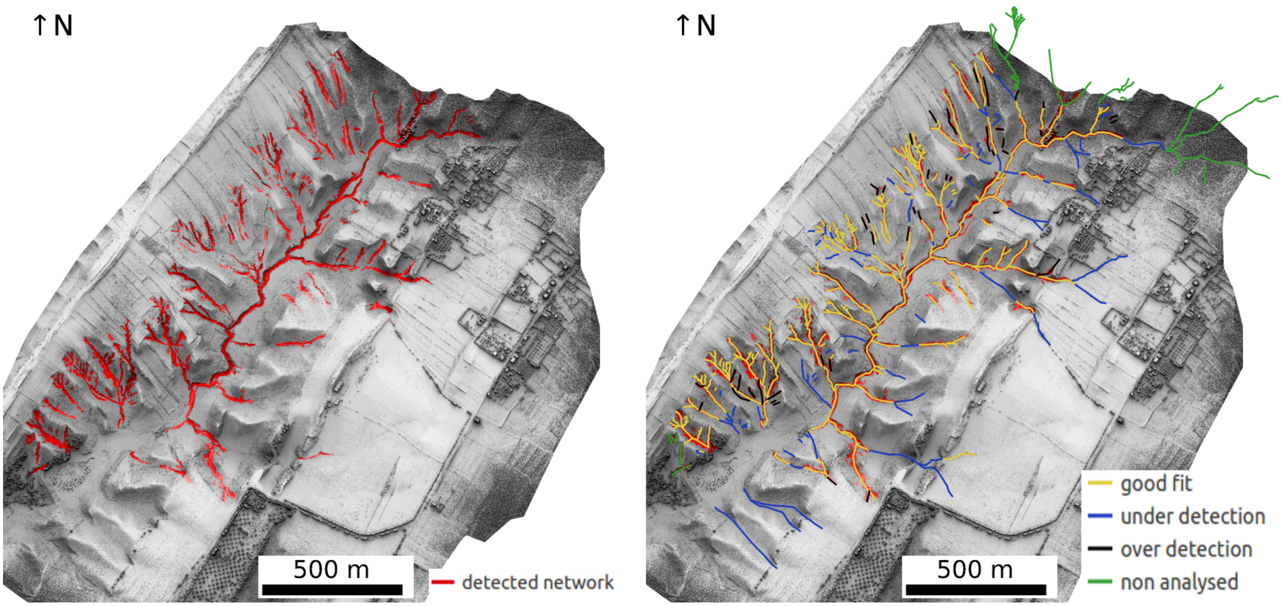

Figure 9. Final rResults of the proposed gully detectionmapping algorithm. Left: The gully network identified from the kite DEM is represented in red and superimposed on the shaded DEM. Right: comparison with ground survey; yellow lines represent the part of the network correctly detected by our algorithm; black thick lines represent gullies detected by our algorithm where no gully was surveyed in the field (over-detection); blue lines represent gullies that were identified on the ground but not detected by our algorithm (under-detection); green lines represent gullies that were identified on ground but not used for error statistics, because they were outside the Kamech catchment area or their heads were outside of the area covered by the kite DEM.

An inspection of the comparison map showed that most gullies that were not detected by our algorithm were located on the left bank (i.e. the southeastern half), where gullies are less incised than those located on the right bank. Furthermore, most over-detections (gullies found by our algorithm but not surveyed on the ground) consisted of small gully segments mainly located on the right bank of the catchment.

Next, validation of the 3-D gully map was performed at the local scale and at a very high-resolution. Figure 10 shows a 3-D comparison between a gully modelled by the kite DEM and a dense ground survey performed at the scale of this gully with a total station.

Comparison of the profiles extracted from the kite DEM and from the surveyed DEM showed good agreement along the whole profile, except for areas covered by vegetation. The influence of vegetation was clearly detected (subfigure 10-c), with elevation differences significantly differing from the surrounding noise. These observations were supported by the associated error statistics (Table 5), with a mean error of +0.08 m which decreases to +0.002 m when not taking into account zones covered by vegetation (parts of the profiles surrounded by vertical dashed lines in subfigures 10-b and 10-c).

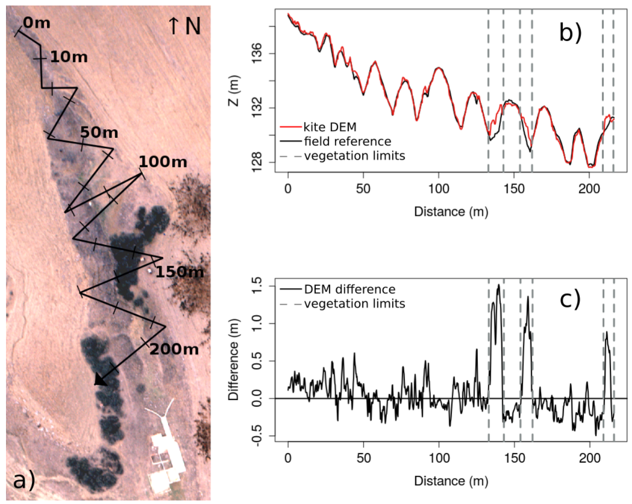

Figure 10. Comparison of the kite DEM with the ground survey. a) Plan view of the gully showing a gauging station at the gully outlet (white), two dense shrub patches of approximately one metre height on the sides of the gully (dark black) and three patches of recent manure application (brown) in the field on the left bank of the gully; the graduated black line shows where profiles have been extracted. b) Comparison of kite DEM (red) and ground survey (black) profiles; the vertical dashed lines delimit areas covered with shrubs. c) Difference between the kite DEM and the ground survey along the same profile. Error statistics computed on this area are reported in Table 5.

Table 5. Error statistics at the scale of the gully shown in Figure 10

Error stat. (m)	Whole gully	Gully without vegetation
Min.	-0.49	-0.49
1st Qu.	-0.13	-0.14
Median	+0.003	-0.01
Mean	+0.08	+0.002
Standard deviation	0.33	0.20
3rd Qu.	+0.19	+0.14
Max.	+1.52	+0.66

These results indicate that the kite DEM constitutes a reliable source of topographic data for the description of gully erosion forms. These findings seem likely to be extended for other gullies considering the good accordance between error statistics shown in Table 5 and in Table 3.

Moreover, a comparison of the quartiles estimated from the whole gully and from the non-vegetated part of the gully showed that vegetation mainly resulted in larger positive extrema, whereas the first, second and third quartiles remained comparable. The results at this scale were very similar to those computed with the 469 ground points sampled near the lake (Table 3 above), with a standard deviation of the error for the DEM statistics being closer to that for the non-vegetated case. This result may indicate that vegetation is more likely to result in local errors rather than in a global deviation.

4 Discussion

In this study, we comprehensively assessed a cost-effective workflow to map gullies at the scale of the elementary watershed from images acquired by kite. Several important considerations have emerged. These considerations refer to the image acquisition step, the quality of the kite DEM and the accuracy of the gully map.

4.1 ~~Effectiveness of image acquisition and processing~~Large photogrammetric datasets with kites

Our study showed that achieving coverage of several square kilometres with decimetre resolution was possible with basic equipment for the acquisition of a photogrammetric dataset. These results represent an improvement over those presented in El Maaoui et al. (2015), where the same acquisition method was also used successfully over an area of only one tenth of that covered in this study. In other works that obtained DEMs with kites, the maximum areas covered were also on the order of several hectares (Wundram and Loeffler, 2008; Marzolff and Poesen, 2009; Smith et al., 2009; Bryson et al., 2013, 2016; Currier, 2015). Our results clearly constitute an extension of the kite's capability. In particular, our work presents novel findings on the conditions that must be met to make kite photogrammetric acquisition successful at this scale. A correct realisation of a planned flight is hence a critical issue for tethered platforms, as has been noted by others (Verhoeven, 2009; Murray et al., 2013). Numerical and field experiments have revealed that the choice of kite line was a key factor in the success of our workflow. To the best of our knowledge, the importance of the kite line has not yet been considered in previous works except for safety reasons (Aber et al., 2010).

If kites are proven to be valuable platforms for photogrammetric acquisition, they have some limitations. The two main limitations are (i) the fact that the line must be clear of obstacles and (ii) the need for a minimal wind speed. We faced the first issue in the most upstream part of the catchment because of a power line. Such problems may also appear in the case of dense vegetation or densely urbanised areas. This problem has also been discussed by Verhoeven (2009) who concluded that not every place is suitable for performing image acquisition from tethered platforms. The second issue, also noted by Bryson et al. (2013), can be approached as in Vericat et al. (2009), who used a kite to which a small helium blimp was added. Marzolff and Poesen (2009) used kites and balloons in alternation. In our opinion, in most cases, when the use of RPAS is not hampered by local regulations, kites associated with small-format multi-rotor RPAS represent a relevant all-weather solution. Indeed, as stated by Nex and Remondino, 2014, the great advantage of small RPAS systems, in addition to being fairly inexpensive platforms, is "*the ability to quickly deliver high temporal and spatial resolution information and to allow a rapid response in a number of critical situations*". However, typical small-format RPAS may remain grounded during windy periods, thus preventing the requested rapid response. The other main niche for kites is related to local regulations, either for the flight itself or due to regulations regarding crossing borders with the equipment.

On another note, kites can fly for hours when weather conditions are appropriate. Such autonomy represents a completely different paradigm relative to that for most RPAS. With the equipment presented above, the overall autonomy was only limited by the internal power supply of the camera. Within a single flight of three hours, several thousand overlapping images can be acquired. This figure gives an idea of the mapping potential of this method, which produces DEMs in the gigapixel range.

4.2 DEM quality

~~For SfM applications in geosciences, a lot of authors express DEM quality in terms of quality of model geometry estimation. This is commonly measured by calculating a RMSE on GCPs. This expresses how well algorithms managed to fit the model to sparse ground data given as an input. This RMSE can give some information about the quality of elevation estimation but only in a very indirect manner. Thematic applications and further processing of obtained DEMs necessitate having an idea of the quality of topography representation. In SfM application from very light platforms, this issue is quite a delicate one, for two main reasons. First, only few authors using kites present external validation of the estimated elevation data. Then, and more generally, DEM quality estimation is itself an ongoing research question. As raised by some authors (e. g. Lane, 2000), data quality and ways to qualify topographic data is a critical issue and, as pointed recently by Smith et al. (2016), this is all the more critical with a new and fast emerging technology.~~

~~Back to validation of high-resolution topographic data obtained by kites, Marzolff and Poesen (2009) did quality check by subtracting different DEMs and examining the detected terrain dynamics. These authors observe that feature characteristics (position, shape, size) are consistent with erosion processes and hence confirmed the validity of their approach.~~

~~Several other authors performed quantitative validation with external data, with the same validation methods as the ones identified by Smith et al. (2016). A key point to keep in mind before comparing results of different studies is the fact that elevation estimation erroris strongly correlated to the ground sampling distance. This is a well known characteristic in classical photogrammetry (e.g. Kraus and Waldhäusl, 1993) and is all the more true with multi-view SfM due to the high amount of images covering the same area. It is indeed not rare that a point is seen more than ten times.~~

Beyond the ability to acquire 3-D data over several square kilometres with kites, our aim was to demonstrate that these topographic data were reliable. We showed that the estimated altimetric bias was lower than the pixel size and that the estimated deviations were in the order of pixel size. In other words, validation with an independent ground survey showed that the produced DEM had a decimetre resolution and accuracy.

Few works using kites have assessed the DEM elevation error. Our results compare quite well with those works. Wundram and Loeffler (2008) ~~used images with a 0.25 m ground sampling distance and one thousand independent validation points. They~~achieved a +0.13 m mean error, 0.36 m standard deviation of the error and 0.75 m maximal error on a 0.25 m resolution

DEM (one thousand validation points). Smith et al. (2009) acquired images with an estimated 0.01-0.02 m ground sampling distance. ~~Error statistics obtained with 399 independent validation points is~~ The authors obtained a -0.01 m ~~for the~~ mean error and ~~and~~ 0.065 m standard deviation error estimated with 399 independent validation points. El Maaoui et al. (2015) computed a DEM with a ground sampling distance of 0.06 m~~and assessed DEM quality~~. A quality check with 176 independent validation points ~~. Mean error is~~ resulted in a mean error of +0.04 m and a standard deviation of ~~the error~~ 0.07 m. Finally, ~~Bryson et al. (2016) surveyed three times~~ with 0.004 m resolution images acquired on a 50 by 150 m area ~~. The second time, the authors acquired 86 independent validation points with a RTK DGPS. Images had an approximate ground resolution of 0.004 m. The DEM was computed with a~~ and a final DEM ground sampling distance of 0.05 m~~. Mean error was estimated~~ , Bryson et al. (2016) estimated the mean error at -0.019 m and ~~standard deviation of the error was~~ the standard deviation at 0.055 m~~.~~ with 86 validation points.

~~Our error statistics are consistent with the ones of other works, both in terms of bias and dispersion. Mean error of our study remained "within the pixel" ; in other words, observed bias was of the same order of magnitude as the ground sampling distance. Standard deviation of the error was also of the same order of magnitude as the ground sampling distance. We hence shown that the proposed method allowed topographic mapping on several kilometre square areas with decimetric resolution, both altimetric and planimetric, and decimetric altimetric precision and accuracy.~~ Our work confirmed that the range of kites can be extended to several square kilometres with decimetre resolution while maintaining the accuracy in the pixel size range.

4.3 ~~Gullies mapping~~Gully network map and 3-D gully morphology

Although the overall accuracy of 74% proved that our method was effective, the very process of validating the gully maps obtained from high-resolution DEM processing raises issues. To begin, validation methods are quite varied in the literature. Most authors (Evans and Lindsay, 2010; Baruch and Filin, 2011; Höfle et al., 2013; Castillo et al., 2014) have used manual digitization of the gullies on the DEM as validation data and focused on different gully characteristics: width and depth (Evans and Lindsay, 2010), visual comparison (Baruch and Filin, 2011; Höfle et al., 2013), areal and volume difference (Höfle et al., 2013; Castillo et al., 2014). Some authors (e.g. Noto et al., 2017) did not even validate the gully mapping results. Infrequently, studies such as Thommeret et al. (2010) have used field surveys as validation data for gullies that were automatically mapped from a DEM. Similar to their study, our validation data were in the form of a channel network, and we used the same indicators as they did. We obtained a false positive rate (over-detection) of 8% and a false negative rate (under-detection) of 26%. Our results compare favourably to those of Thommeret et al. (2010), who had false positive rates ranging from 5% to 16% and false negative rates ranging from 29% to 55%. Moreover, our results follow the same tendency, with false negatives rates being higher than false positives. This result may be explained by the fact that all gully mapping algorithms, including the one presented here, are based on the morphological characteristics of gullies (i.e., what a gully is) but do not benefit from characteristics that are known not to be shown by gullies (i.e., what a gully is not). In our opinion, this approach would be especially useful for avoiding confusion between gullies and man-made structures, which may be among the most delicate features to handle. This confusion may indeed explain some of the remaining inaccuracies we observed, and more generally, these issues have also been faced by others (Castillo et al., 2014).

The detection of gullies in DEMs faces the difficulty of determining an unambiguous and generic definition of what a gully is. Castillo et al. (2014) indicated that to their knowledge, no one has yet assessed where gullies 'begin' in the transverse direction. Conversely, Evans and Lindsay (2010) stated that "*gully edges are the critical features for gully mapping*". Baruch and Filin (2011) noted that the assumptions usually used in channel-like extraction techniques do not apply to the environment of alluvial fans in which they hence propose an ad hoc gully mapping method. In brief, due to the variety of gully shapes and the fuzzy definition of their extent, each gully mapping algorithm in the literature so far requires the manual tuning of parameters and/or thresholds and is preferably applied to specific landscape types.

A possible workaround would be the use of multi-scale analysis, which was still seen by Passalacqua et al. (2015) as a future research direction for high-resolution topography analysis. For future work in this direction, our algorithm has the advantage of being based on Fourier transforms instead of sliding windows, which makes the computation time independent of the characteristic size of the kernel and hence opens the door to multi-scale filtering with controlled computation times. Computing time is indeed one issue for DEM processing; Castillo et al. (2014) have been, for instance, unable to process the full resolution of their largest DEM. Considering that upcoming topographic datasets will probably be more extensive and will have increasing resolutions, this may still be an issue that will have to be mitigated by algorithmic improvements such as the one we have proposed.

The interest in multi-scale approaches is as strong as the 3-D information of such DEMs is rich, which is the case for the data obtained in our study. The comparison of dense elevation profiles between the kite DEM and ground reference hence showed good agreement. These findings thus confirmed at the very local scale the results on DEM accuracy found at the scale of the whole DEM. However, this detailed analysis raised the issue of vegetation cover. This issue is present in several classical cases where image-based approaches have limits that LiDAR does not have. However, with big image datasets, SfM DEMs can reach densities that are comparable with or even exceed those of aerial LiDAR point clouds. This property would allow for the development of vegetation filtering algorithms tailored to these dense and multi-view image data. Second, our results can be compared to the work of Marzolff and Poesen (2009), who used kites and balloons with a focus on two gullies. They determined that gully morphology and even gully changes could be assessed. In our case, with comparable sensibility and data available at the scale of the whole catchment, such morphological information would enable the description of different processes that occurred in different gullies or even at different times in the same gully, such as renewed erosion in older gully systems. Further work may then repeat our experiments to monitor ongoing gully erosion processes. Such experiments would indeed be of great help, for instance, in understanding the source of sediments responsible for reservoir siltation.

5 Conclusions

This paper proposes a complete workflow, from image acquisition with kites to a final gully map at the scale of a kilometre-square catchment with a careful assessment of each step. For image acquisition, we found that a key factor was the use of a thin and light line, which results in steady kite flight angles and thus a proper realisation of a kite photogrammetric flight in such large areas. Then, we showed that low-tech kite aerial photography could be successfully used for the acquisition of a high-resolution DEM covering more than three square kilometres with decimetre resolution and accuracy. Finally, we demonstrated that an appropriate gully mapping algorithm developed and applied to this DEM proved to be appropriate for the characterisation of gullies with 3-D decimetre details. Correct matches were obtained for 74% of the gully lengths at the scale of an entire channel network. Still, kites require minimal wind speeds. This technique may therefore be thought of as a tool to be used in conjunction with small-format RPAS, especially when the latter cannot fly because of technical or administrative obstacles. Then, the proposed gully mapping method requires the intervention of an operator for the digitization of gully heads. This approach may not be adapted to contexts with an excessive number of individual channels but proved appropriate in pruning the false positives produced by automatic procedures on anthropogenic features. Nevertheless, our study demonstrated that kite aerial photography using simple but appropriate equipment and an appropriate gully mapping algorithm represents a valuable tool for accurately surveying several hundred gullies at the scale of a kilometre-square watershed with decimetre detail, which may compare favourably with most ground surveys at these scales. These findings suggest that kites, SfM, and adequate gully mapping algorithms provide greater access to high-resolution topographic data of kilometre-square watersheds and will facilitate a better understanding of gullying processes in a broader spectrum of conditions.

Appendix A: MicMac workflow

Description of the commands used sequentially in the typical MicMac pipeline, from images to DEM and orthophotograph:

- *Tapioca*: SIFT points computing and matching; image resampling ratio affects the number of SIFT points
- *Tapas*: Image orientation and autocalibration; memory requirements grow with the number of SIFT points and images and can be prohibitive ; possible workarounds with *RedTieP*/*OriRedTieP*
- *Tarama*: First raw mosaic of the area; used to have a quick estimate of the covered area
- *SaisieMasq*: Manual delimitation of the interest area
- *SaisieAppuis*: Manual measuring of GCPs position in images
- *GCPBascule*: Georeferencing of the model
- *Malt*: Dense image matching; final DEM resampling ratio & regularisation parameters can be adjusted
- *Tawny*: Orthophotograph mosaicing

Appendix B: Criteria for the choice of the camera

Appendix C: Notes for future kite users

Table 6. Advantages and drawbacks of three different camera technologies for acquisition with a kite for photogrammetry. The two first criteria are specific to kite borne photogrammetry while the last criteria are more general and apply to any photogrammetric application.

Criteria	importance	compact	hybrid	DSLR*
Weight	high	+++	++	-
Cost	medium	++	+	-
Prime lens	medium (**)	No	Yes	Yes
Lens without moving parts	high	No	Yes	Yes
Camera options (***)	high	+/-	+	++
Image quality	medium	+/-	+++	+++

* Digital Single Lens Reflex

** a lens with the zoom ring scotch-tapped is a decent workaround if no prime lens is available

*** including the possibility to switch off the autofocus and the image stabilizer, which both make autocalibration difficult.

It is worth noting that flying large kites, especially in strong winds, can raise security issues. Aside from Aber et al. (2010), these facts are still barely reported in the scientific literature. The problems we faced appeared only under conditions of strong winds. These problems include small burns on hands, arms or clothes when the line is moving too fast, or when the winder is temporarily out of control during a wind gust. This problem may also occur when the kite shows erratic movement in strongest winds when the operator is walking upwind. To avoid such problems, the following safety measures can be adopted: (i) ensuring physical protection of the operator with leather gloves and covering clothes and ensuring the security of other people by keeping the downwind zone free of any lightweight and large equipment; (ii) keeping in mind that danger - and necessary expertise - grows with wind strength, a clever decision may be not to fly if conditions are not met; (iii) securing the flying gear (attaching it with hooks, for instance); (iv) keeping attention on the equipment and the surrounding people.

Competing interests. The authors declare no competing interests.

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