Gully geometry: what are we measuring?

J. Casalí, R. Giménez and M. A. Campo-Bescós
Department of Projects and Rural Engineering
Public University of Navarre
Los Olivos Building, 31006 Pamplona, Spain

Point-by-point response to the reviews and a list of all relevant changes made in the manuscript

Anonymous Referee #1

This paper aims to propose a measurement protocol of the geometry of (ephemeral) gullies (width and depth) with the goal of pooling criteria in future works. The uncertainty of these measurements, especially in the case of complex cross section shapes, is a real problem felt by the researchers involved in studies on this kind of erosion, especially considering the general lack of information in the literature. Therefore, the subject is both interesting and challenging. The authors define "an equivalent prismatic gully (EPG)" obtained subtracting the "detailed digital elevation model (DEM) of a gully whose geometry we wish to determine" from the DEM of the same area before the gully in question would have been formed. Some points, however, need to be addressed before this paper can be considered for publication. My major concerns are:

1. The technique suggested is not new among users of the GIS, but it is necessary to find the answers to some questions before it can be proposed as a standardized method for future research. The main questions are:

- what does it mean "detailed" DEM (P. 327, l. 20)? I suppose the authors refer to the detail of the field survey to build the DEM. But, what is the level of details required to reduce the error with respect to the simplified techniques? Do we have to survey a mesh of 1 mm, 10 mm, 100 mm? Clearly, the answer depends also on the size of the channel to detect and involves the choice of suitable instruments for the survey;
-what is the error reduction with respect to the usual?
-what is the error reduction respect to the usual technique improved measuring more than one width and depth for each section?
-what is the difference in terms of economic engagement and hours of labor invested?
-what is the advantage of minimizing the type of error described, compared to that due to other uncertainties, e.g. the choice of the distance between the cross sections to be surveyed? (P. 328, L. 8 "a multitude of other points xi along the channel").

Firstly, it must be stated that in this paper the authors do not expect to address the type of details that the Referee #1 indicates, although they are, obviously, very interesting and relevant. We think that they should be considered in a subsequent development of the methodology. In fact, this is rather a conceptual paper.

The main purpose is to propose an objective, repeatable and of general validity definition of "width of a gully cross section", which is a key magnitude that conditions the assessment of the gully volume and depth. This definition is based on gully genesis criteria instead of gully geometry, the latter with even arbitrary limits. "Equivalent prismatic gully", "effective width" and "effective depth" are concepts that ultimately derive from the definition of "width of a gully cross section", and try to standardize the assessments of gully characteristics.

Obviously, the width of a gully cross section, as defined in this paper, depends on the DEMs pixel size and, in agreement with Referee #1, it depends on the type and size of the studied channel. Hengl (2006) concluded that, to avoid the loss of relevant information, the maximum pixel size must be the average of the minimum distances between sampling points. In the same way, Garbrecht and Martz (1994) fixed the pixel size to the size of the minimum *distinguishable object. On the other hand, the new available methodologies (terrestrial or aerial LIDAR, 3D photo-reconstruction, etc.), provide a very detailed information, which are more than enough, in our opinion, for the purposes of these studies. The assessment methodology itself, as pointed out by Referee #1, it not new for GIS users and it is clear that the highest the DEMs' resolution, the closer to reality the assessments will be. However, these thresholds should be explored in future researches.*

Another point is what happens in terms of the application of the proposed protocol when the DEMs are not available; or when field assessments made in the past must be evaluated; or when in present time it is only possible to use traditional techniques such as profilometers, tapes, etc. We think that even in this case the proposed protocol provides orientation for identifying the gully cross section width. We believe that this is an advance itself, both for guiding the direct assessment in the field and for defining the gully cross section width in the office from other data bases collected in the field. In this way, "equivalent prismatic gully", "effective width" and "effective depth" are concepts which are applicable whatever the assessment methodology or protocol was used. Different issue is the accuracy of this properties or variables, which depend on the detail and resolution of the baseline information. Anyway, we believe that, despite this limitation, the mentioned concepts are also a quite remarkable contribution when standardizing the assessment and characterization criteria.

It is difficult to quantify the assessment error reduction when implementing this definition. For that purpose, series of assessment experiments with different scientific teams should be carried out. From these experiments, it would be possible to compare the results achieved using conventional techniques with those achieved after using the proposed definition and protocol. We feel that it is appropriate to insist in the necessity of high density and detailed assessments, as Casalí et al. (2006) stated.

2. The use of an equivalent prismatic gully defined by a single value of width (We) and depth (De) involves the loss of valuable information (e.g. the maximum depth of the different segments of the channel, etc.). This may be acceptable or not depending on the purpose of the measurements.

It is not our intention to eliminate from the analyses any relevant information for gully research. Moreover, as a consequence of using very detailed DEMs, as we propose, very detailed information of gully characteristics and of its spatial variation will be available. Our proposal is oriented towards providing an important additional information, aiming at the unity of criteria when characterizing the gully morphology and its most important properties, emphasizing its width, depth and volume.

3. The authors affirm that the problem of reducing the type of error discussed is not even usually recognized by the researcher. I think it should be obvious that the researcher analyzes the shape of the section and choose what measures to take, in order to reduce errors in the estimation of the surface area of the cross section. These operations are not usually described in literature just because they are obvious for a researcher. In my opinion, the real explanation is, rather, that until recently the researchers who dealt with (ephemeral) gullies aimed to reduce errors, but only in order to compare measurements made by the same research team. Of course, the transition to a phase of comparison between the experimental results obtained by various research teams imposes a shared definition of standardized measurement protocols and techniques, as proposed by the authors in the manuscript.

There is no doubt that scientists do their best to get the most accurate assessments. However, in many cases, it is very difficult to be objective, consistent, even for experts. Then, in our opinion, the obviousness that Referee #1 points out is not enough, and we think that it is necessary go in depth. Anyway, there is great subjectivity that must be delimited. In effect, and in agreement with Referee #1, it is necessary to make the results general and universally comparable, and not only valid for one specific research group.

In conclusion, in order to define a standardized measurement protocol of the (ephemeral) gully geometry, the authors should: - compare different measurement techniques for different sizes of the channel and, for the reconstruction of the DEM, for different survey meshes; - evaluate the related errors; - suggest the type of equipment necessary for create a detailed DEM.

In our opinion, and in agreement with previous discussions, we think that it is not necessary to make the suggested operations, because they are not required to achieve the objectives considered in this paper.

Other specific comments for the authors: P. 328, l. 9. and P. 329, l. 9. The authors define the width (We) and the depth (De) of the equivalent prismatic gully (EPG) as "effective". I think it should be better to use a different term, e.g. "mean equivalent".

We accept the suggestion made by Referee #1. The texts will be modified accordingly.

References

Garbrecht, J., Martz, L., 1994. Grid size dependency of parameters extracted from digital elevation models. Computers and Geosciences 20, 85-87.

Hengl, T., 2006. Finding the right pixel size. Computers and Geosciences 32, 1283; 1298-1283; 1298.

Casalí, J., Loizu, J., Campo, M. A., De Santisteban, L. M., Álvarez-Mozos, J., 2006. Accuracy of methods for field assessment of rill and ephemeral gully erosion. Catena 67(2), 128-138.

Anonymous Referee #2

General Comments. The aim of this paper is to propose a measurement protocol for ephemeral Gullies for comparing the results obtained by different researchers. This topic is very interesting, because the lack of a standardized measurement protocol makes the results of volume of eroded soil, cannot be compared easily. The paper would improve if authors include analysis of proposed methodology with different gully geometry datasets".

We agree with Referee #2: it is highly convenient to include an analysis of the proposed methodology using data bases from gullies of different geometry. In fact, we think that this objective has been properly achieved in this paper. In effect, the method is applied to six ephemeral gullies of different lengths, widths and depths. These gullies were recently assessed using a very accurate methodology. Other data sets from gullies with varied morphology could have been used, but their assessment was not so accurate. In our opinion, it is preferable to use the more recent and accurate information. Besides, in our opinion, they provide enough information and in accordance with the length of the paper. On the other hand, I must be taken into account that the main objective of this paper is to present a first introduction of the protocol and of the methodology, and not to show an in depth analysis of that, which can be done in further studies.

Specific comments

* Page 325 Lines 20-23, the authors say "it is usually assumed that the width is defined by the imaginary line whose ends are located at both points of the two banks, where an abrupt change in slope is manifested." The authors say the problem of presence of more than one points of slope inflection in one or both banks, it can use the concept used in stream geomorphology to determine the bankfull stage with the minimum width to depth ratio, bankfull represents in stream the breakpoints between in-channel and floodplain processes (see: NRCS 2007 Stream restoration design, Part 654. National Engineering Handbook. Department of Agriculture, Natural Resources Conservation Service; Pickup, G., and R.F. Warner. 1976. Effects of hydrologic regime on magnitude and frequency of dominant discharge. J. of Hydrol. 29:51–75.)

In this paragraph, and for defining gully width, Referee #2 alludes to a methodology previously used in rivers. However, in our opinion, such methodology is not a contribution in gully research, because using it the uncertainty about where the gully limit must be located persists.

* Page 327 Lines 12-18, what criteria is used to determine the gully width in the figures3b and 3c?

No particular criteria have been followed. It is just one example to illustrate: i) the great differences in volumes that can be obtained fixing the gully widths arbitrarily; ii) the error that can be generated and; iii) the necessity of stablishing rigorous and objective criteria and protocols.

* Page 328 Lines 6-9, "This same operation could be repeated in a multitude of other points xi along the channel, thus obtaining the two width values of each new section(Wi).", I don't know how the authors obtain the two width values at each section, it could be the two width values of the reach.

There is one mistake in this sentence, which is modified as follows: "This same operation could be repeated in a multitude of other points xi along the channel, thus obtaining the width value of each new section (Wi)". This sentence will be included in the final text.

* Page 328 Lines 9-10. "Finally, the average of the values Wi would define the effective width of the whole gully, We." I think it's better to use weighted average using distance between the adjacent gully cross-sections.

Considering the nature of this paper, it does not seem necessary to include such modification. In the text, it is explained that the operations to obtain the gully width "could be repeated in a multitude of other points xi along the channel". Therefore, it is assumed that lots of measurements will be available, and that their average is representative of all the cross section morphologies. In case that there were less information available (cross section widths), the use of weighted average could be considered.

* It's not clear for me the proposed methodology to calculate the gully width value when I haven't the DEM prior to the appearance of the gully (DEM year n).

We realize that our proposal presented in this paper can be considered as peculiar because, in order to define the gully cross section width and to describe the protocol, it is assumed that the DEM year n is known, which is very difficult. However, we believe that, despite this difficulty, our proposal is still a remarkable contribution, because it provides an approximation to the true definition of the gully cross section width, a key variable that also determines other gully properties. In relation with the above mentioned difficulty, it is the challenge of reconstructing or knowing the DEM year n, which can be considered as a new line of research. This, and depending on the gully type, can be addressed for example from unaltered areas not affected by erosion. In this way, and for ephemeral gullies, it can be assumed that tilled areas close to the channel without erosion evidences can show or identify singular points of the original topography before erosion. In this way, and for ephemeral gullies, after tillage operations, one DEM can be obtained (DEM year n), and the DEM year n+1 con be obtained after erosion occurred. From this information, patterns for obtaining DEM year n from DEM year n+1 can be explored. In any case, even when DEM year n cannot be obtained, the proposed protocol can still be developed, so that the effective width and depth and the equivalent prismatic gully, can be calculated. We think that this is a contribution in the way to standardize measurements, characteristics and properties in gully science.

These sentences above, slightly modified, will be included in the final text.

* The text of conclusions is very similar to abstract.

We agree with Referee #2, and the conclusions have been modified as follows:

In order to progress in gully erosion research, clear criteria to define and determine the key morphological characteristics of gullies and their related properties (such as volumes) are needed. It would allow to make adequate comparisons under homogeneous conditions. In this paper, a new proposal to advance towards such goal is shown. In this way, starting from a precise definition of the width of each gully cross section, the mean equivalent gully width and depth are defined, and also the equivalent prismatic gully (EPG). By using the EPG it is possible, in a simple but rigorous way, to represent a gully, making easier the comparison among different gullies. The definition of the width of each gully cross section assumes that the topography of the area before the gully appearance is known. It is, in fact, really infrequent, so that a new line of research arises. Anyway, we believe that the proposal is a considerable advance in the applied research on gullies, because it allows to standardize the definition and determination of the most important characteristics of these erosion forms.

Technical corrections

* Page 324 lines 16-20, Change the sentence order "Rill erosion is produced in the form of numerous channels of a few centimeters in depth, distributed uniformly and randomly over sloping lands (Soil Science Society of America, 2015) and which can easily be obliterated by conventional tillage (Hutchinson and Pritchard, 1976). Also, permanent gullies are distinguished from ephemeral ones (Foster, 1986; Thorne et al., 1986; Casalí et al., 1999).

The suggestion made is accepted. The text will be modified accordingly.

* Page 325, lines 2-3 "Rills, however, occur entirely on one single slope (Casalí et al., 1999); their formation is, therefore...

The suggestion made is accepted. The text will be modified accordingly.

* Page 325, line 11 "ratio" instead of "quotient".

The suggestion made is accepted. The text will be modified accordingly.

Topical Editor

The evaluations of the referees were positive, nevertheless, all their questions have not been replied yet. I suggest the improvement of the manuscript following the points mentioned by the referees 1 and 2:

1. Relationships between DEM and gully width.

Firstly, it must be stated that in this paper the authors do not expect to address points like what a "detailed" DEM is, or what is the level of detail required to reduce the error with respect to the simplified techniques. Besides, the answer depends also on the size of the channel to detect and involves the choice of suitable instruments for the survey. These points are, obviously, very interesting and relevant, but we think that they should be considered in a subsequent development of the methodology. In fact, this is rather a conceptual paper. The main purpose of this paper is to propose an objective, repeatable and of general validity definition of "width of a gully cross section", which is a key magnitude that conditions the assessment of the gully volume and depth. This definition is based on gully genesis criteria instead of gully geometry, the latter with even arbitrary limits. "Equivalent prismatic gully", "mean equivalent width" and "mean equivalent effective depth" are concepts that ultimately derive from the definition of "width of a gully cross section", and try to standardize the assessments of gully characteristics. However, to accomplish with the Editor's request, the following sentences will be included in the text:

(At the end of section 3). "The width of a gully cross section, as defined in this paper, depends on the DEMs pixel size and it depends on the type and size of the studied channel. Hengl (2006) concluded that, to avoid the loss of relevant information, the maximum pixel size must be the average of the minimum distances between sampling points. In the same way, Garbrecht and Martz (1994) fixed the pixel size to the size of the minimum distinguishable object. On the other hand, the new available methodologies (terrestrial or aerial LIDAR, 3D photo-reconstruction, etc.), provide a very detailed information, which can be more than enough, in our opinion, for the purposes of these studies. However, these thresholds should be explored in future researches".

2. Specific applications of the equivalent prismatic gully additional to the model AnnAGNPS.

The text shown below will be added at the end of the actual last paragraph in section 3:

"In effect, we believe that the concept of equivalent prismatic gully shows several benefits and applications. Probably the principal is that it allows for determining the most important characteristics of a complete gully (V, L, Wme y Dme), using objective and repeatable criteria. Otherwise, there is the risk of assigning information from specific cross sections or reaches to the whole gully. Besides, the gully properties (V, L, Wme y Dme), as defined here, can be incorporated in statistical analyses or similar studies in which many gullies are involved, using a common language, repeatable and comparable among different researchers. On the other hand, by using the concept of equivalent prismatic gully, sets of complete gullies can be graphically represented easily, which allows for a quick and explanatory visual comparison".

3. Following the advice of referee 2, to discuss/develop the content of Figure 5 (analysis of the proposed methodology with different gully geometry datasets) in order to provide more details about its usefulness.

We agree with Referee #2: it is highly convenient to include an analysis of the proposed methodology using data bases from gullies of different geometry. In fact, we think that this objective has been properly achieved in this paper. In effect, the method is applied to six ephemeral gullies of different lengths, widths and depths. These gullies were recently assessed using a very accurate methodology. Other data sets from gullies with varied morphology could have been used, but their assessment was not so accurate. In our opinion, it is preferable to use the more recent and accurate information. Besides, in our opinion, they provide enough information and in accordance with the length of the paper. On the other hand, I must be taken into account that the main objective of this paper is to present the protocol and the methodology, and not to show an in depth analysis of that, which can be done in further studies.

4. To add the advantages associated to the standardization of gully measurements in different contexts (lines 13-16, page 326) in the conclusions.

A new version of the conclusions including the requirements of both Editor and Referee #2 has been written:

In order to progress in gully erosion research, clear criteria to define and determine the key morphological characteristics of gullies and their related properties (such as volumes) are needed. In this paper, a new proposal to advance towards such goal is shown. In this way, starting from a precise definition of the width of each gully cross section, the mean equivalent gully width and depth are defined, and also the equivalent prismatic gully (EPG). This approach allows for determining the most important characteristics of a complete gully (V, L, Wme y Dme), using objective criteria. Besides, such gully properties as defined here, can be incorporated in statistical analyses using a common language among different researchers. On the other hand, by using the EPG, sets of complete gullies can be graphically represented easily, which allows for an explanatory visual comparison. The definition of the width of each gully cross section assumes that the topography of the area before the gully appearance is known. It is, in fact, really infrequent, so that a new line of research arises. Anyway, we believe that the proposal is a considerable advance in the applied research on gullies, because it allows to standardize the definition and determination of the most important characteristics of these erosion forms.

Specific comments:

- Figure 3. Please, explain the content of the figures b) and c), in the figure caption and in the text (page 327, lines 15-19).

The figure caption has been modified as follows:

Figure 3. Illustration of the effect that the criterion followed to determine the cross section width has on the computed volume of a gully reach. a) Selected gully reach and location of the three cross sections used for calculating the volume of the reach (P1, P2 and P3); the distance between cross sections is known. b) Calculated eroded volume (in blue) when considering a possible criterion for defining the gully cross sections widths. c) Calculated eroded volume (in red) when considering another possible criterion for defining the gully cross sections widths.

The text on page 327, starting from line 16 (included) has been modified as follows:

However, an overall review of all the sections conforming the gully being studied would give a better assessment of this measurement error. Fig. 3 tries to illustrate the effect that the criterion followed to determine the cross section width has on the computed volume of a gully reach. A real gully reach was selected and three cross sections were used for calculating the volume of the reach (P1, P2 and P3) (Fig. 3a), being the distance between cross sections known. First, the eroded volume was calculated considering a possible criterion for defining the gully cross sections width (in blue, Fig. 3b). Then, the eroded was calculated again but considering another possible criterion for defining the gully cross sections widths (in red, Fig. 3b). The difference in the calculated volume for both situations is remarkable, increasing a 96% from option b to option c. Figure 3 is just one example to illustrate: i) the great differences in volumes that can be obtained fixing the gully widths arbitrarily; ii) the error that can be generated and; iii) the necessity of stablishing rigorous and objective criteria and protocols. The purpose of figure 3 is similar to figure 2, the latter illustrating the effect of the uncertainty in the determination of width in a single cross-section of a gully.

- Figure 4. Please, at the end of the figure caption 4, include the chapter of the text to follow the explanation.

At the end of the figure caption the following text has been included:

"See section 3 for details."

-Figure caption 5, please correct “different”.

It will be corrected.

List of all relevant changes made in the manuscript

The expression "mean equivalent" (width and the depth) has been used instead of "effective" as suggested by Referee *#1*. W_{me} and D_{me} are used everywhere instead of W_e and D_e.

The following references have been included in the reference list:

Garbrecht, J., Martz, L., 1994. Grid size dependency of parameters extracted from digital elevation models. Computers and Geosciences 20, 85-87.
Hengl, T., 2006. Finding the right pixel size. Computers and Geosciences 32, 1283; 1298-1283; 1298.
Casalí, J., Loizu, J., Campo, M. A., De Santisteban, L. M., Álvarez-Mozos, J., 2006. Accuracy of methods for field assessment of rill and ephemeral gully erosion. Catena 67(2), 128-138.

As suggested by Referee *#2,* the sentence "This same operation could be repeated in a multitude of other points xi along the channel, thus obtaining the two width values of each new section (W_i)" has been replaced by: "This same operation could be repeated in a multitude of other points *xi* along the channel, thus obtaining the width value of each new section (Wi)".

As suggested by Referee *#2,* the text on page 324 lines 16-20 has been changed to say: "Rill erosion is produced in the form of numerous channels of a few centimeters in depth, distributed uniformly and randomly over sloping lands (Soil Science Society of America, 2015) and which can easily be obliterated by conventional tillage (Hutchinson and Pritchard, 1976). Also, permanent gullies are distinguished from ephemeral ones (Foster, 1986; Thorne et al., 1986; Casalí et al., 1999)".

As suggested by Referee #2, the text on page 325, lines 2-3 has been changed to say: "Rills, however, occur entirely on one single slope (Casalí et al., 1999); their formation is, therefore, mainly subjected to the high spatial variability of intrinsic factors of the soil (structural stability, hydraulic conductivity, etc.) and of its tillage".

As suggested by Referee #2, on page 325, line 11 "ratio" has been used instead of "quotient".

As suggested by the Topical Editor, the following paragraph has been included at the end of section 3:
"The width of a gully cross section, as defined in this paper, depends on the DEMs pixel size and it depends on the type and size of the studied channel. Hengl (2006) concluded that, to prevent the loss of relevant information, the maximum pixel size must be the average of the minimum distances between sampling points. In the same way, Garbrecht and Martz (1994) fixed the pixel size to the size of the minimum distinguishable object. Additionally, the new methodologies available (terrestrial or aerial LIDAR, 3D photo-reconstruction, etc.), provide a very detailed information, which may be more than enough, in our opinion, for the purposes of these studies. However, these thresholds should be explored in future researches".

As suggested by the Topical Editor, the following paragraph has been included at the end of the actual last paragraph in section 3:
"In effect, we believe that the concept of equivalent prismatic gully shows several benefits and applications. Probably the principal one is that it permits the determination of the most important characteristics of a complete gully (V, L, W_{me} and D_{me}), using objective and repeatable criteria. Otherwise, there is the risk of assigning information from specific cross sections or reaches to the whole gully. Besides, the gully properties (V, L, W_{me} and D_{me}), as defined here, can be incorporated into statistical analyses or similar studies in which many gullies are involved, using a common language, repeatable and comparable among different researchers. Furthermore, by using the concept of an equivalent prismatic gully, sets of complete gullies can easily be graphically represented, which enables a quick and explanatory visual comparison".

A new version of the conclusions including the requirements of both Topical Editor and Referee #2 has been written:

"In order to progress in gully erosion research, clear criteria to define and determine the key morphological characteristics of gullies and their related properties (such as volumes) are needed. In this paper, a new proposal for advancing towards that goal has been submitted. Thus, starting from a precise definition of the width of each gully cross section, the mean equivalent gully width and depth are defined, and also the equivalent prismatic gully (EPG). This approach permits the determination of the most important characteristics of a complete gully (V, L, W_{me} and D_{me}), using objective criteria. Besides, the gully properties defined here can be incorporated into statistical analyses using a common language among different researchers. On the other hand, by using the EPG, sets of complete gullies can be easily graphically represented, which allows for an explanatory visual comparison. The definition of the width of each gully cross section assumes that the topography of the area before the gully appearance is known. This is, in fact, really infrequent, so that a new line of research arises. Anyway, we believe that the proposal is a considerable advance in the applied research on gullies, because it allows one to standardize the definition and determination of the most important characteristics of these erosion forms".

As suggested by the Topical Editor the caption of Figure 3 has been modified as follows:

"Illustration of the effect that the criterion followed to determine the cross section width exerts on the computed volume of a gully reach. a) Selected gully reach and location of the three cross sections used for calculating the volume of the reach (*P1*, *P2* and *P3*); the distance between cross sections is known. b) Calculated eroded volume (in blue) when considering a possible criterion for defining the gully cross sections widths. c) Calculated eroded volume (in red) when considering another possible criterion for defining the gully cross sections widths".

As suggested by the Topical Editor, the text on page 327, starting from line 16 (included) has been modified as follows:

"However, an overall review of all the sections conforming the gully being studied would give a better assessment of this measurement error. Fig. 3 aims to illustrate the effect that the criterion followed to determine the cross section width exerts on the computed volume of a gully reach. A real gully reach was selected and three cross sections were used for calculating the volume of the reach (*P1*, *P2* and *P3*) (Fig. 3a), the distance between cross sections being known. First, the eroded volume was calculated considering a possible criterion for defining the gully cross sections width (in blue, Fig. 3b). Then, the eroded soil was calculated again but considering another possible criterion for defining the gully cross sections widths (in red, Fig. 3b). The difference in the calculated volume for both situations is remarkable, increasing by 96% from option b to option c. Figure 3 is just one example illustrating: i) the great differences in volumes that can be obtained in fixing the gully widths arbitrarily; ii) the error that can be generated and; iii) the necessity of establishing rigorous and objective criteria and protocols. The purpose of figure 3 is similar to figure 2, the latter depicting the effect of the uncertainty in the determination of width in a single cross-section of a gully".

As suggested by the Topical Editor, at the end of Figure caption 4 the following text has been included: "See section 3 for details".

As suggested by the Topical Editor, on Figure caption 5, the word "different" has been corrected.

Marked-up manuscript version

All relevant changes previously described are marked in red. The English language has been revised.

Gully geometry: what are we measuring?

J. Casalí[1], R. Giménez[1] and M. A. Campo-Bescós[1]

[1] Department of Projects and Rural Engineering, Public University of Navarre, Los Olivos Building, 31006 Pamplona, Spain

Abstract

Many of the research works on (ephemeral) gully erosion comprise the determination of the geometry of these eroded channels especially their width and depth. This is not a simple task due to uncertainty generated by the wide range of variability of gully cross-section shapes found in the field. However, in the literature, this uncertainty is not recognized so that no criteria in their measurement procedures are indicated. The aim of this work is to make researchers aware of the ambiguity that arises when characterizing the geometry of an ephemeral gully and similar eroded channels. In addition, a measurement protocol is proposed with the ultimate goal of pooling criteria in future works. It is suggested the geometry of a gully could be characterized through its mean equivalent width and mean equivalent depth, which, together with its length, define an "equivalent prismatic gully" (EPG). The latter would facilitate the comparison between each other of different gullies.

1. Introduction

The classic forms of water erosion are caused by non-concentrated or laminar flow and concentrated flow; in the latter, rill and gully erosion has been recognized (Hutchinson and Pritchard, 1976). Rill erosion is produced in the form of numerous channels of a few centimeters in depth, distributed uniformly and randomly over sloping lands (Soil Science Society of America, 2015), and which can easily be obliterated by conventional tillage (Hutchinson and Pritchard, 1976). Also, permanent gullies are distinguished from ephemeral ones (Foster, 1986; Thorne et al., 1986; Casalí et al., 1999). Permanent gullies are erosion channels which are too large to be eliminated by conventional tillage (Soil Science Society of America, 2015). Ephemeral gullies –present in agricultural soils– are, like rills, small enough for it to be possible to eliminate them by traditional tillage (Soil Science Society of America, 2015), hence their being qualified as ephemeral. However, when they form again, and contrary to what is observed in rills, they tend to appear in the same places. This is explained by the fact that the ephemeral gullies are formed in the thalweg which configures the confluence of two opposing slopes, a fact which conditions the trajectory of the runoff. Rills, however, occur entirely on one single slope (Casalí et al., 1999); their formation is, therefore, mainly subjected to the high spatial variability of intrinsic factors of the soil (structural stability, hydraulic conductivity, etc.) and of its tillage.

The objectives of a large number of works on gully erosion have been the estimation of the spatial and/or temporal evolution of a gully or a network of them under different conditions (i.e. climate, land use, etc.) (e.g., Casalí et al, 2006; Gabet and Bookter, 2008; Campo-Bescós et al., 2013). For that purpose, as a first step, a morphological characterization is made of these channels. The most frequent way to do so is by the measurement of their width and depth –and the ratio between both parameters– (e.g., Giménez et al., 2009); and their typology is also studied (for example, whether their cross section presents a general shape like a U or a V). If the measurement of the length of the gully is added to this, it might be possible to arrive at determining their volume (eroded soil).

Consequently, for a precise description of the geometry of a gully, the correct determination of its width is a key factor. This is not always an easy task, especially when faced with cross sections with intricate shapes and diffuse limits. However, in the numerous scientific works on the subject, no uncertainty whatever is expressed on this measurement, and neither are the criteria followed in the procedure specified. We believe that, as a general rule, it is usually assumed that their width is defined by the imaginary line whose ends are located at both points of the two banks, where an abrupt change in slope is manifested. This criterion would be followed both in direct measurements in situ, and in indirect ones taken from digital elevation models and mathematic algorithms ad hoc (e.g., Evans and Lindsay, 2010; Parker et al., 2012; Castillo et al., 2014). This procedure, at first sight reasonable and unquestionable, raises, however, two objections. First, there is the presence of more than one point of slope inflection in one or both banks. Second, although only one visible inflection point is presented on the slope of each bank – with the width of the channel thus being clearly defined – this poses a question. Do the limits of this channel, defined in this way, really correspond to the transversal limits of the erosive process which gave rise to the gully? Only by knowing the topography of the land at moments before the formation of the gully would that question be answered with any certainty.

On the other hand, the width of a gully defines the upper limit of its cross section, therefore conditioning the subsequent determination of the depth of that channel. Furthermore, in this latter measurement (depth of the gully), another important ambiguity is added, i.e. the determination of the lower limit of the cross section (channel bed). This latter limit is usually located –in our belief– at the lowest point of the cross section, which is questionable in beds with a highly irregular cross sectional profile. Even so, nor is the difficulty inherent in measuring a gully depth usually emphasized in the literature.

In short, the lack of any protocol or universal criterion in determining the geometry of gullies would then cause a certain uncertainty at the moment of comparing between each other the experimental results obtained by different researchers; for example, erosion rate values.

In this work it is sought to make the scientific community aware of the –precisely, inadvertent doubts– which are triggered when characterizing the geometry of an ephemeral gully, and for this purpose some examples of real cases will be shown. Also, a measurement protocol is proposed with the ultimate aim of pooling criteria in future works and experimentation. Although they are proposed for ephemeral gullies, these same criteria would equally apply for similar erosion channels.

2. Uncertainties in measuring the width and depth of a gully

Researchers, especially newcomers, when confronted with the measurement of gully geometry, assume that the limits of the erosion channel will present themselves in the field as being clearly defined, and, in fact, this is often true (see Fig. 1.1-1.3). However, on many occasions this is not the case (Fig. 1.4-1.6). It is therefore possible that a clear break in the slope of one of the banks (Fig. 1.6) or in both of them (Fig. 1.5) may not be noticed. Another possible ambiguity –independent or added to the previous one– is that which arises when both banks of the channel are uneven (Fig. 1.4, Fig. 1.6). This means that determining a single height value to trace an imaginary horizontal line between both banks is highly subjective. It is understood that the length of this line would be defining the width of the cross section being measured.

In another sense, when defining the depth of a gully, the lower limit of the cross section is usually well defined by the lowest point of the bed (see Fig. 1.2). However, what usually happens is that the location of this limit is also controversial as can be seen in the cross sections in Figures 1.1. and 1.3., where it is precisely not clear if this limit would really be represented by the lower height of the bed.

An incorrect determination of the width and/or depth of a certain gully may cause (important) errors in the determination of its volume; i.e. in the estimation of the eroded soil (Fig. 2 and Fig. 3). The magnitude of this potential experimental error would be less obvious, and even underestimated, if we analyze the cross sections individually (Fig. 2). However, an overall review of all the sections conforming the gully being studied would give a better assessment of this measurement error. Fig. 3 aims to illustrate the effect that the criterion followed to determine the cross section width exerts on the computed volume of a gully reach. A real gully reach was selected and three cross sections were used for calculating the volume of the reach (P1, P2 and P3) (Fig. 3a), the distance between cross sections being known. First, the eroded volume was calculated considering a possible criterion for defining the gully cross sections width (in blue, Fig. 3b). Then, the eroded soil was calculated again but considering another possible criterion for defining the gully cross sections widths (in red, Fig. 3b). The difference in the calculated volume for both situations is remarkable, increasing by 96% from option b to option c. Figure 3 is just one example illustrating: i) the great differences in volumes that can be obtained in fixing the gully widths arbitrarily; ii) the error that can be generated and; iii) the necessity of establishing rigorous and objective criteria and protocols. The purpose of figure 3 is similar to figure 2, the latter depicting the effect of the uncertainty in the determination of width in a single cross-section of a gully.

3. Topographic definition of gully width, equivalent prismatic gully (EPG)

Let`s suppose that we have a detailed digital elevation model (DEM) of a gully whose geometry we wish to determine (Fig. 4a). Similarly, we would also have a DEM, not more than one year old, of the same area, but before the gully in question would have formed. Remember that the cycle of the formation and obliteration of an ephemeral gully is conditioned by the periodicity (usually one year) of the agricultural tillage responsible for it. We shall call the DEM prior to the appearance of the gully $DEM_{year\ n}$, whereas that of the following year –that is, with the gully now present– $DEM_{year\ n+1}$ (Fig. 4a).

Let`s imagine now that, at any point x along the longitudinal axis of length L of the gully, we draw a vertical plane P_x, perpendicular to that axis (Fig. 4b). If in this plane P_x we substract the $DEM_{year\ n+1}$ from the $DEM_{year\ n}$, we should obtain the eroded area or cross section of the gully (Fig. 4b). Now, the imaginary line which arises from joining the two points of the intersection of both DEMs would define, in turn, the width of the gully in that section (P_x) (Fig. 4b). In the case of both points being uneven, a horizontal projection of the line should be considered. This same operation could be repeated in a multitude of other points *xi* along the channel, thus obtaining the width value of each new section (W_i). Finally, the average of the values W_i would define the mean equivalent width of the whole gully, W_{me}. Those widths, determined thus, would undoubtedly be the true transversal limit of the erosion process which caused the gully in question.

If we now carry out the substraction of both DEMs but on their entire surface, we should obtain the volume V of the gully (Fig. 4a).

Also, knowing V and W_{me}, we could, in turn, determine a mean equivalent depth D_{me} expressed as:

$$D_{me} = V / (W_{me}\ L) \qquad (1)$$

This depth value would be more representative of the whole gully than that resulting from considering the minimum height of the bed as being the lower limit of the cross section (see above).

Finally, the gully could be represented as a rectangular-based prism (W_{me} D_{me}) of a length L, which we would call “equivalent prismatic gully” (EPG) (Fig. 4c and Fig. 5).

This sort of normalization of the complex geometry of a certain gully –by means of its respective EPGs– would permit, for example, a quick visual comparison of the individuals of a varied population(s) of gullies (Fig. 5). It would thus be an interesting tool for incorporating into simulation models (e.g., AnnAGNPS, Gordon et al., 2007).

In effect, we believe that the concept of equivalent prismatic gully shows several benefits and applications. Probably the principal one is that it permits the determination of the most important characteristics of a complete gully (V, L, W_{me} and D_{me}), using objective and repeatable criteria. Otherwise, there is the risk of assigning information from specific cross sections or reaches to the whole gully. Besides, the gully properties (V, L, W_{me} and D_{me}), as defined here, can be incorporated into statistical analyses or similar studies in which many gullies are involved, using a common language, repeatable and comparable among different researchers. Furthermore, by using the concept of an equivalent prismatic gully, sets of complete gullies can easily be graphically represented, which enables a quick and explanatory visual comparison.

The width of a gully cross section, as defined in this paper, depends on the DEMs pixel size and it depends on the type and size of the studied channel. Hengl (2006) concluded that, to prevent the loss of relevant information, the maximum pixel size must be the average of the minimum distances between sampling points. In the same way, Garbrecht and Martz (1994) fixed the pixel size to the size of the minimum distinguishable object. Additionally, the new methodologies available (terrestrial or aerial LIDAR, 3D photo-reconstruction, etc.), provide a very detailed information, which may be more than enough, in our opinion, for the purposes of these studies. However, these thresholds should be explored in future researches.

4. Conclusions

In order to progress in gully erosion research, clear criteria to define and determine the key morphological characteristics of gullies and their related properties (such as volumes) are needed. In this paper, a new proposal for advancing towards that goal has been submitted. Thus, starting from a precise definition of the width of each gully cross section, the mean equivalent gully width and depth are defined, and also the equivalent prismatic gully (EPG). This approach permits the determination of the most important characteristics of a complete gully (V, L, W_{me} and D_{me}), using objective criteria. Besides, the gully properties defined here can be incorporated into statistical analyses using a common language among different researchers. On the other hand, by using the EPG, sets of complete gullies can be easily graphically represented, which allows for an explanatory visual comparison. The definition of the width of each gully cross section assumes that the topography of the area before the gully appearance is known. This is, in fact, really infrequent, so that a new line of research arises. Anyway, we believe that the proposal is a considerable advance in the applied research on gullies, because it allows one to standardize the definition and determination of the most important characteristics of these erosion forms.

Acknowledgements

This study was partly funded by the Spanish Ministry of Science and Innovation (project CGL2011-24336).

References

Campo, M. A., Flores-Cervantes, J. H., Bras, R. L., Casalí, J., Giráldez, J.V.: Evaluation of a gully headcut retreat model using multitemporal aerial photographs and digital elevation models. Journal of Geophysical Research - Earth Surface, 118, 1–15, 2013.

Casalí, J., López, J. J., Giráldez, J.V.: Ephemeral gully erosion in southern Navarra (Spain). Catena 36 (1-2): 65-84, 1999.

Casalí, J., Loizu, J., Campo, M.A., De Santisteban, L. M., Álvarez-Mozos, J.: Accuracy of methods for field assessment of rill and ephemeral gully erosion. Catena 67 (2): 128-138, 2006.

Castillo, C., Taguas, E. V., Zarco-Tejada, P., James, M. R., Gómez, J. A.: The normalized topographic method: An automated procedure for gully mapping using GIS. Earth Surface Processes & Landforms 39: 2002-2015, 2014.

Evans, M., Lindsay, J.: High resolution quantification of gully erosion in upland peatlands at the landscape scale. Earth Surface Processes and Landforms 35:876-886, 2010.

Foster G. R.: Understanding ephemeral gully erosion. In Soil Conservation. Assessing the National Resources Inventory 2. Committee on Conservation Needs and Opportunities, Board of Agriculture, National Research Council. National Academy Press, Washington: 90–125, 1986.

Gabet, E. J., Bookter, A.: A morphometric analysis of gullies scoured by post-fire progressively bulked debris flows in southwest Montana, USA. Geomorphology 96: 298–309, 2008

Garbrecht, J., Martz, L.: Grid size dependency of parameters extracted from digital elevation models. Computers and Geosciences 20: 85-87, 1994.

Giménez, R., Marzolff, I., Campo, M. A., Seeger, M., Ries, J. B., Casalí, J., Álvarez-Mozos, J.: Accuracy of high-resolution photogrammetric measurements of gullies with contrasting morphology. Earth Surface Processes and Landforms 34: 1915-1926, 2009.

Gordon, L. M., Bennett, S. J., Bingner, R. L., Theurer, F. D., Alonso, C.V.: Simulating ephemeral gully erosion in AnnAGNPS. Transactions of the American Society of Agricultural and Biological Engineers 50(3): 857-866, 2007.

Hengl, T.: Finding the right pixel size. Computers and Geosciences 32: 1283; 1298-1283; 1298, 2006.

Hutchinson, D. E., Pritchard, H. W.: Resource conservation glossary. Journal of Soil and Water Conservation 31: 1-63, 1976.

Parker, C., Clifford, N. J., Thorne, C. R.: Automatic delineation of functional river reach boundaries for river research and applications. River Research and Applications 28, 1708-1725, 2012.

Soil Science Society of America: Glossary of Soil Science Terms. Soils Science Society of America, Madison, WI, https://www.soils.org/publications/soils-glossary#, 2015.

Thorne C. R., Zevenbergen, L.W., Grissinger, E. H., Murphey, J.B.: Ephemeral gullies as sources of sediment. Proceedings of the Fourth Federal Interagency Sedimentation Conference 1: 3–152, 3–161, 1986.

Figures

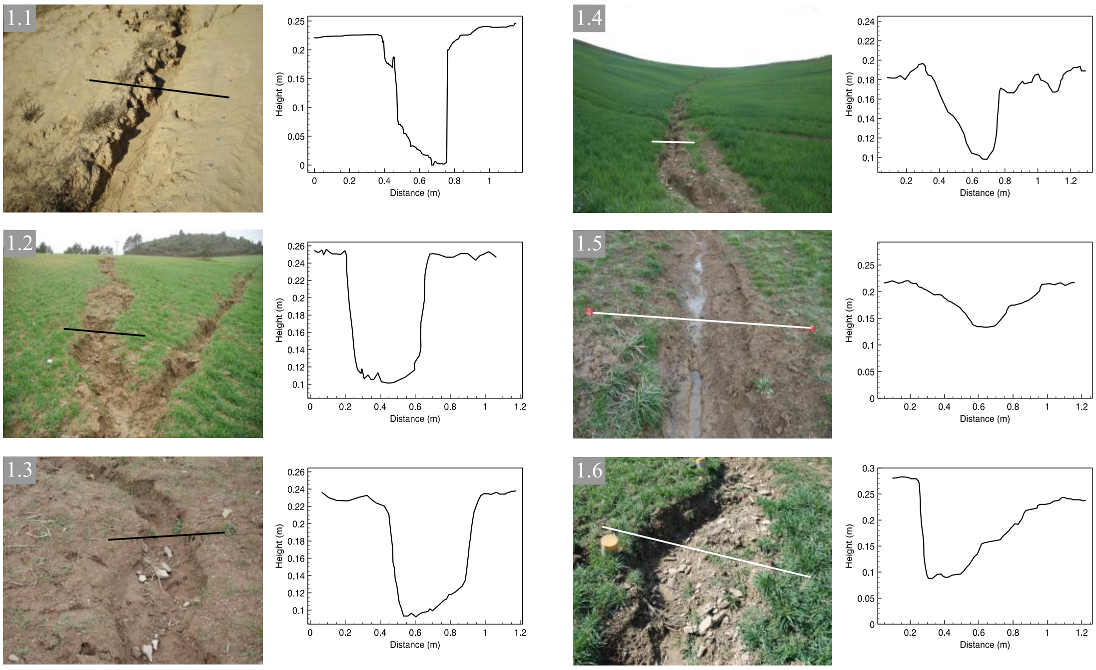

Figure 1. Examples of cross-sections of typical ephemeral gullies (Navarre, Spain).

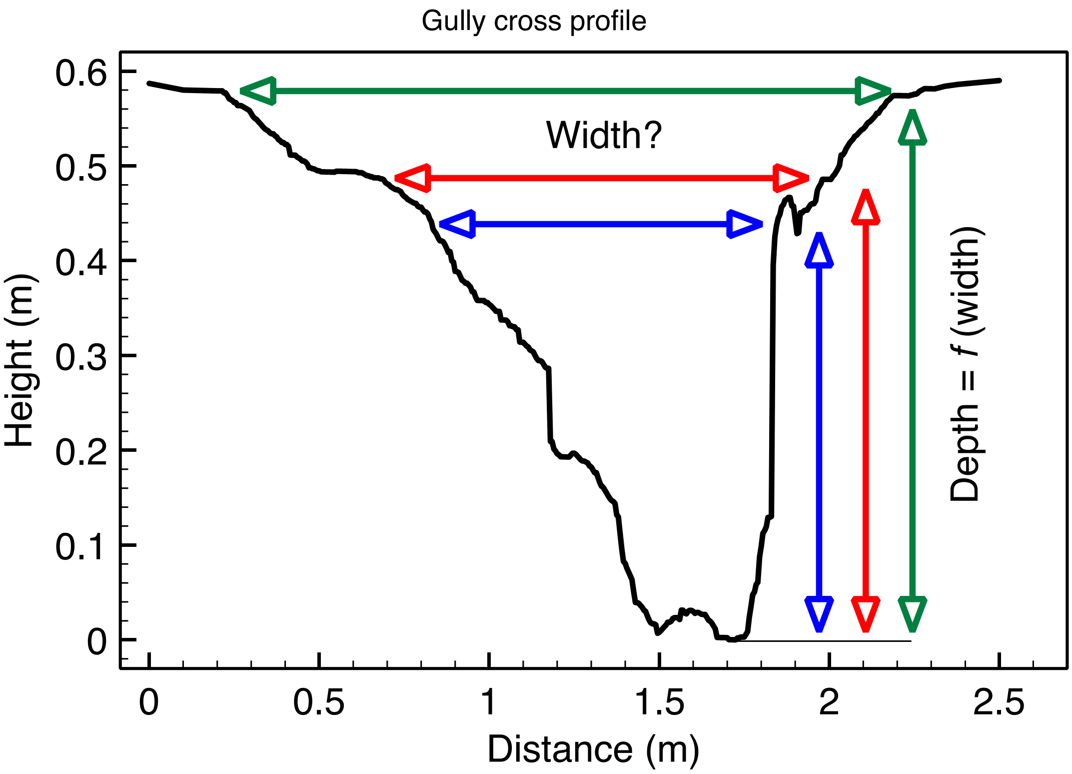

Figure 2. Uncertainty in the determination of a width in a cross-section of a gully (real example).

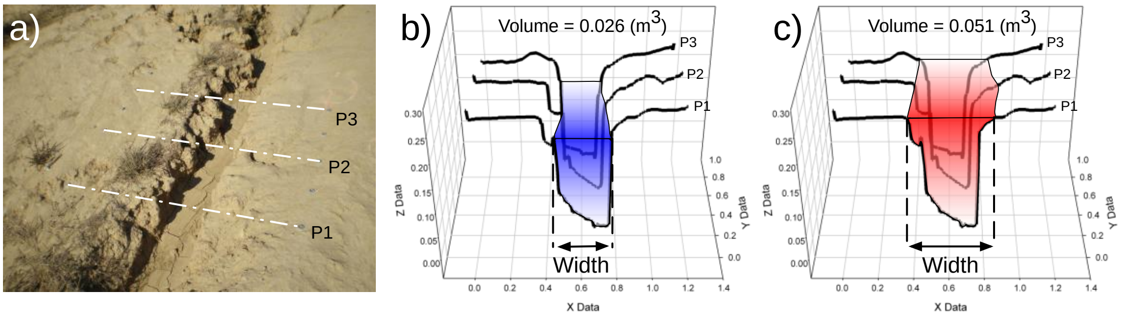

Figure 3. Illustration of the effect that the criterion followed to determine the cross section width exerts on the computed volume of a gully reach. a) Selected gully reach and location of the three cross sections used for calculating the volume of the reach (*P1*, *P2* and *P3*); the distance between cross sections is known. b) Calculated eroded volume (in blue) when considering a possible criterion for defining the gully cross sections widths. c) Calculated eroded volume (in red) when considering another possible criterion for defining the gully cross sections widths.

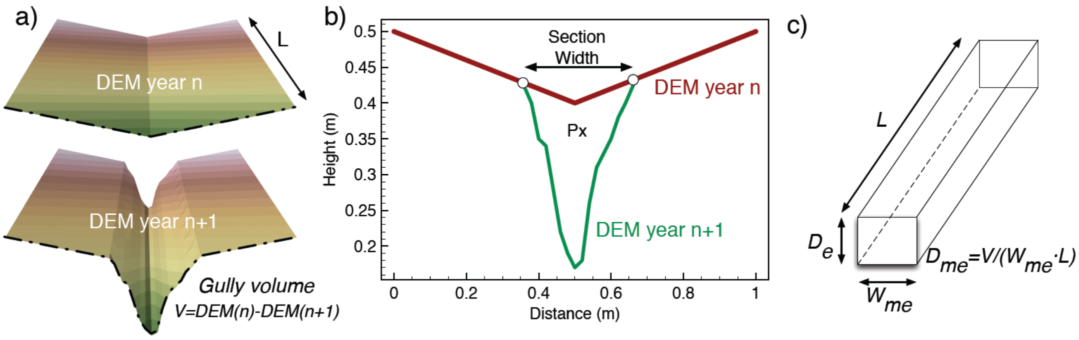

Figure 4. a) Sketch of two separated digital elevation models of a fictitious plot before ($DEM_{year\ n}$) and after ($DEM_{year\ n+1}$) a gully has been formed in the plot thalweg; b) sketch cross section area depicted at any point *x* along the longitudinal axis of the gully; c) equivalent prismatic gully (EPG). See section 3 for details.

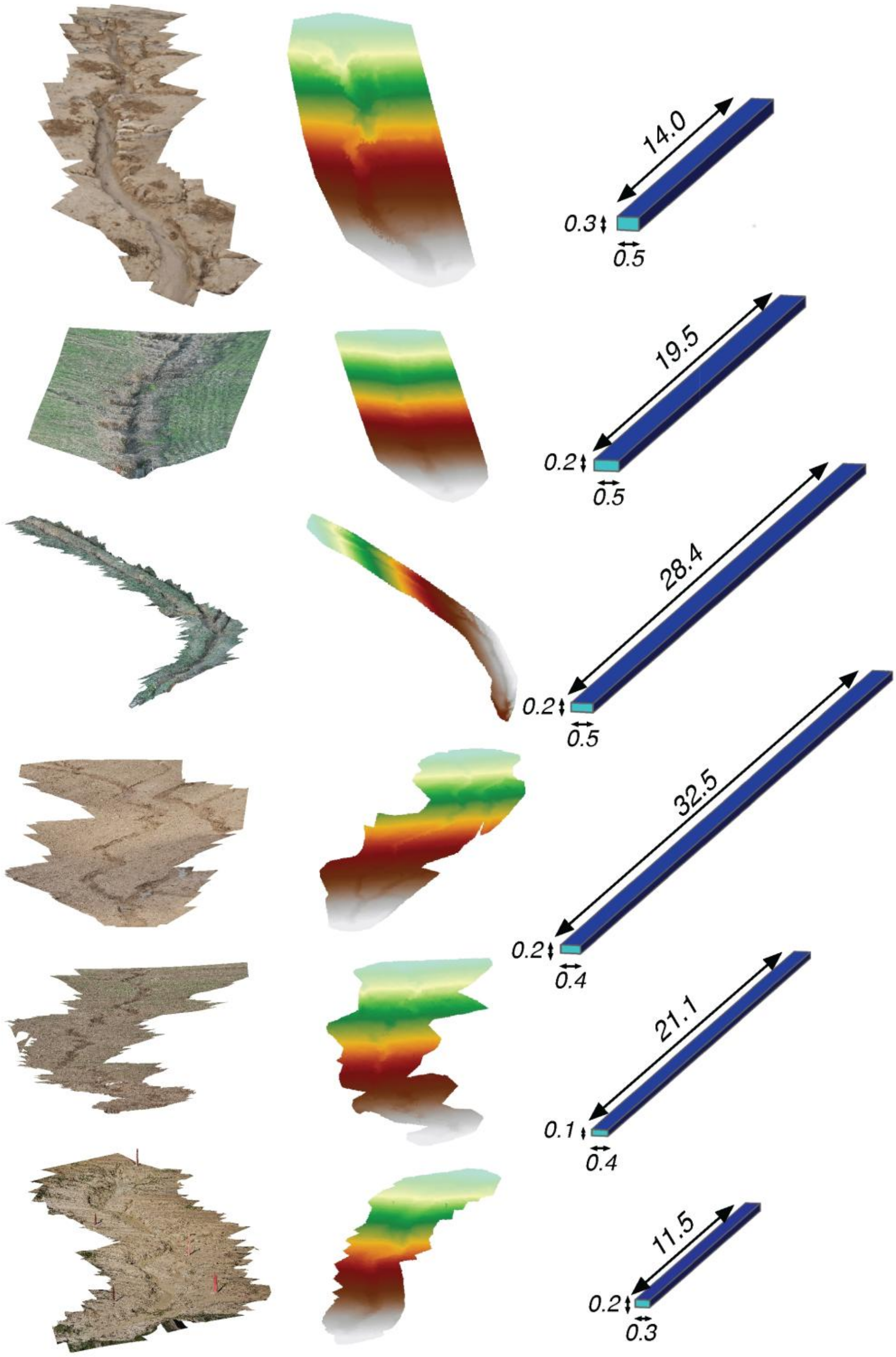

Figure 5. a) Pictures of ephemeral gullies of different shapes (Navarre, Spain); b) Digital elevation model (*DEM*$_{year\ n+1}$, see Figure 4) of each gully; c) Equivalent prism of the gullies (since there was not a DEM available prior to the gully formation (*DEM*$_{year\ n}$, see Figure 4) the width was arbitrarily defined from abrupt changes at both gully banks (see text for more explanation). It should be made clear that the geometry of the equivalent prisms could have (dramatically) changed if we had also counted with the corresponding *DEM*$_{year\ n}$. (Lengths in m)