Professor Erwin Zehe
Executive Editor of HESS
Handling editor of paper hess-2019-572

April 12th, 2020

Dear Prof. Erwin Zehe,

We are very pleased with the positive evaluation of our manuscript entitled "Structural and functional control of surface-patch to hillslope-scale runoff and sediment connectivity in Mediterranean-dry reclaimed slope systems" (ref. hess-2019-572). The article has clearly benefited from the helpful suggestions of the two anonymous referees.

Please, find below a complete list of answers to the comments and changes to the paper carried out to carefully address your remarks and the suggestions proposed by the two referees. The comments are shown below in italics. Our responses are presented below each comment in regular font. Changes in the text of the revised version of our paper are presented in our responses between quotation marks and in italics. A marked-up version of the manuscript showing the specific changes we made is submitted along with this letter.

Looking forward to hearing from you soon,

On behalf of the co-authors,
Yours sincerely,
Mariano Moreno de las Heras

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1. Comlments by the Editor, Erwin Zehe

General comment:

After a close look at your manuscript I concur with both reviewers, that your study needs minor revisions. In this respect I regard the outlined changes in your response to reviewer 1 as very much appropriate.

Response to the general comment: We thank Erwin Zehe for the positive evaluation of the paper. We have modified the paper according to the outlined changes that we proposed in the interactive discussion of the original paper. These changes and modifications are presented in detail below, along with our responses to the referee comments.

2. Comments by Referee # 1

General comment:

In this paper presents a promising way to put the theoretical concept of structural and functional hydrological connectivity into practice by evaluating the connectivity between patch- and hillslope-scale with innovative measures for hydrological connectivity. Definition and measures of hydrological connectivity is an important field of hydrological research and offers additional value for sedimentological and geomorphological re-search. This study uses a threshold for vegetation cover combined with a high resolution digital elevation model to derive a measure for structural connectivity. Functional connectivity was determined for a defined precipitation event as the ratio of runoff/sediment contributions from the hillslope scale to the corresponding contributions on a virtual hillslope represented the integrated patch-scale contributions. Functional hydrological and sedimentological connectivity was successfully modeled using a generalized linear model. Model predictors included various measures of precipitation data as well as the structural connectivity measure. Surveyed data, methods and results contribute to the understanding of hydrological processes and the practical use of the hydrological connectivity concept in the Mediterranean-dry. Thus, I recommend the publication after the revision of this manuscript.

Response to the general comment: We thank Referee # 1 for his/her positive assessment of the scope and contents of our study, and for his/her thoughtful comments and detailed edits, which helped to improve significantly our paper. All his/her comments are addressed in detail below.

Specific comments (SCs):

SC Line 14: *The first sentence is very general: "multiple factors", "variety of spatial scales", "variable degrees of connection". The sentence is also closely related to the second sentence. I suggest to merge the content in one precise sentence. You may also introduce the "Mediterranean-dry* *reclaimed mining slope systems" here to avoid confusion with the term "systems" later and also introduce an abbreviation for the full term for later in the text.*

Response to SC Line 14: Following the recommendations, we have simplified the first three sentences of the abstract, removing imprecise concepts and introducing clearly the study systems: "*Connectivity has emerged as a useful concept for exploring the movement of water and sediments between landscape locations and across spatial scales. In this study, we examine the structural and functional controls of surface-patch to hillslope-scale runoff and sediment connectivity in three Mediterranean-dry reclaimed mining slope systems that have different long-term development levels of vegetation and rill networks*". The use of an abbreviation for the term "Mediterranean-dry reclaimed mining slope systems" is introduced a bit later in the text, in the Introduction section.

SC Line 15: *Connection or connectivity?*

Response to SC Line 15: We meant "connectivity". This specific sentence was removed in the revised version of the paper, following the previous recommendations of comment SC Line 14.

SC Line 15(b): *"In these systems" – there are no systems defined before*.

Response to SC Line 15(b): After merging and simplifying the first three sentences of the abstract (please, see above our response to SC Line 14 for details of the changes) all vague citations to generic "systems" have been removed.

SC Line 16: *movement of water, runoff is already moving water*.

Response to SC Line 16: Following the recommendations, we have changed "movement of runoff" to "movement of water".

SC Line 18: *The sub-sentence beginning with "or the extent to which..." interrupts the reading flow, I suggest to transfer the sub-sentence into a second sentence*.

Response to SC Line 18: Following the recommendations, we have transferred the sub-sentence to end of the text structure: "*Structural connectivity was assessed using flowpath analysis of coupled vegetation distribution and surface topography, providing field indicators of the extent to which surface patches that facilitate runoff/sediment production are physically linked to one another in the studied hillslopes*".

SC Line 21: *Same as line 18, better breaking the sentence into two parts, or leaving out the sub-sentence "determined as...". This leaves space to mention the GLM model in the abstract*.

Response to SC Line 21: Thanks for the suggestions. We have removed the sub-sentence: "*Functional connectivity was calculated using the ratio of surface-patch to hillslope-scale observations of runoff and sediment yield for 21 monitored hydrologically active rainfall events*". In addition, we have introduced new information mentioning our modelling methods in the abstract: "*The impact of the dynamic interactions between rainfall conditions and structural connectivity on functional connectivity were further analyzed using general linear models with a backward model structure selection approach*".

SC Line 21(b): *"...was further explored..." may be changed to e.g. "...was calculated as..."*.

Response to SC Line 21(b): Following the recommendations, we have changed "*was further explored*" to "*was calculated*".

SC Line 22: *The sentence may be rephrased like "Functional hydrological connectivity during precipitation events was found to be dynamically controlled by antecedent precipitation conditions and rainfall intensity and further strongly modulated by the structural connectivity of the slopes"*

Response to SC Line 22: We have rephrased the sentence following these specific recommendations.

SC Line 24: *"On slopes without rill networks, both runoff..."*

Response to SC Line 24: We have rephrased the sentence following these specific recommendations.

SC Line 25: *"analyzed systems": there are no defined systems, may use e.g. hillslopes or research slopes*

Response to SC Line 25: Following the recommendations, we have changed "*systems*" to "*hillslopes*".

SC Line 29: *transference of both "water" and sediment (without yield).*

Response to SC Line 29: We have rephrased the sentence following these specific recommendations.

SC Line 34-40: *These sentences are very close to the first sentences of the abstract. Rephrase either of them.*

Response to SC Line 34-40: The text of the first sentences of the abstract have been modified very considerably (please, see above our response to SC Line 14 for details of the changes), also minimizing redundancy with the information of the first sentences in the Introduction.

SC Line 36: *Connection or connectivity? See also line 15. Please be specific about the terminology and definition of hydrological connectivity (also line 42).*

Response to SC Line 36: Following the recommendations and in order to provide coherence in the use of terminology, we have changed along the paper "connection" to "(hydrological) connectivity".

SC Line 46: *could be misread as "transfer of sediment fluxes". Better just "transfer of water and sediments" or "fluxes of water and sediment".*

Response to SC Line 46: Following the recommendations, we have changed "transfer of water and sediment fluxes" to "transfer of water and sediments".

SC Line 47: *I suggest to use: "the activation of connections of runoff..."*

Response to SC Line 47: Following the recommendations, we have changed "the generation of active connections" to "the activation of connections".

SC Line 47b: *I suggest not to write "In the case of runoff..." but "Functional connectivity of runoff depends on the dynamics...". Also I suggest to split this sentence to have one sentence for the runoff sub-sentence and one for the sedimentological.*

Response to SC Line 47b: We have added the suggested changes: "*Functional connectivity of runoff depends on the dynamics of overland flow generation, routing, and downward re-infiltration. For sediments, functional connectivity is a function of the detachment, entrainment, deposition and remobilization of sediments across scales*".

SC Line 52: *Leave out the "For example,"*

Response to SC Line 52: Following the recommendations, we have removed "For example" in the text.

SC Line 55: *Leave out the "In fact,"*

Response to SC Line 55: Following the recommendations, we have removed "In fact" in the text.

SC Line 56: *Instead of "terraces) controls" may use "were shown to control" also: "from a structural connectivity perspective"*

Response to SC Line 56: We have added the suggested changes: "*The spatial arrangement of surface features (e.g., vegetation cover, rills, gullies, channels, terraces) were shown to control the distribution of source and sink elements in these landscapes from a structural connectivity perspective, largely driving the production and transference of runoff and sediments across scales*".

SC Line 63: *This sentence may needs to be rephrased. The strength of the transport vector may be important for the sedimentological functional connectivity for pure hydrological connectivity the establishment of a water flux between the patches of the landscape already represent fully functional connectivity between those patches no matter how big the flux is.*

Response to SC Line 63: Following the recommendations, we have rephrased the sentence: "*The interactions between precipitation conditions and the structural connectivity of a landscape determines functional connectivity*".

SC Line 65: *"to determine the initiation of runoff and thus, the transport of water and sediments..."*

Response to SC Line 65: We have rephrased the sentence following these specific recommendations.

SC Line 76: *You could make use of an abbreviation from line 14 here.*

Response to SC Line 76: The term "reclaimed mining slope systems" is now abbreviated along the paper from this line: "*Mediterranean-dry reclaimed mining slope systems (hereafter RMSSs)*".

SC Line 81: *to my understanding the routing of runoff is part of the structural connectivity while the processes which cause infiltration/excess of water to initialize, maintain or interrupt the flow of water is part of the functional hydrological connectivity.*

Response to SC Line 81: Following the recommendations and for coherence with the applied terminology, we have reworded this sentence: "*the processes that initialize, maintain or interrupt the fluxes of water and sediments from the surface patch to the broader, hillslope scale*".

SC Line 84/88/91/95: *Use abbreviation for the slope system.*

Response to SC Line 84/88/91/95: Following the recommendations, we have applied the abbreviation "RMSS" in these lines and throughout the paper.

SC Line 91: *"transference of water..."*

Response to SC Line 91: Following the recommendations, we have changed "transference of runoff" to "transference of water".

SC Line (either) 101/129: *Add a short sentence like: "The field work was accomplished between October 2007 and November2008." After mentioning the dates of the survey no need for further repetition of the dates during the methods/results/discussion e.g. line 124/126....*

Response to SC Line (either) 101/129: Following the recommendations, the fieldwork dates are now detailed in a single sentence located in the first lines of the Methods: "*The study site* *encompasses three experimental slopes, all north facing with a general gradient of about 20º (Figures 1b and 1d), which were surveyed intensively between October 2007 and December 2008*".

SC Line 103: *Sentence is incomplete and does not make sense.*

Response to SC Line 103: We have reworded the sentence: "*Mean annual precipitation (MAP) is 450 mm, most of which occurs in spring and autumn. Potential evapotranspiration (PET; Hargreaves and Samani, 1985) is around 900 mm and the hydrological deficit (MAP-PET) is approx. 450 mm, concentrated in the summer months (López-Martín et al., 2007)*".

SC Line 105: *Just: "Remarkable is..."*

Response to SC Line 105: We have rephrased the sentence following these specific recommendations.

SC Line 115: *This sentence suggests that Slope 2 also has significant amounts of overland flow and erosion, which to my understanding is not the case.*

Response to SC Line 115: The berm that acts as a runoff contribution structure is much smaller in Slope 2 than in Slope 1, which limits its impact in the former as compared to the later. *We* have rephrased this sentence to avoid confusions: "*These variations occurred due to the existence of a very steep (40º) and bare soil, runoff contributing berm integrated at the top of two of the experimental slopes (Slopes 1 and 2, with berm sizes of 50 and 20 m^2, respectively; Figure 1b). This runoff contributing structure promoted soil erosion and conditioned the early dynamics of the experimental slopes, particularly in Slope 1, where the berm area is bigger and produces important amounts of overland flow*".

SC Line 121-125: *This may also part of the results section.*

Response to SC Line 121-125: Although we understand the comment raised by the reviewer, we prefer to keep this information (gross runoff and sediment production of the slopes) in the description of the experimental site, as these numbers are already published in a previous paper (Merino-Martín et al. 2012a) and we do not apply any direct analysis of these gross variables (we just refer here to the published general information).

SC Line 127: *Already mentioned that in the abstract and introduction. No need to have that long introduction here for the methods.*

Response to SC Line 127: Following the recommendation, we have deleted the redundant information from the text.

SC Line 130: *"...Merino-Martin et al., 2012a), that included naturally delimited runoff/erosion plots distributed at the (i) hillslope and the (ii) surface-patch scale."*

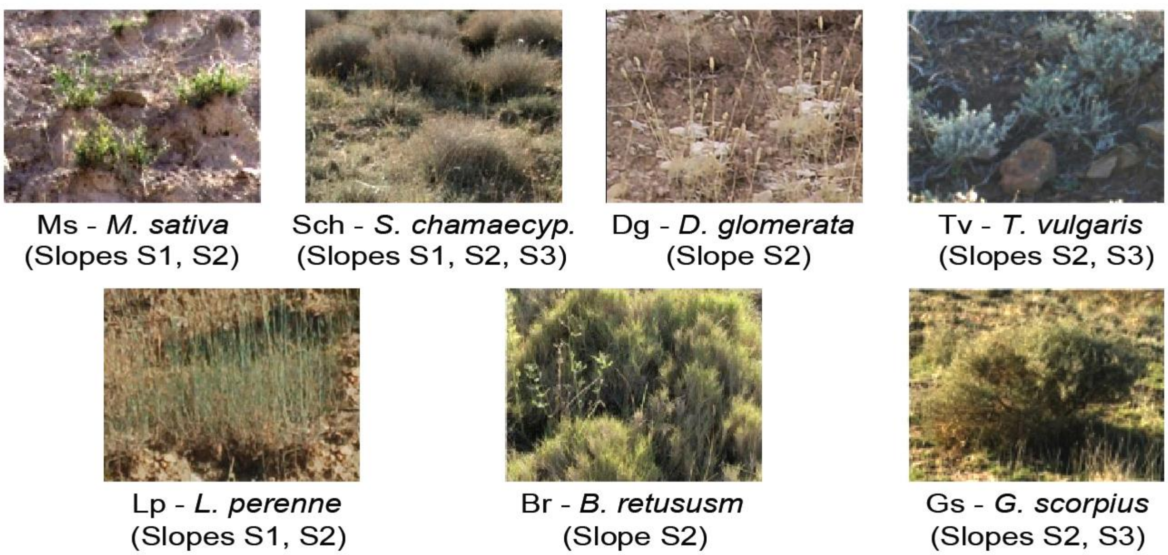
Response to SC Line 130: We have rephrased the sentence following these specific recommendations.

SC Line 136-139: *You mention Fig. 1d and 1f but not 1e. Usually the parts of the figures are described according to their alphabetic order. Either restructure the text or the figure.*

Response to SC Line 136-139: Please, note that panel Fig. 1e is already cited in the text (line 145 of the original manuscript), although it is cited after Fig. 1f. We have re-ordered the citations in the text and the panels in Fig. 1 to describe them according to their alphabetic order.

SC Line 140-143 & fig. 1f: *Categories for the species would increase direct readability of the figure. E.g. Medicago sativa (Ms – A), Dactylis glomeratea (Dg - B), Santolina chamaecyparissus (Sch - B),...*

Response to SC Line 140-143 & Fig. 1f: We believe that increasing the complexity of the species abbreviations in the text with new characters has probably little interest in terms of increased readability of the paper. However, we agree with Referee # 1 that linking these species with the hillslopes in the figure can be useful. Therefore, we have modified panel (f) of figure 1 to link the dominant species with the hillslopes using the following labels/codes:



SC Line 150-151: *Sedimentological methods, may adjust header of the chapter to field measurements.*

Response to SC Line 150-151: We have adjusted the header of the (sub)section to: "*2.2 Field acquisition methods of hydro-sedimentary and precipitation data*".

SC Line 153-169: *Climatological, soil hydrological and statistical analytical methods mixed. I suggest to split the statistical part from the pure data acquisition part. A table showing an overview of the climatological statistics would be beneficial also for the introduction of the predictors for the GLM later on.*

Response to SC Line 153-169: Following the recommendations, we have split the statistical and data acquisition information and generated a new section in the Methods for the description of the statistical methods (section "*2.5 Data analysis and statistics*"). In addition, we have added the following new table (new Table 1) that shows an overview of the precipitation condition variables applied in the study:

	Description	Units
Dp	Storm depth	mm
Rd	Rainfall duration	h
I_{15}	15-min max rainfall intensity	mm h^{-1}
I_{30}	30-min max rainfall intensity	mm h^{-1}
Im	Mean rainfall intensity	mm h^{-1}
API	Antecedent precipitation index	mm

SC Line 171: *"Previous research carried out..." (References missing!).*

Response to SC Line 171: Although the reference was already included in the original version of the paper (line 175: Moreno-de-las-Heras et al., 2009), we agree with the referee that the first line of the information is a better place to the citation in the text: "*Previous research carried out in the Utrillas field site applying small-scale (0.25 m^2) rainfall simulations (Moreno-de-las-Heras et al., 2009) (…)*".

SC Line 172: *Why using a range here when a non-dynamic threshold of 50% is applied?*

Response to SC Line 172: We have modified the text, in line with the applied non-dynamic threshold of vegetation cover: "*surface patches with vegetation cover under 50% can generate important amounts of runoff/sediments*".

SC Line 179: *(0.5m resolution)*

Response to SC Line 179: We have added the suggested change in the text.

SC Line 184: *"To this end," is a fill word and can be deleted.*

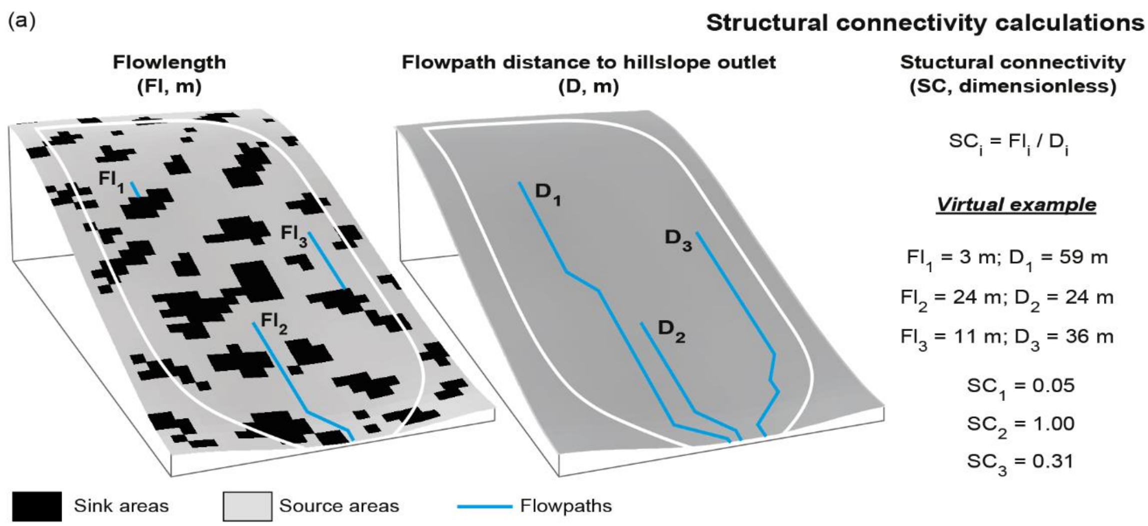
Response to SC Line 184: Following the recommendations, we have removed the expression "to this end".

SC Line 199: *Maybe better: "...until a sink (i.e. >50% vegetation cover) or the outlet of the system is reached." And "outlet of the system is reached" is unclear which system patch or hillslope?*

Response to SC Line 199: Following the recommendations, we have reworded this sentence: "*until a sink (i.e., >50% vegetation cover) or the outlet of the hillslope is reached*".

SC Line 199(b): *In general, introducing a figure to illustrate the different steps of the calculation and also the use of mathematical symbols and equations to clarify the calculated ratio in line 201 could help to increase understanding for the reader.*

Response to SC Line 199(b): We agree with Referee # 1 that illustrating the different steps of the calculations in a figure can strongly facilitate understanding of the calculated index of structural connectivity. We have added the following schematic figure (new Fig. 2a) illustrated with a virtual example that is linked to the text using fully explicit mathematical symbols and equations:



SC Line 206: *"Mean Sc values ((Sc) Ì˘E)...": The mean should be indicated by a dash above the whole symbol of which the mean is calculated.*

Response to SC Line 206: Following the recommendation, we have modified the symbol along the text and all figures of the paper.

SC Line 209-214: *Again a repetition of the introduction sentences. It would be sufficient to leave it to very short general introduction sentences for the sub-headers in the methods*

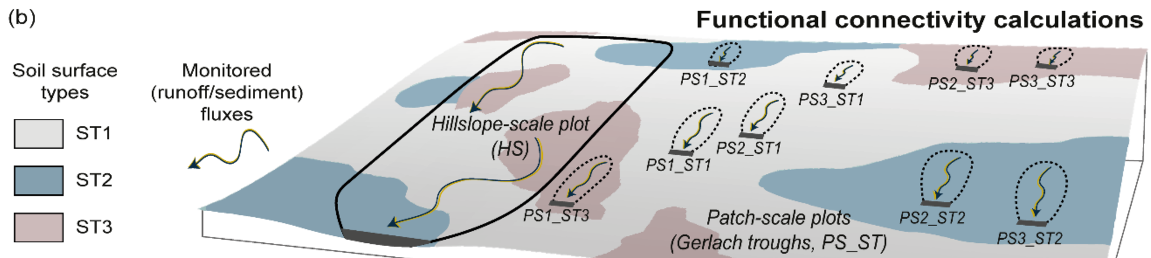
Response to SC Line 209-214: Following the recommendation, we have deleted all the redundant information from this section of the text.

SC Line 213: *I recommend to stick with functional connectivity to stay within the framework of hydrological connectivity and not switch between spatial continuity and functional connectivity. Within the methods functional connectivity should defined for this study.*

Response to SC Line 213: Following the recommendations, we now provide in the Methods of the revised version of this study a clear definition of functional connectivity ("*Functional connectivity for this study is defined as the continuity of runoff and sediment fluxes from the surface-patch to the hillslope scales*") and stick with this concept in the Discussion.

SC Line 214-220: *Same as for structural connectivity: Figure and mathematical structure could help to increase understanding. Both connectivity measures could be visualized next to each other in one figure.*

Response to SC Line 214-220: Same as for SC, we have added to the paper the following schematic figure (new Fig 2b) for illustrating the functional connectivity calculations using a virtual example that is linked to the text using fully explicit mathematical symbols and equations:



Virtual event example

Unit-area runoff and sediment yield

	Runoff R (mm)	Sediments S (g m^{-2})
HS	1.2	3.9
PS_ST1*	4.4	22.8
PS_ST2*	0.8	2.0
PS_ST3*	3.2	9.5

*Averaged from the corresponding PS_STi plots

Proportional area of surface types in HS

	ST1	ST2	ST3
A	0.60	0.20	0.20

Integrated patch-scale response of runoff (R_{IPS}, mm)

$$R_{IPS} = \sum_{i=1}^{n} (R_{PS\_STi} * A_{STi})$$

$$R_{IPS} = 3.44 \text{ mm}$$

of sediment yield (S_{IPS}, g m^{-2})

$$S_{IPS} = \sum_{i=1}^{n} (S_{PS\_STi} * A_{STi})$$

$$S_{IPS} = 15.98 \text{ g m}^{-2}$$

Functional connectivity of runoff (C_R, dimensionless)

$$C_R = R_{HS} / R_{IPS}$$

$$C_R = 0.35$$

of sediments (C_S, dimensionless)

$$C_S = S_{HS} / S_{IPS}$$

$$C_S = 0.24$$

SC Line 233-238: *This may not belong in the section under the header functional connectivity but in a section of statistical analysis.*

Response to SC Line 233-238: We have moved this information to a new section for the description of the statistical methods (section "*2.5 Data analysis and statistics*").

SC Line 234: *No need to mention the dates of the study period again.*

Response to SC Line 234: Following the recommendations, we have removed the dates of the study period in this section.

SC Line 239: *Same header as previous sub-section. Needs to state the statistical modeling/analysis.*

Response to SC Line 239: We have moved this information to a new section for the description of the statistical methods (section "*2.5 Data analysis and statistics*").

SC Line 240-248: *Have you checked for correlations among the predictors. The predictor set used in a GLM should not have high correlated predictors.*

Response to SC Line 240-248: Please, note that we applied a backward model selection procedure to optimize the final model structure. This stepwise procedure automatically pulls out from the optimal model any secondary predictors that strongly covariate with the final, selected predictors.

SC Line 240: *As stated above (line 153-169) a table for the predictors would be helpful. This could be referenced here instead of "(Dp, Rd, I15, I30, and Im)"*

Response to SC Line 240: Following the recommendations, we have added a new table (new Table 1) showing an overview of the precipitation condition variables applied in the study (please, see above our response to SC Line 153-169 for details). This new table is now cited in this section of the text to detail the predictor variables applied in the modelling tasks.

SC Line 243: *I suggest: "We modeled Cr and Cs using a generalized linear model (GLM, Christensen, 2002) approach with an automated stepwise backward model selection." Which link function did you use? Which program was used to implement the model and model selection?*

Response to SC Line 243: Please, note that we have not applied "generalized" linear models (GLiM), but "general" linear models (GLM). Both, our details in the text and the cited reference (Christensen, 2002) refer to "general" linear models. While for GLiM the link function (and error distribution family) can be selected among a range of common options, the link function is always linear for GLM.

We have adapted the text following the recommendations ("*We modelled C_R and C_S using general linear models (GLM; Christensen, 2002) and a backward model structure selection approach*"). We have added also a few words detailing the software applied in the analysis: "*All data analyses and statistics were developed within the R statistical computing and language programming software environment (R Core Team, 2019)*".

SC Line 259: *"This fact violates..." the relation of the "this fact" is unclear. I guess you mean the values of >1 for Cs. But the sentence ends with the values <1 for Cr which is not a violation against the GLM assumptions.*

Response to SC Line 259: The asymptotic behavior of Cr breaks the GLM assumption of linearity (please, note the non-linear behavior of Cr in the back-transformed results of our modelling exercise; figure 4b-c in the original paper). We have clarified this point in the text: "*While C_S may* *take values (largely) above 1 when active rilling takes place, C_R is constrained to values ≤1 and consequently, may asymptotically approach 1 as rainfall increases. The asymptotic behaviour of C_R violates the GLM assumption of linearity for large values of the model predictors. We, therefore, applied logarithmic transformation to the precipitation co-variables (Table 1) to comply with the GLM assumptions for C_R modelling*".

SC Line 260: *either reference the suggested table again or may write "...transformation to the climatological co-variables..."Line 263/265: no need to mention the vegetation cover again as it is defined in the methods.*

Response to SC Line 260: Following the recommendations, we have cited the new table (Table 1) showing the predictor variables applied in the modelling tasks.

SC Line 269/276/279: *"not physically linked"/ "physical contiguity" you mean "were not connected"/ "structural (functional) connectivity"?*

Response to SC Line 269/276/279: We have added the suggested changes to the text.

SC Line 271: *"...largely interfering the structural connection..."*

Response to SC Line 271: We have added the suggested text edit.

SC Line 277: *"almost 50%"?*

Response to SC Line 277: Please, note that the values corresponding to Prob. SC≥1 (i.e., the proportion of source pixels or locations in a hillslope that are connected with the outlet of the hillslope) are not equivalent to the mean SC values ($\overline{SC}$) of the hillslope. For the particular case detailed in this comment (Slope 1) applies: "*the probability of finding runoff/sediment source areas physically linked to the outlet of the slope system (Probability SC_i = 1) was 42%, leading to a large mean structural connectivity at the hillslope level ($\overline{SC}$=0.47)*".

SC Line 278: *"...lower (12% for Slope 2 and <1% for Slope 3)..."*

Response to SC Line 278: We have added the recommended changes to the text: "*… lower (Prob. SC_i = 1 is 12% and <1% for Slopes 2 and 3, respectively)*".

SC Line 283: *"Functional connectivity of runoff across scales showed important differences..." The information in between was previous mentioned in the methods.*

Response to SC Line 283: Following the recommendation, we have deleted the redundant information from the text.

SC Line 285: *"...decreased from the [...] hillslope-scale from Slope 1 to Slope 3 (Figure3a)".*

Response to SC Line 285: The suggested change alters significantly the original meaning of the sentence. We have adjusted the text to: "*Cumulative runoff production along the study period (2007-08) decreased from the surface-patch to the hillslope-scale for all the three experimental slopes (Figure 4a). However, these variations in runoff production across scales showed remarkable differences between the slopes*"

SC Line 288: *"that 72% of..."*

Response to SC Line 288: We have added the recommended change to the text.

SC Line 289: *"...of the system and 28% of the runoff was redistributed or re-infiltrated."*

Response to SC Line 289: We have added the recommended change to the text.

SC Line 290: *Please just use the precise numbers here and not "less than" etc.*

Response to SC Line 290: Following the recommendation, we now apply precise numbers in the text: "*connectivity of cumulative runoff was 0.17 and 0.06 for Slope 2 and 3, respectively*".

SC Line 305: *"(Cs=0)"*

Response to SC Line 305: We have added the recommended change to the text.

SC Line 306: *"...other events at Slope 1 hillslope-scale..."*

Response to SC Line 306: We have added the recommended edit to the text.

SC Line 369: *could be use of the abbreviation for Mediterranean-dry r.s.s.*

Response to SC Line 369: We have added the recommended edit to the text.

SC Line 382: *The large differences between Slope 2 and 3 were not pointed out in the results.*

Response to SC Line 382: We have modified the text in the results to detail these differences: "*Furthermore, the large spatial dominance of sink patches in the middle and bottom section of Slope 3 ($\overline{SC}$=0.02) very considerably reduced the structural connectivity of this hillslope as compared to Slope 2 ($\overline{SC}$=0.17), where the bottom section of the hillslope is dominated by source patches*".

SC Line 424: *"...largely controls the functional connectivity of the runoff responses..."*

Response to SC Line 424: We have added the recommended edit to the text.

SC Line 461-463: *The differences might also be explained by differences in temporal resolution of the precipitation measurements.*

Response to SC Line 461-463: We do not follow the logic suggested by the referee. Our results suggest that mean rainfall intensity (Im) may be more relevant for the connectivity of sediments than maximum (e.g., I_{15}, I_{30}) rainfall intensity, which could be explained by the impact of sustained levels of intense rainfall during the events ("*in the present study, sediment connectivity is better explained by mean rainfall intensity (Im), which may suggest enhanced conditions for sediment transfer and rill incision by sustained (rather than maximum) high intensity rainfall*"). However, we acknowledge that both mean and maximum rainfall intensities are strongly correlated for the events of our study, so the rainfall events that showed the highest levels of sediment connectivity also showed (at the same time) the highest levels of both maximum and mean rainfall intensities ("*the high correlation that links the maximum (I_{30}) and mean (Im) rainfall intensities of the analysed events (Pearson's R= 0.92, p<0.01) reveals that the storms displaying the best conditions for the formation of spatially connected sediment flows along the study period (top C_S whisker values in Fig. 3d) were characterized by both high maximum and averaged rainfall intensity (up to 33 and 6 mm h^{-1} I_{30} and Im, respectively)*").

SC Line 497: *"...movement of water..."*

Response to SC Line 497: We have added the recommended edit to the text.

SC Line 502: *This sentence has a very complicated structure. I suggest to re-write the sentence and may break it into two. You also mention rills as "preferential pathways" in your conclusions. This topic could be a little bit more emphasized in the discussion as it is a dominant element for the generation of runoff and sediment fluxes.*

Response to SC Line 502: Following the recommendations, we have split and simplified the sentence: "*Our results revealed an important role of the hillslope position of vegetation patches on the distribution of potential runoff and sediment flowpaths. More critically, the rill networks emerged as key elements of structural connectivity in the slopes, providing preferential pathways that dominate the production, spatial organization and routing of the fluxes of water and sediments*". In addition, we have emphasized the role of the rill networks in key locations of the Discussion, for example "*rill networks provide very efficient erosive flow routing pathways that largely facilitate the transference of water and sediments across sections of the hillslopes with little or no potential for runoff re-infiltration and sediment deposition*", "*Besides the key influence of rills for the spatial transmission of runoff, these hillslope structural elements were also found to play a dominant role in the generation of sediment fluxes and its spatial distribution* (…) *In this context, rills not only facilitate within-slope transference of water and sediment fluxes but also work as powerful sources of sediments that can significantly contribute with freshly eroded particles to the analysed sediment fluxes between the surface-patch and hillslope scales*", or "*These non-linear hydro-geomorphological responses are strongly conditioned by the dynamics of Slope 1, where the* *presence of a well-organized rill network provides the system with cross-scale hillslope structural elements for intensive sediment production and effective flow routing*", among others.

<u>Technical corrections (TC)</u>:

TC Line 43: *"were proposed" instead of "have been proposed"*

Response to TC Line 43: We have added the recommended text edit.

TC Line 68: *"Several research approaches were applied..."*

Response to TC Line 68: We have added the recommended text edit.

TC Line 696: *Year missing. Link of public access of the review available?*

Response to TC Line 696: We have updated the information of the reference: "*Saco, P. M., Rodríguez, J. F., Moreno-de-las-Heras, M., Keesstra, S., Azadi, S., Sandi, S., Baartman, J., Rodrigo-Comino, J., and Rossi, M. J.: Using hydrological connectivity to detect transitions and degradation thresholds: application to dryland systems, Catena, 186, 104354 (1-14), https://doi.org/10.1016/j.catena.2019.104354, 2020*"

TC Fig. 4: *versus in captions needs to not italic*

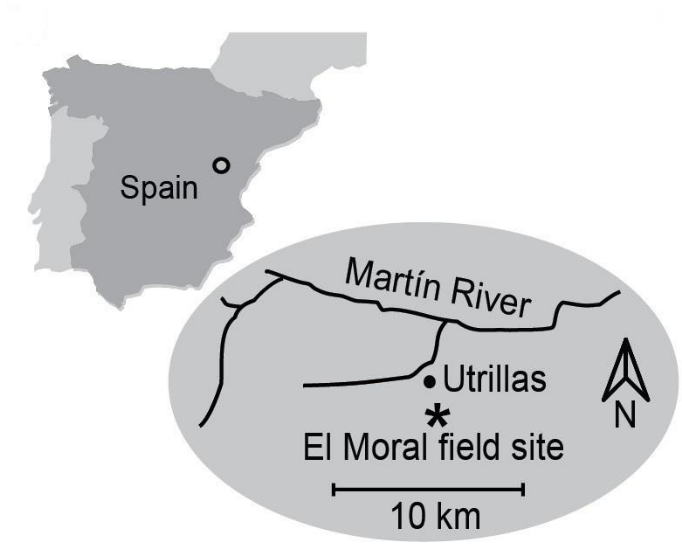
Response to TC Fig. 4: We have added the recommended text edit to the captions.

TC Tables: *A table summarizing predictor variables for the GLM would be beneficial.*

Response to TC Tables: We have added the recommended table (please, see above our response to SC Line 153-169 for details).

TC Fig. 1a: *The local map could be enlarged compared to the overview map of Spain.*

Response to TC Fig. 1a: The local map is now enlarged in the figure compared to the overview map of the Iberian Peninsula



TC Fig. 1e: *The setup is hard to see in the images. Taking the lower part of the left image may would be sufficient. Adding a schematic may would be helpful.*

Response to TC Fig. 1e: Following the recommendations, we have enlarged the lower part of the left image and added some schematic elements in the right image to improve the representation of the Gerlach troughs:

TC Fig. 1f: *Colored classes or class indication with capital letters for the dominant species of the three hillslopes could help to connect the species to the related hillslopes. If colors are used they can be also used to indicate the corresponding slopes in Fig. 1b and d.*

Response to TC Tables: We have added codes to the images of Fig. 1f to link the plant species with the study hillslopes (please, see above our response to SC Line 140-143 & Fig. 1f).

TC Fig. 2-5: *Please adjust the color scheme to suit the needs of colorblind. Testing the figures can be done by e.g. https://www.color-blindness.com/coblis-color-blindness-simulator/*

Response to TC Fig. 2-5: We have adapted the color scheme of the figures to suit the needs for different forms of colorblindness (protanopia, deuteranopia and tritanopia).

TC Fig. 4/5: *Abbreviations do not necessarily be explained in the captions.*

Response to TC Fig. 4/5: We have removed those abbreviations that are not necessary to be detailed in the captions.

3. Comments by Referee # 2

General comment:

Dear authors,

I find your manuscript very useful and a very good contribution for connectivity studies. I must say I found it very well and clear written. I can only say as a very minor correction that I would reduce the conclusion because I find the current one too long and descriptive.

Congratulations!

Response to the general comment: We thank Referee # 2 for his/her very positive assessment of our study. Following the suggested changes for the conclusions, we have reduced significantly the length of this section (from 376 to 275 words), reducing also the descriptive character of the text:

"*We developed in this study a practical application of the conceptual elements of structural and functional connectivity for the analysis of surface-patch to hillslope-scale transmission of runoff and sediments in three Mediterranean-dry reclaimed mining slope systems showing different levels of long-term development of vegetation and rill networks. Our results revealed an important role of the hillslope position of vegetation patches on the distribution of potential runoff and sediment flowpaths. More critically, the rill networks emerged as key elements of structural connectivity in the slopes, providing preferential pathways that dominate the production, spatial organization and routing of the fluxes of water and sediments. On the other hand, both runoff and sediments were largely redistributed within the analysed slope systems in the absence of rill networks. The interactions between the structural connectivity of the experimental slopes and both antecedent precipitation and rainfall intensity largely controlled event functional connectivity. The results showed that rainfall intensity and, more importantly, antecedent precipitation largely increased the spatial continuity of runoff fluxes under rilled slope conditions, where active rill incision under high intensity rainfall induced large non-linear increases in hillslope-scale sediment yield.*

In sum, this study provides empirical evidence of the feasibility of using the hydrological connectivity concept for practical applications, remarking specifically its usefulness for understanding how hillslope structural elements dynamically interact with storm characteristics and rainfall conditions to generate spatially continuous runoff and sediment fluxes. Overall, our study approach of structural and functional connectivity offers a useful framework for assessing the complex links and *controlling factors that regulate the generation and movement of runoff and sediments across different scales and elements of the landscape in Mediterranean-dry and other water-limited environments*".

Structural and functional control of surface-patch to hillslope-scale runoff and sediment connectivity in Mediterranean-dry reclaimed slope systems

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Abstract. Connectivity has emerged as a useful concept for exploring the movement of water and sediments between landscape locations and across spatial scales. In this study, we examine the structural and functional controls of surface-patch to hillslope-scale runoff and sediment connectivity in three Mediterranean-dry reclaimed mining slope systems that have different long-term development levels of vegetation and rill networks. Structural connectivity was assessed using flowpath analysis of coupled vegetation distribution and surface topography, providing field indicators of the extent to which surface patches that facilitate runoff/sediment production are physically linked to one another in the studied hillslopes. Functional connectivity was calculated using the ratio of surface-patch to hillslope-scale observations of runoff and sediment yield for 21 monitored hydrologically active rainfall events. The impact of the dynamic interactions between rainfall conditions and structural connectivity on functional connectivity were further analysed using general linear models with a backward model structure selection approach. Functional runoff connectivity during precipitation events was found to be dynamically controlled by antecedent precipitation conditions and rainfall intensity, and strongly modulated by the structural connectivity of the slopes. On slopes without rills, both runoff and sediments for all events were largely redistributed within the analysed hillslopes, resulting in low functional connectivity. Sediment connectivity increased with rainfall intensity, particularly in the presence of rill networks where active incision under high intensity storm conditions led to large non-linear increases in sediment yield from the surface-patch to the hillslope scales. Overall, our results demonstrate the usefulness of applying structural and functional connectivity metrics for practical applications, and for assessing the complex links and controlling factors that regulate the transference of both surface water and sediments across different landscape scales.

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1 Introduction

Surface processes in Mediterranean landscapes are affected by multiple factors (e.g., rainfall characteristics, soil surface properties, vegetation, micro-topography, landforms) that interact at a variety of spatial scales (from the soil surface patch to the plot, hillslope and catchment scales), resulting in intricate responses of runoff and sediment yield (Puigdefabregas et al., 1999; Calvo-Cases et al., 2003; Cammeraat, 2004; Yair and Raz-Yassif, 2004; Boix-Fayos et al., 2006; Moreno-de-las-Heras et al., 2010; Mayor et al., 2011; Gallart et al., 2013; Marchamalo et al., 2016). In these complex systems, connectivity has emerged as a useful concept for studying the movement and transference of surface water and water-borne materials (e.g., sediments, nutrients, seeds) between landscape locations or scales (Bracken and Croke, 2007; Wainwright et al., 2011; Bracken et al., 2013; Reaney et al., 2014; Keesstra et al., 2018; Saco et al., 2019).

Two conceptual elements of hydrological connectivity that facilitate the analysis of the spatial and temporal dynamics of both runoff and sediments throughout hillslopes and catchments were proposed: structural and functional connectivity (Turnbull et al., 2008; Wainwright et al., 2011; Okin et al., 2015). Structural connectivity refers to the spatial arrangement of hydrologically significant units or elements, and it captures the extent to which these units are physically linked to each other to allow for the transfer of water and sediments. The second, functional (or process-based; Bracken et al., 2013) connectivity, refers to the activation of connections of runoff and/or sediment pathways during a particular rainfall event. Functional connectivity of runoff depends on the dynamics of overland flow generation, routing, and downward re-infiltration. For sediments, functional connectivity is a function of the detachment, entrainment, deposition and remobilization of sediments across scales (Wainwright et al., 2011; Bracken et al., 2013; Turnbull and Wainwright, 2019).

Multiple studies have focused on the analysis of the effects of landscape structural components of connectivity on runoff and soil erosion, particularly in Mediterranean-dry and other dryland systems. In water-limited environments with patchy vegetation, measures related to the spatial organization (i.e., the pattern, patch size and landscape position) of vegetation explain runoff and soil erosion better than average vegetation cover (Bautista et al., 2007; Arnau-Rosalén et al., 2008; Puigdefabregas, 2005). The spatial arrangement of surface features (e.g., vegetation cover, rills, gullies, channels, terraces) were shown to control the distribution of source and sink elements in these landscapes from a structural connectivity perspective, largely driving the production and transference of water and sediments across scales (Cammeraat, 2004; Lesschen et al., 2009; Turnbull et al., 2010; Merino-Martin et al., 2015; Marchamalo et al., 2016; Moreno-de-las-Heras et al., 2019). Structural connectivity can be highly dynamic over long time periods (e.g., decades or longer) as a result of changes in vegetation, land use and surface morphology. However, structural connectivity is generally considered a static landscape feature over the time periods of interest (e.g., the hydrological year), which has facilitated the application of this concept in hydrological and geomorphological studies using surface contiguity indexes (Heckmann et al., 2018 and references therein).

The interactions between precipitation conditions and the structural connectivity of a landscape determines functional connectivity (Wainwright et al., 2011; Bracken et al., 2013; Reaney et al., 2014; Okin et al., 2015). Surface patches respond to rainfall characteristics and (antecedent) soil moisture conditions to determine the initiation of runoff and thus, the transport

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of water and sediments through the landscape (Cantón et al., 2011; Mayor et al., 2011; Rodríguez-Caballero et al., 2014). Thus, functional connectivity may dynamically vary between rainfall events. There is little consensus, however, on how to quantify functional connectivity (Okin et al., 2015). Several research approaches were applied to analyse functional aspects of connectivity in terms of the continuity of runoff and sediment fluxes along hillslopes, landscapes and catchments. These approaches cover a wide array of methods including hierarchical (i.e., nested, stratified and/or scaled) runoff/sediment yield measurements (Cammeraat, 2004; Yair and Raz-Yassif, 2004; Moreno-de-las-Heras et al., 2010; Mayor et al., 2011), field-based mapping and modelling of active runoff/sediment flowpaths (Arnau-Rosalén et al., 2008; Marchamalo et al., 2016; Turnbull and Wainwrigth, 2019), fallout radionuclide and rare-earth element sediment tracing applications (Masselink et al., 2017a; Moreno-de-las-Heras et al., 2018) or particle-in-motion tracers and overland flow sensors (Hardy et al., 2017; Masselink et al., 2017b).

Mediterranean-dry reclaimed mining slope systems (hereafter RMSSs) are characterized by the local convergence of high storm erosivity, poorly developed soils, scarce vegetation cover, and rough topography. These characteristics can lead to the genesis of important amounts of overland flow, promoting soil erosion processes, which typically lead to rill and gully development (Nicolau and Asensio, 2000; Nicolau, 2002; Moreno-de-las-Heras et al., 2009; Martín-Moreno et al., 2018). The analysis of runoff and sediment connectivity has a critical relevance for landscape management in these human-made, water-limited environments, where the functional components of runoff and sediment connectivity (e.g., the processes that initialize, maintain or interrupt the fluxes of water and sediments from the surface patch to the broader, hillslope scale) can shape on-site structural connectivity factors (e.g., vegetation patterns, spatial distribution of rill networks and sedimentation areas) over long periods, conditioning the long-term eco-geomorphic stability of the reclaimed systems (Moreno-de-las-Heras et al., 2011a). In fact, within-slope spatial redistribution of runoff and sediment fluxes in these Mediterranean-dry RMSSs feeds back into patch-scale hydrological behaviour by controlling the availability of water and soil resources for the long-term development of vegetation cover (Espigares et al., 2011; Moreno-de-las-Heras et al., 2011b; Merino-Martín et al., 2015). Furthermore, the magnitude and cross-scale transmission of runoff and sediments in these RMSSs largely determines their off-site effects in the form of runoff and sediment conveyance to downstream channels and environments (Martín-Moreno et al., 2018).

In this study, we apply the concepts of structural and functional connectivity to analyse the factors that control the transference of water and sediments from the surface patch to the hillslope scale in three Mediterranean-dry RMSSs that differ in their vegetation organization and landform features (i.e., rill networks). Our assessment is based on the analysis of patch-to-hillslope runoff/sediment flow continuity of 21 active events monitored during 2007-08 using a hierarchical (scaled) measurement approach (Merino-Martín et al., 2012a). Specifically, our analysis aims to determine how structural components of the three reclaimed slope systems (i.e., the spatial distribution of vegetation cover and micro-topography, including rill networks) dynamically interact with rainfall characteristics (i.e., storm depth, rainfall duration and intensity) and antecedent storm conditions to generate spatially continuous runoff and sediment fluxes.

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2. Materials and Methods

2.1 Study Area

This work was carried out in the Utrillas field site (Figure 1a), an experimental station located in "El Moral", a reclaimed surface coalmine in central-eastern Spain (40º47'24'' N, 0º49'48'' W, 1100 m). The climate is Mediterranean-dry, with a mean annual air temperature of 11ºC. Mean annual precipitation (MAP) is 450 mm, most of which occurs in spring and autumn. Potential evapotranspiration (PET; Hargreaves and Samani, 1985) is around 900 mm and the hydrological deficit (MAP-PET) is approx. 450 mm, concentrated in the summer months (López-Martín et al., 2007). The average number of precipitation events in the area is 50-70 per year. Remarkable is the rainfall erosivity of high-intensity late-spring and summer convective thunderstorms (<10% rainfall events), which can reach up to 100 mm rainfall in 24h (Peña et al., 2002).

The study site encompasses three experimental slopes, all north facing with a general gradient of about 20º (Figures 1b and 1d), which were surveyed intensively between October 2007 and December 2008 (Merino-Martín et al., 2012a; 2015). The slopes were reclaimed during 1987-89 with the following procedure. First, a 100-cm-thick layer of clay-loam overburden substratum was spread over the slopes. Next, the surface was prepared for re-vegetation by applying cross-slope ploughing to create a transversal pattern of surface roughness that would facilitate water storage and infiltration. Finally, the slopes were sown with a seed mixture of perennial grasses and leguminous herbs (*Festuca rubra*, *Festuca arundinacea*, *Poa pratensis*, *Lolium perenne*, *Medicago sativa* and *Onobrychis viciifolia*).

Although the three slopes were originally restored using the same procedure, their subsequent evolution and ecosystem recovery level displayed differences due to variations in their geomorphological design, particularly in the upper section of the slopes. Specifically, these variations occurred due to the existence of a very steep (40º) and bare soil, runoff contributing berm integrated at the top of two of the experimental slopes (Slopes 1 and 2, with berm sizes of 50 and 20 m^2, respectively; Figure 1b). This runoff contributing structure promoted soil erosion and conditioned the early dynamics of the experimental slopes, particularly in Slope 1, where the berm area is bigger and produces important amounts of overland flow. These mechanisms resulted in the formation of a deeply incised (up to 35 cm depth in the middle and lower sections of the slope) and fairly dense (0.6 m per m^2 density) rill network in Slope 1 and, also, important variations in vegetation development among the three experimental slopes. After 20 years of dynamic evolution from initial reclamation, the three experimental slopes showed different levels of vegetation development (30%, 45% and 55% cover for Slopes 1, 2 and 3, respectively), soil erosion intensity (2007-08 sediment yield was 1824, 81 and 4 g m^{-2} for Slopes 1, 2 and 3, respectively) and runoff production (2007-08 runoff coefficient was 14.5%, 2.1% and 0.4% for Slopes 1, 2 and 3, respectively; Table S1 in the online supplement).

2.2 Field acquisition methods of hydro-sedimentary and precipitation data

We monitored runoff and soil erosion in the experimental slopes by applying a scaled approach (Merino-Martín et al., 2012a) that included naturally delimited runoff/erosion plots distributed at (a) the hillslope scale, and (b) the surface-patch scale (Figure 1c).

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Three broad, hillslope-scale runoff/erosion plots were installed in naturally delimited catchments in the experimental slopes (Figure 1d: catchment areas are 498, 511 and 1474 m^2 for slopes 1, 2 and 3, respectively). At the foot of each catchment, two collectors and a central cemented outlet were installed. From the outlet, runoff was routed through a pipe into 200-litre storage tanks connected by multi-slot runoff Geib (1933)-type dividers (Figure 1d).

At the patch scale, seven different soil surface types were identified within the experimental slopes as a function of vegetation community composition and soil surface traits (e.g., dominant plant species, species richness, cover, presence of soil surface crusts and small pedestals). The soil surface patch types (Figure 1e; Table S1 in the online supplement) included: barely covered areas (<5% cover) with scattered clumps of perennial forbs dominated by *Medicago sativa* (Ms); sparsely covered areas (cover approx. 30%) with grasses dominated by *Dactylis glomerata* (Dg), or with dwarf shrubs dominated by either *Santolina chamaecyparissus* (Sch) or *Thymus vulgaris* (Tv); and finally, densely covered areas (>70% cover) dominated by grass species (*Lolium perenne*, Lp, and *Brachypodium retusum*, Br) or by shrubs (*Genista Scorpius*, Gs). In order to monitor runoff and sediment yield at the patch scale, 27 Gerlach (1967) troughs (each 0.5m wide and connected to 100-litre drums for runoff and sediment storage; Figure 1f) were distributed in the slopes between the seven surface types. The spatial organization of the surface types and contributing area of the Gerlach troughs in the experimental slopes was determined in the field using a total station (Topcon GTS212). Catchment area of the Gerlach troughs, delimitated by surface micro-topography and vegetation barriers, ranged from 1 to 16 m^2 (Table S1 in the online supplement).

Runoff amount was measured in the storage tanks/drums within a day after each runoff event (runoff-producing events occurring within a 24 h period were considered to belong to the same event). The stored runoff was stirred, and 1-litre representative samples were taken. Sediment concentrations were determined by oven-drying the collected runoff samples (at 105ºC) until a constant weight was achieved.

A set of six precipitation variables (Table 1) were measured for each of the monitored events. Rainfall depth (Dp, mm) for each event was measured using three bulk precipitation collectors located within the experimental slopes. Rainfall duration (Rd, h) and both 15- and 30-min maximum rainfall intensities (I_{15} and I_{30}, respectively, mm h^{-1}) were measured using an automated recording raingauge (Davis GroWeather) installed in the experimental station. Mean rainfall intensity (Im, mm h^{-1}) for each event was calculated as the ratio of total precipitation to rainfall duration. In order to characterize the antecedent rainfall conditions of the events, we used the Antecedent Precipitation Index (API, mm; Kohler and Linsley, 1951). API is calculated as:

$$API = \sum_{t=-1}^{-T} P_t k^{-t} \qquad (1)$$

where, P_t (mm) is the precipitation on a given day t; k is a dimensionless decay coefficient that represents a measure of the declining influence of past precipitation on current soil moisture state; and T (days) is the antecedent period considered for the calculation of the index. We used fortnightly soil moisture records obtained in the experimental slopes (3x12 TDR profiles of 50-cm depth; Merino-Martín et al. 2015) to parameterize API for this study (k= 0.98, T= 10 days; complimentary field-calibration details of API parameters in Supplementary Methods S1 of the online supplement).

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A total of 21 rainfall events out of 74 precipitations produced runoff/erosion at the patch scale during the study period (October 2007-December 2008, total rainfall 703 mm), although only 17 generated significant hydrological responses at the hillslope scale (Merino-Martin et al. 2012a). We used the complete set of 21 hydrologically active events for this study (full hydro-sedimentary and precipitation data is available in Table S2 of the online supplement).

2.3 Structural connectivity quantification: distribution of sources and sinks

Previous research carried out in the Utrillas field site applying small-scale (0.25 m^2) rainfall simulations (Moreno-de-las-Heras et al., 2009) indicated that surface patches with vegetation cover under 50% can generate important amounts of runoff/sediments, thus acting as "sources" of water runoff and sediments within the slopes. Conversely, surface patches with vegetation cover above 50% regulate soil surface hydrological responses very efficiently and may also operate as flow obstructions, behaving as "sinks" of runoff and sediments. Structural connectivity for this study (i.e., the physical linkage of runoff/sediment source areas within the experimental slopes) has been quantified from coupled analysis of binary maps of vegetation density (above/below 50% cover) derived from high-resolution multispectral aerial photography and field-based digital elevation models (DEMs) of the experimental slopes.

Multispectral information of the experimental slopes was obtained from a high-resolution four-band aerial image (0.5m resolution) captured by the Spanish National Plan for Aerial Orthophotography (PNOA, Spanish National Geographic Institute) in late spring 2009. We used the red and near-infrared bands to generate raster maps of the Normalized Difference Vegetation Index (NDVI). NDVI is a chlorophyll-sensitive vegetation index that strongly correlates with vegetation cover and green biomass density (Anderson et al., 1993). We applied field based NDVI thresholding (Scanlon et al., 2007) to transform the raster NDVI maps of the experimental slopes into binary maps of sinks and sources of runoff and sediments. First, we used reference vegetation density data collected in the field (3x35 quadrats of 0.25m^2 size regularly distributed within the experimental slopes; Merino-Martin et al. 2012b) for determining the proportional abundance of sink areas with above 50% vegetation cover for each analysed slope system. We then classified the pixels in each slope by thresholding the NDVI values in the raster maps to match the ground-based proportional abundance of sink areas obtained in the first step. The application of this image processing methodology resulted in the generation of a high resolution binary map product representing the distribution of sinks and sources (>50% and <50% cover patches, respectively) of runoff and sediments for each experimental slope.

Detailed digital elevation data for the analysis of structural connectivity was obtained from a topographical field survey (Merino-Martín et al., 2015). DEM break lines and filling points (~0.5 points m^{-2} data density) were obtained using a total station (Topcon GTS212). Scattered elevation data was interpolated using thin plate splines to match the (0.5m resolution) grid-based binary maps of sources and sinks of the experimental slopes.

We used the flowlength calculator developed by Mayor et al. (2008) along with the source/sink binary maps and the obtained DEM data to analyse the physical linkage of runoff/sediment source areas in the experimental slopes (Figure 2a). This calculator applies a D8 flow routing algorithm (O'Callaghan and Marks, 1984) to determine the length of the runoff paths

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in the downslope direction (flowlength, Fl, m) until a sink (i.e., >50% vegetation cover) or the outlet of the hillslope is reached. Flowpath measurements were standardized to obtain a structural connectivity indicator (SC; dimensionless). Standardization was carried out for every pixel in the raster maps of the experimental slopes by determining the ratio of the calculated Fl values to the topography-based flowpath distance (D, m) of the pixels to the outlet of the hillslopes ($SC_i = Fl_i/D_i$; Figure 2a). SC values range from 0 (sink pixels) to 1 (source pixels connected to the outlet of the slope system without the interference of any sinks).

2.4 Functional connectivity quantification: flow continuity across scales

Functional connectivity for this study is defined as the continuity of runoff and sediment fluxes from the surface-patch to the hillslope scales. We applied a two-step approach to determine functional connectivity (Figure 2b). First, for each event and experimental slope we determined the integrated patch-scale response of runoff and sediment yield (R_{IPS}, mm, and S_{IPS}, g m^{-2}, respectively). This integrated patch-scale response was computed by weighing the surface-patch runoff and sediment observations (from the data recorded in the Gerlach troughs) with the proportional area of the different soil surface types monitored in each slope system. Second, functional connectivity, assessed as the cross-scale flow continuity of runoff and sediment fluxes (C_R and C_S, respectively), was quantified for each event and experimental slope as the ratio of the hydrological and sediment observations recorded in the broad, hillslope-scale plots (R_{HS}, mm, and S_{HS}, g m^{-2}, respectively) to the determined, integrated patch-scale responses of runoff and sediment yield ($C_R = R_{HS}/R_{IPS}$, $C_S = S_{HS}/S_{IPS}$; Figure 2b).

The functional connectivity of runoff (C_R, dimensionless) ranges between values 0 and 1. C_R equals 0 when there is complete within-slope spatial redistribution of runoff (i.e., no runoff generated at the surface-patch scale reaches the outlet of the slope system). C_R increases as runoff redistribution decreases across scales, and equals 1 when all runoff generated at the patch scale reaches the outlet of the slope system. Previous research in our study site suggests that any further contributions to hillslope runoff production (e.g., subsurface return fluxes captured by the rill networks) have a marginal impact on the hydrological response of these water-limited systems (Nicolau, 2002; Moreno-de-las-Heras et al., 2010; Merino-Martín et al., 2012a).

The functional connectivity of sediments (C_S, dimensionless) decreases from 1 to 0 when significant amounts of sediments generated at the patch scale are deposited within the slope system before reaching the outlet. However, C_S may take values over 1 if active rill incision takes place in the experimental slopes, causing the entrainment of significant amounts of sediments between the patch and hillslope scales (Moreno-de-las-Heras et al., 2010).

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Bajado [2]: For each experimental slope, we calculated the cumulative probability distribution function (CDF) of the structural connectivity (Sc) values. Differences between the three experimental slopes on the Sc probability distribution were analysed using two-sample Kolmogorov-Smirnov tests. Mean Sc values (hereafter S̄c) were calculated for each slope system as an integrative indicator of the structural connectivity at the hillslope-scale level.¶

Eliminado: The study of variations of surface hydrological responses (i.e., runoff and sediment yield) at a range of scales provides a tool for the assessment of the dominant processes regulating the routing of runoff and sediments (e.g., flow concentration, transmission losses among landscape elements, downslope runoff re-infiltration, sedimentation) across the landscape (Cammeraat, 2004; Yair and Raz-Yassif, 2004; Moreno-de-las-Heras et al., 2010; Mayor et al. 2011; Sidle et al., 2017)

Bajado [1]: To determine the spatial continuity (or functional connectivity) of both runoff and sediment fluxes across scales (i.e., from the surface-patch to the hillslope scale) in the experimental slopes,

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Bajado [3]: Differences between the three experimental slopes on the connectivity of runoff (C_R) and sediments (C_S) were tested for the set of 21 hydrologically active events recorded during the study period (October 2007-December 2008) using Kruskal-Wallis ANOVA. In addition, the broad, hillslope-scale hydrological (sediment) responses of the experimental slopes were tested against the analysed, per-event functional connectivity of the studied systems

2.5 Data analysis and statistics

2.5.1 General patterns of structural and functional connectivity

For each experimental slope, we calculated the cumulative probability distribution function (CDF) of the structural connectivity (SC) values. Differences between the three experimental slopes on the SC probability distribution (Probability $SC_i \geq SC$) were analysed using two-sample Kolmogorov-Smirnov tests. Mean SC values (hereafter $\overline{SC}$) were calculated for each slope system as an integrative indicator of the structural connectivity at the hillslope-scale level.

Differences between the three experimental slopes on the functional connectivity of runoff (C_R) and sediments (C_S) were tested for the set of 21 hydrologically active events recorded during the study period using Kruskal-Wallis ANOVA. In addition, the broad, hillslope-scale hydrological (sediment) responses of the experimental slopes were tested against the analysed, per-event functional connectivity of the studied systems by determining the best fitting regression function linking the determined runoff (sediment) connectivity values and the observed hillslope runoff coefficients (soil losses).

2.5.2 Controlling factors of runoff and sediment connectivity

We applied the general descriptors of precipitation characteristics and antecedent rainfall conditions (Table 1), and the obtained $\overline{SC}$ index of structural connectivity to determine the main controlling factors that drive the functional responses of runoff and sediment connectivity in the experimental slopes for the studied (21 hydrologically-active) runoff/erosion events. We modelled C_R and C_S using general linear models (GLM; Christensen, 2002) and a backward model structure selection approach. First, an exploratory pre-screening analysis of the dynamic relationships between the functional connectivity indexes (C_R and C_S) and both the rainfall characteristics and antecedent precipitation conditions was performed using Spearman's R correlations. Second, the pre-screened variables that showed significant correlations (at α=0.05) with the C_R and C_S values of the storms were further applied to model the surface-patch to hillslope-scale transfer (or flow continuity) of runoff and sediments.

In order to identify the set of explanatory variables that produce the best model for C_R and C_S prediction, alternative GLM configurations were compared. These alternative GLM configurations included (i) $\overline{SC}$ as a factor with three levels representing the structural connectivity of the three experimental slopes, (ii) all the possible combinations of significant (Spearman's R) pre-screened variables of rainfall characteristics and antecedent conditions, and (iii) the interaction terms between $\overline{SC}$ and the pre-screened variables included in each comparison of model structure. The Akaike Information Criterion (AIC; Akaike, 1974) and the adjusted coefficient of determination (Adj R^2), which represent a trade-off between model complexity and goodness of fit, were used to select the best model for C_R and C_S prediction. Finally, the model root-mean-squared error (RMSE), and both the effect size (eta-squared values, η^2) and significance of the model predictors were evaluated for the selected, optimal GLM configurations. While C_S may take values (largely) above 1 when active rilling takes place, C_R is constrained to values ≤1 and consequently, may asymptotically approach 1 as rainfall increases. The asymptotic behaviour of C_R violates the GLM assumption of linearity for large values of the model predictors. We, therefore, applied logarithmic transformation to the precipitation co-variables (Table 1) to comply with the GLM assumptions for C_R modelling.

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All data analyses and statistics were developed within the R statistical computing and language programming software environment (R Core Team, 2019).

3. Results

3.1 Source/sink distribution and structural connectivity of the slopes

Runoff/sediment sinks in Slope 1 were particularly concentrated in its central section, mainly distributed as grass patches dominated by *Lolium perenne* (Lp soil surface patch type; Figure 3a). A well-developed rill network (density 0.6 m m^{-2}) linked the runoff/sediment source areas located at the top of the experimental slope with both the source areas distributed at the bottom of the slope and the outlet of the system. Similarly, runoff/sediment sink areas for Slope 2 (Figure 3b) were preferentially distributed in the central part of the slope system, mostly in the form of densely vegetated grass and shrub patches (surface patch types Lp, Br, Dg and Gs). However, runoff/sediment source areas at the top of Slope 2 were connected with the source areas distributed at the bottom of this experimental slope. Finally, sink areas for Slope 3 were broadly distributed in the form of densely vegetated shrub clumps (Gs and Sch surface patch types) within the central and lower sections of the slope system (Figure 3c), largely interfering the structural connectivity between the source areas distributed at the top of the slope and the outlet of the system.

Figure 3d shows the cumulative probability distribution function of the structural connectivity metric (SC CDF) in the three experimental slopes, along with their mean hillslope values ($\overline{SC}$). Two-sample Kolmogorov-Smirnov tests indicated that the SC CDFs significantly differed between the three experimental slopes at α=0.01. For the rilled system (Slope 1), the probability of finding runoff/sediment source areas physically linked to the outlet of the slope system (Probability SC_i = 1) was 42%, leading to a large mean structural connectivity at the hillslope level ($\overline{SC}$=0.47). Conversely, the abundance of barely covered, source areas connected with the outlets of the two non-rilled slope systems (Slope 2 and Slope 3) was substantially lower (Prob. SC_i = 1 is 12% and <1% for Slopes 2 and 3, respectively). Furthermore, the large spatial dominance of sink patches in the middle and bottom section of Slope 3 ($\overline{SC}$=0.02) very considerably reduced the structural connectivity of this hillslope as compared to Slope 2 ($\overline{SC}$=0.17), where the bottom section of the hillslope is dominated by source patches.

3.2 Functional connectivity: cross-scale continuity of runoff and sediments

Functional connectivity of runoff across scales showed important differences for the three experimental slopes. Cumulative runoff production along the study period (2007-08) decreased from the surface-patch to the hillslope-scale for all the three experimental slopes (Figure 4a). However, these variations in runoff production across scales showed remarkable differences between the slopes. For the rilled slope system (Slope 1), the cross-scale connectivity of 2007-08 cumulative runoff was 0.72, indicating that 72% of the runoff that was generated at the patch-scale level during the study period effectively reached the outlet of the system (in other words, 28% runoff was redistributed or re-infiltrated within the slope during 2007-08).

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Differently, less than 20% of the patch-scale runoff reached the outlets of the non-rilled systems (i.e., connectivity of cumulative runoff was 0.17 and 0.06 for Slope 2 and 3, respectively; Figure 4a).

Runoff connectivity displayed an important variability among the various monitored events (C_R; Figure 4c). The values of runoff connectivity across scales in Slope 1 ranged from 0 to around 1 for the 21 active events. In particular rainfall events there was complete runoff redistribution within this slope (i.e., C_R=0), while in other events all runoff generated at the patch-scale level reached the outlet of the system (i.e., C_R about 1). In the case of Slopes 2 and 3, the maximum and mean values of runoff connectivity were notably smaller than for Slope 1, indicating that for all the events, larger fractions of patch-scale runoff were spatially redistributed (i.e., downslope re-infiltrated) within the two non-rilled systems.

Functional connectivity of cumulative (2007-08) sediment yields also showed important differences among the experimental slopes (Figure 4b). For the rilled system (Slope 1), cumulative sediment yield at the hillslope scale was 1.6 times bigger than patch-scale sediment production. Conversely, the continuity of sediment fluxes across scales was very low for the non-rilled slopes: less than 15% cumulative sediments generated at the patch-scale level in Slopes 2 and 3 during the study period reached the outlet of these non-rilled slope systems.

At the rainfall-event level, the cross-scale continuity of sediment fluxes showed a large variability (C_S; Figure 4d). This effect was especially important for the rilled system (Slope 1), where there was complete spatial redistribution of sediments for particular events (i.e., C_S=0) while for other events in this slope, hillslope-scale sediment yield was up to 5 times bigger than patch-scale sediment production. Flow continuity of sediments across scales for the non-rilled slope systems (Slopes 2 and 3) was low for all the recorded events (maximum sediment connectivity was 0.4 and 0.07 for Slopes 2 and 3, respectively), showing substantial sediment deposition from the patch to the hillslope scales.

Per-event hillslope runoff coefficient and soil erosion increased non-linearly with increasing runoff (C_R) and sediment (C_S) connectivity, respectively. Hillslope runoff production showed slight variations with cross-scale runoff connectivity up to C_R values about 0.5 (50% runoff redistribution between the patch and hillslope scales) over which, the runoff coefficients of the experimental slopes increased very rapidly (from ~5% to about 30%; Figure 4e). Similarly, hillslope soil erosion showed little change with C_S <1, when active within-slope sediment deposition took place (Figure 4d). However, for C_S values above 1, when the rill networks actively contributed with fresh sediments to the flow, broad hillslope-scale soil erosion increased very strongly, up to two orders of magnitude. These very high C_S values, observed during extreme sediment response events (C_S peaking up to nearly 5; Figure 4d), suggest that erosion from the rill networks can contribute with up to 4 times more sediments to the outlet than the poorly covered (source) surface patches acting in the experimental slopes.

3.3 Impact of structural and dynamic factors on runoff and sediment connectivity

Exploratory analysis of the relationship between runoff connectivity (C_R) and the event characteristics indicated that antecedent precipitation (API), both maximum (I_{15}, I_{30}) and mean (Im) rainfall intensity, as well as storm depth (Dp) significantly correlated with the continuity of runoff across scales (Table 2). These correlations were particularly strong for antecedent precipitation in all the analysed slope systems (0.75-0.80 Spearman's R). GLM modelling of observed C_R values using the

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pool of significant event characteristics (API, I_{15}, I_{30}, Im and Dp) pointed to the effects of (log-transformed) API and I_{30} variables, hillslope structural connectivity ($\overline{SC}$) and their corresponding interaction terms ($\overline{SC}$:API and $\overline{SC}$:I_{30}) as the best model structure predictors (R^2=0.81, Adj R^2=0.78, NRMSE=12%; Figure 5a). No additional increments of GLM complexity resulted in significant improvements of explained C_R variance (Adj R^2 values of alternative models in Table S3 of the online supplement). The eta-squared values for the optimal C_R model (η^2; Figure 5a) revealed a primary influence of hillslope structural connectivity, which absorbed 44.1% and 16.8% of C_R variance in the form of direct ($\overline{SC}$) and interaction ($\overline{SC}$:API and $\overline{SC}$:I_{30}) effects, respectively. The direct effects of the event-driven (API and I_{30}) variables accounted for an additional 20% of the observed C_R variance (12.9% and 7.1% for API and I_{30}, respectively).

An increase in both antecedent precipitation and 30-min maximum rainfall intensity led to non-linear increases in runoff connectivity for all the analysed slope systems (Figures 4b and c). C_R increased rapidly for values within 0-20 mm h^{-1} maximum rainfall intensity and 0-50 mm antecedent precipitation, tending to saturate for larger I_{30} and API values. However, the structural connectivity ($\overline{SC}$) of the analysed slope systems exerted a strong control on these effects. Both maximum rainfall intensity and antecedent precipitation increased runoff connectivity very little for Slopes 2 and 3, as a result of the large within-slope redistribution of runoff that prevailed under all rainfall conditions for these poorly connected ($\overline{SC}$≤0.17) systems. Instead, C_R strongly increased with I_{30} and API for the rilled slope system (Slope 1), where runoff producing low-cover areas showed a large spatial contiguity ($\overline{SC}$=0.47). Furthermore, antecedent precipitation had a higher impact compared to the influence of maximum rainfall intensity on runoff connectivity. In fact, I_{30} displayed a limited impact on runoff connectivity under dry antecedent conditions (e.g., if API=5.1 mm, C_R in Slope 1 can increase up to ~0.4 for large I_{30} values; Figure 5b). Nevertheless, antecedent precipitation showed an efficient capacity to increase runoff connectivity, even for moderate and low intensity rainfall events (e.g., if I_{30}=3.4 mm h^{-1}, C_R in Slope 1 may grow up to ~0.8 for large API values; Figure 5c).

The continuity of sediment fluxes across scales (C_S) strongly correlated with mean (Im) and maximum (I_{15}, I_{30}) rainfall intensity, particularly for Slopes 1 and 2 (Table 2). Although considerably less intense, we also found significant correlations between C_S and antecedent precipitation (API). GLM modelling of C_S using these rainfall variables (Im, I_{15}, I_{30} and API) identified mean rainfall intensity (Im), hillslope structural connectivity ($\overline{SC}$) and their corresponding interaction term ($\overline{SC}$:Im) as best model structure contributors for predicting sediment connectivity (R^2=0.81, Adj R^2=0.79, NRMSE=8%; Figure 6a). No additional increments of GLM complexity produced significant improvements of explained C_S variance (Adj R^2 values of alternative models in Table S4 of the online supplement). Similarly to the best C_R model, the η^2 values for the optimal C_S model indicated a key influence of hillslope structural connectivity, which explained 38.0% and 26.8% of C_S variance for its direct ($\overline{SC}$) and interaction $\overline{SC}$:Im) effects, respectively (Figure 6a). The direct effect of mean rainfall intensity explained an additional 16.1% of the observed C_S variance.

C_S increased linearly with mean rainfall intensity (Im) for the three experimental slopes (Figure 6b). However, the impact of rainfall intensity on the patch- to hillslope-scale continuity of sediment fluxes was highly dependent on the structural connectivity of these slope systems. For Slopes 2 and 3, with poorly connected low cover areas that act as sediment sources

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($\overline{SC}$≤0.17), increases of rainfall intensity along the observed Im range (0-6 mm h^{-1}) resulted in very small increases in sediment connectivity, pointing to a large within-slope redistribution of sediments for all the explored rainfall conditions. Very differently, for Slope 1, with a well-developed rill network that provides good structural connectivity of low cover areas ($\overline{SC}$=0.47) and within-slope conditions for channel incision, C_S largely increased over 1 along the range of observed mean rainfall intensities, therefore reflecting large increases of unit-area sediment yield from the patch to the hillslope scales under high intensity rainfall.

4 Discussion

Connectivity and scaling are key aspects for the understanding of hydrological and geomorphological processes in the continuum from small plots to hillslopes and catchments (Bracken and Croke et al., 2007; Sidle et al., 2017). In this study we shift from the very active, present conceptual discussion of the connectivity theory and their derived hydro-geomorphic study approaches (Wainwright et al., 2011; Bracken et al., 2013; Okin et al., 2015; Heckmann et al. 2018; Keesstra et al., 2018; Saco et al., 2020) to the practical application of the concepts of structural and functional connectivity for the analysis of surface-patch to hillslope scale continuity of runoff and sediment fluxes in Mediterranean-dry RSSs.

4.1 Structural connectivity: organization of vegetation patterns and rill networks

Both vegetation distribution, which largely influences the spatial organization of patch hydro-sedimentary behaviour, and surface topography, which controls water and sediment flow direction, represent the major determinants for the potential transfer of water and sediments in the flowpath-based approach of structural connectivity applied in our study. Dryland vegetation is frequently organized in patches, ranging from barely to densely covered surfaces, which interact as interconnected source and sink areas of runoff and sediments (Puigdefabregas, 2005; Saco et al., 2019). This source/sink behaviour largely controls the within-slope retention of water and soil resources, and has been extensively described as a key structural control for the production and routing of runoff and sediments in both natural Mediterranean semiarid landscapes (Puigdefabregas et al., 1999; Cammeraat, 2004; Arnau-Rosalen et al., 2008; Mayor et al., 2011) and reclaimed Mediterranean-dry systems (Moreno-de-las-Heras et al., 2009; Merino-Martín, 2012b, 2015; Espigares et al., 2013). Our results reveal that hillslope position of densely vegetation patches is a significant factor affecting the structural connectivity of the analysed reclaimed slope systems. In our study, the preferential concentration of densely vegetated, sink patches in the middle and lower sections of Slope 3 considerably reduces the connectivity of source areas as compared to Slope 2, where the bottom of the slope is dominated mainly by poorly covered areas (Fig. 2b-d). These results agree with other empirical studies in the Mediterranean region that indicate that the presence of dense vegetation in and near the lower sections of plots and hillslopes provides a strong structural control for runoff and sediment delivery (Bautista et al., 2007; Boix-Fayos et al., 2007).

Our analysis of the structural components of connectivity suggest that rill networks are key elements for the transfer of water runoff and sediments. The densely developed rill network of Slope 1 acts as a dominant, primary factor enhancing the

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spatial contiguity between the barely covered, source areas distributed along the hillslope and the outlet of the experimental slope, very largely increasing the structural connectivity of the system (Fig. 2c-d). In fact, rill networks provide very efficient erosive flow routing pathways that largely facilitate the transference of water and sediments across sections of the hillslopes with little or no potential for runoff re-infiltration and sediment deposition (Nicolau, 2002; Bracken and Crocke, 2007; Moreno-de-las-Heras et al., 2010; Wester et al., 2014; Lu et al., 2019).

4.2 Functional connectivity: formation of connected runoff and sediment fluxes

Rainfall characteristics and antecedent conditions dynamically interact with the range of structural elements of the hillslopes to enable or enhance connected flow. Our analysis reveals that maximum rainfall intensity and antecedent precipitation are the most relevant storm event factors providing dynamic control of surface-patch to hillslope scale continuity (or functional connectivity) of runoff (Fig. 4). Both maximum rainfall intensity and antecedent moisture conditions are commonly perceived as the main rainfall factors involved in the generation of runoff in Mediterranean landscapes (Calvo-Cases et al., 2003; Castillo et al., 2003; Cammeraat, 2004; Cantón et al., 2011; Mayor et al., 2011; Marchamalo et al., 2016; Martínez-Murillo et al., 2018; Rodríguez-Caballero et al., 2014). Infiltration-excess runoff triggered by high intensity rainfall typically dominates the hydrological responses of Mediterranean hillslopes under dry conditions. Saturation-excess runoff may also occur in Mediterranean-dry hillslopes, particularly on soils previously wetted by antecedent rainfall, inducing saturation of the top layer of the soil profile with moderate intensity precipitation (Martínez-Mena et al. 1998; Puigdefabregas et al., 1999; Calvo-Cases et al., 2003; Castillo et al., 2003). The poor soil development conditions that characterize our reclaimed study sites may facilitate these two runoff generation mechanisms (Nicolau and Asensio, 2000; Moreno-de-las-Heras, 2009). Whilst rapid formation of surface crusts in barely covered patches of these reclaimed soils can largely facilitate the formation of infiltration-excess runoff, the massive structure of the soils, particularly in intermediate to deep layers showing moderate to low vegetation root activity, can also facilitate the formation of runoff from the temporary saturation of the top (5-20 cm) soil layer (Nicolau, 2002; Moreno-de-las-Heras et al., 2011a).

Our results also indicate a higher efficiency of antecedent precipitation than maximum rainfall intensity in providing conditions for the generation of patch- to hillslope-scale runoff continuity (Figs. 4b and c). Similarly, other Mediterranean-dry hillslope and catchment studies have highlighted the primary role of antecedent precipitation on establishing spatial continuity in the generation and routing of runoff (Puigdefabregas et al., 1999; Fitzjohn et al., 1998; Boix-Fayos et al., 2007; Marchamalo et al., 2016). Under dry antecedent conditions, runoff generation is spatially heterogeneous due to the fine-scale spatial variation of infiltration capacity. This variability is generated by both patchy vegetation and soil variability, which promote large discontinuities in hydrological pathways inducing spatial isolation of runoff producing areas (Calvo-Cases et al., 2003; Boix-Fayos et al., 2007). Differently, wet conditions reduce soil infiltration capacity (Cerdà, 1997; Moreno-de-las-Heras et al., 2009) and blur the spatial variation in hydrological properties by facilitating the formation of runoff from saturation of the top and subsoil layers (Puigdefabregas et al., 1999; Calvo-Cases et al., 2003), thus resulting in increased spatial continuity of active hydrological pathways for both the generation of runoff and the transference of water among scales and elements of the

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landscapes (Fitzjohn et al., 1999; Boix-Fayos et al., 2007; Marchamalo et al., 2016). Our results suggest that 30-50 mm of precipitation accumulated over an antecedent period of 10 days can notably enhance the hydrological connectivity in our study slopes (Fig. 4c). These conditions mainly take place in the area during the autumn and spring seasons.

The structural connectivity of the studied slope systems largely controls the functional connectivity of the runoff responses to rainfall intensity and antecedent precipitation (Figs. 4b and c). Differently to Slopes 2 and 3, where the low spatial contiguity of runoff source areas strongly limits the impact of rainfall conditions on runoff connectivity, the surface-patch to hillslope-scale continuity of runoff is highly sensitive to rainfall intensity and antecedent precipitation in Slope 1. The presence of a well-developed rill network in this slope strongly increases the structural connectivity of the system and provides a very efficient, preferential pathway for the routing of runoff. Modelling results by Reaney et al. (2014) explain the high efficiency of rill networks in the transmission of runoff as a function of their effects on transfer distances. Overall, rills operate as channels that reduce transfer distances in relation to effective contributing area, resulting in enhanced runoff transmission along the hillslope by increased flow velocity and reduced length to flow concentration. In this study, the high runoff transmission efficiency of the rill networks can be illustrated by the resulting cross-scale runoff continuity responses observed in the experimental slopes during the most extremely connected events (top C_R whisker values in Fig. 3c), recorded on early June and November 2008 for rather large rainfall events with moderate intensities occurring under wet antecedent conditions (~50 mm depth, 7-9 mm h^{-1} I_{30} and 35-45 mm API). In such conditions, the high runoff transmission efficiency of the rill network in Slope 1 resulted in the complete transference of patch-scale generated runoff to the outlet of the system, largely differing from the poorly established hydrological connectivity of the two non-rilled slopes, where 60-70% path-scale runoff re-infiltrated downslope before reaching the outlet.

Besides the key influence of rills for the spatial transmission of runoff, these hillslope structural elements were also found to play a dominant role in the generation of sediment fluxes and its spatial distribution. Overall, our experimental slopes display two contrasting sedimentological behaviours that can be compared in light of our sediment connectivity results (Figs. 3b and d). While the two non-rilled slopes (Slopes 2 and 3) show, for all the events analysed, poorly connected sediment flows characterized by important sediment deposition between the surface-patch and hillslope scales, sediment yield can very largely increase (i.e., up to 5 times) with scale for the rilled system (Slope 1) when active rill incision takes place. Similarly, other studies carried out in Mediterranean landscapes indicate that sediment yield generally decreases from the small-plot to the hillslope scales in the absence of rills due to the loss of runoff by downslope re-infiltration, while soil loss per unit area generally increases with plot length when rill erosion processes prevail (Boix-Fayos et al., 2006; Bargarello and Ferro, 2010; Moreno-de-las-Heras et al., 2010; Cantón et al., 2011; Bargarello et al., 2018). In fact, runoff convergence in the rill networks provides these erosive elements with the capacity to produce very important amounts of sediments, frequently resulting in significant increases in sediment yield with slope length (Gimenez and Govers, 2001; Govers et al., 2007; Moreno-de-las-Heras et al., 2011b; Wester et al., 2014; Lu et al., 2019). In this context, rills not only facilitate within-slope transference of water and sediment fluxes but also work as powerful sources of sediments that can significantly contribute with freshly eroded particles to the analysed sediment fluxes between the surface-patch and hillslope scales.

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Rainfall intensity emerges as the main storm property controlling the spatial continuity and scaling of sediment fluxes in our study slopes, particularly for the rilled system (Slope 1), where the ratio of hillslope to surface-patch sediment production (or functional connectivity of sediments) strongly increases with mean rainfall intensity (Fig. 5b). In Mediterranean hillslopes, storm intensity provides direct control on splash erosion and largely influences –through runoff production and concentration– the processes of sheet wash, sediment transport and both rill and gully incision (Bargarello and Ferro, 2010; Moreno-de-las-Heras et al., 2010; Mayor et al., 2011; Cantón et al., 2011; Gallart et al., 2013). These links are frequently identified in the form of strong linear correlations between sediment yield and maximum (e.g., I_5, I_{15}, I_{30}) rainfall intensity (e.g., Cammeraat, 2004; Rodríguez-Caballero et al., 2014). In the present study, sediment connectivity is better explained by mean rainfall intensity (Im), which may suggest enhanced conditions for sediment transfer and rill incision by sustained (rather than maximum) high intensity rainfall. However, the high correlation that links the maximum (I_{30}) and mean (Im) rainfall intensities of the analysed events (Pearson's $R = 0.92$, $p<0.01$) reveals that the storms displaying the best conditions for the formation of spatially connected sediment flows along the study period (top C_S whisker values in Fig. 3d) were characterized by both high maximum and averaged rainfall intensity (up to 33 and 6 mm h^{-1} I_{30} and Im, respectively). These enhanced conditions for the production and routing of sediments were recorded during the summer season, in the form of high intensity convective rainfall. Previous erosion research in this experimental site has highlighted the erosive capacity of late spring and summer convective storms, which are responsible for up to 80% annual soil loss in the area (Nicolau, 1992; Moreno-de-las-Heras et al., 2010; Merino-Martín et al., 2012a).

The frequently observed presence of thresholds and the non-linear character of landscape hydro-geomorphological responses are to a large extent related to the runoff and sediment connectivity that are responsible for transferring surface fluxes of resources from the small plot and surface-patch scales to broader hillslope and catchment scales (Puigdefabregas et al., 1999; Cammeraat, 2004; Bracken and Croke, 2007; Wainwright et al., 2011; Moreno de las Heras et al., 2012; Sidle, 2017). Evidence of these dynamics is provided in this work by the non-linear relationships that link within-slope (functional) connectivity of runoff and sediment fluxes with the runoff coefficients and soil losses observed in the studied systems at the hillslope scale (Figs. 3e and f). Particularly, critical loss of the capacity for redistributing surface fluxes by runoff re-infiltration and sediment deposition mechanisms in the analysed slope systems results in very large increases in hillslope-scale runoff production and soil loss. These non-linear hydro-geomorphological responses are strongly conditioned by the dynamics of Slope 1, where the presence of a well-organized rill network provides the system with cross-scale hillslope structural elements for intensive sediment production and effective flow routing.

Substantial increases in functional connectivity can dynamically feed back into the structural aspects of connectivity by modifying the spatial organization of preferential flowpaths for the production and transmission of runoff and sediments (Turnbull et al., 2008; Wainwright et al., 2011; Okin et al., 2015; Turnbull and Wainwright, 2019). Structural connectivity is perceived in our study as a static property of the explored systems during the entire period of analysis (October 2007 to December 2008), which took place after 20 years of landscape evolution from the initial slope reclamation stage. Changes in structural connectivity of these Mediterranean-dry human-made systems can be particularly important during earlier stages

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(first 5-10 years) of landscape evolution, when the spatial arrangement and redistribution of runoff and sediment fluxes largely shape the initial establishment and further dynamics of both vegetation patterns and rill networks (Nicolau and Asensio, 2000; Moreno-de-las-Heras et al., 2011b). In fact, the rill network of Slope 1 represents a key factor determining the high structural connectivity of this system, but its own existence can be attributed to the development of high levels of (runoff and sediment) functional connectivity during the early stages of landscape evolution. Spatially explicit modelling frameworks of co-evolving landforms and vegetation patterns (e.g., Saco et al., 2020) may facilitate further exploration of the long-term dynamic feedbacks that link functional and structural connectivity.

5 Conclusions

We developed in this study a practical application of the conceptual elements of structural and functional connectivity for the analysis of surface-patch to hillslope-scale transmission of runoff and sediments in three Mediterranean-dry reclaimed mining slope systems showing different levels of long-term development of vegetation and rill networks. Our results revealed an important role of the hillslope position of vegetation patches on the distribution of potential runoff and sediment flowpaths. More critically, the rill networks emerged as key elements of structural connectivity in the slopes, providing preferential pathways that dominate the production, spatial organization and routing of the fluxes of water and sediments. On the other hand, both runoff and sediments were largely redistributed within the analysed slope systems in the absence of rill networks. The interactions between the structural connectivity of the experimental slopes and both antecedent precipitation and rainfall intensity largely controlled event functional connectivity. The results showed that rainfall intensity and, more importantly, antecedent precipitation largely increased the spatial continuity of runoff fluxes under rilled slope conditions, where active rill incision under high intensity rainfall induced large non-linear increases in hillslope-scale sediment yield.

In sum, this study provides empirical evidence of the feasibility of using the hydrological connectivity concept for practical applications, remarking specifically its usefulness for understanding how hillslope structural elements dynamically interact with storm characteristics and rainfall conditions to generate spatially continuous runoff and sediment fluxes. Overall, our study approach of structural and functional connectivity offers a useful framework for assessing the complex links and controlling factors that regulate the generation and movement of runoff and sediments across different scales and elements of the landscape in Mediterranean-dry and other water-limited environments.

Supplement link. This online supplement contains complementary information on general site characteristics (Table S1), the rainfall and hydrological data records of the analysed events (Table S2), the full model configurations applied for the analysis of runoff and sediment connectivity (Tables S3 and S4, respectively), and supplementary details on the parameterization of the antecedent precipitation index (API) applied in this study (Supplementary Methods S1).

Data availability. The full hydro-sedimentary and precipitation data applied in this study can be found in Table S2 of the online supplement. Other associated data are available upon request.

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Subido [4]: Both runoff and sediments were largely redistributed within the analysed slope systems in the absence of rill networks.

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Author contributions. All the authors participated in the design of the study. LMM obtained the field data, with contributions from MMdlH, JMN and TE. Data pre-processing and analysis was performed by MMdlH and LMM. MMdlH led the writing of the paper, with significant contributions from all the co-authors.

Competing interests. The authors declare that they have no conflict of interest.

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Table 1. Precipitation condition variables determined for each monitored runoff event.

	Description	Units
Dp	Storm depth	mm
Rd	Rainfall duration	h
I_{15}	15-min max rainfall intensity	mm h^{-1}
I_{30}	30-min max rainfall intensity	mm h^{-1}
Im	Mean rainfall intensity	mm h^{-1}
API	Antecedent precipitation index	mm

Table 2. Spearman's R correlations between the event characteristics/conditions (storm depth, Dp; rainfall duration, Rd; 15-min and 30-min maximum rainfall intensity, I_{15} and I_{30}; mean rainfall intensity, Im; and antecedent precipitation index, API) and the connectivity of runoff and sediments for the three experimental slopes.

		Connectivity of Runoff - C_R	Connectivity of Sediments - C_S
	Slope 1	**0.50***	0.21ns
Dp	Slope 2	0.48*	0.19ns
	Slope 3	**0.60****	0.36ns
	Slope 1	0.23ns	-0.23ns
Rd	Slope 2	0.18ns	-0.25ns
	Slope 3	0.45*	0.23ns
	Slope 1	**0.53****	**0.78*****
I_{15}	Slope 2	**0.56****	**0.55****
	Slope 3	**0.51***	0.39ns
	Slope 1	**0.57****	**0.73*****
I_{30}	Slope 2	**0.61****	**0.64****
	Slope 3	**0.57****	0.43*
	Slope 1	**0.54***	**0.78*****
Im	Slope 2	**0.65****	**0.67*****
	Slope 3	**0.50***	**0.58****
	Slope 1	**0.79*****	0.47*
API (10 days, k=0.98)	Slope 2	**0.75*****	0.46*
	Slope 3	**0.75*****	**0.64****

Sig. codes: '***' p<0.001; '**' p<0.01; '*' p<0.05; 'ns' not significant at α=0.05.
Spearman's R correlation values in bold are ≥0.50.

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Eliminado: , rainfall duration

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Eliminado: , mean rainfall intensity

Eliminado: , antecedent precipitation index

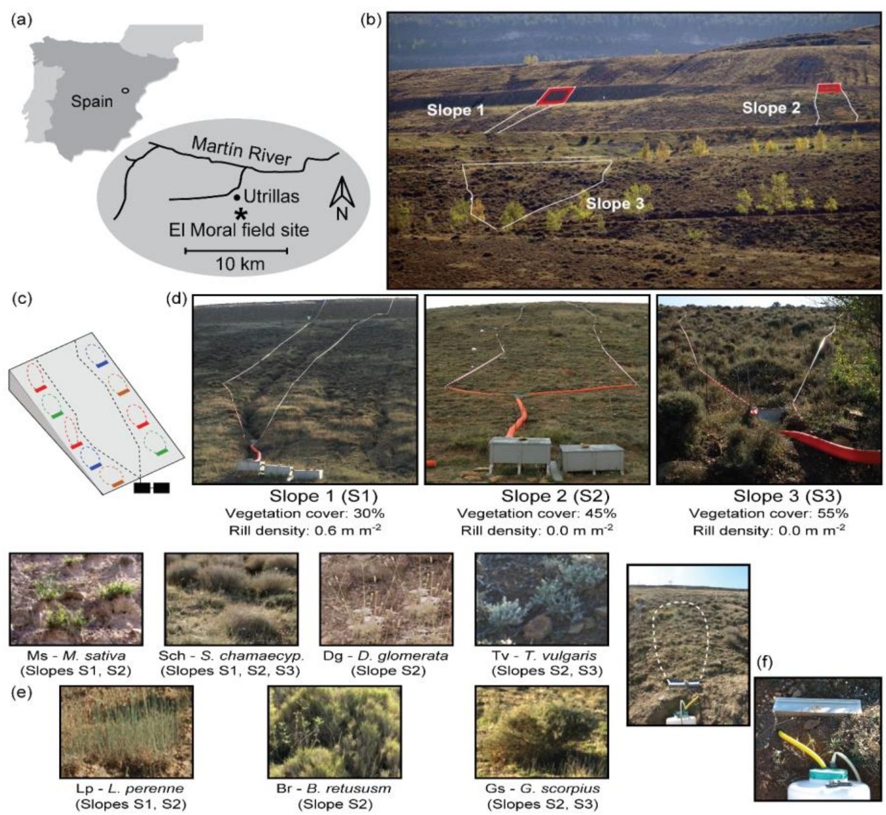
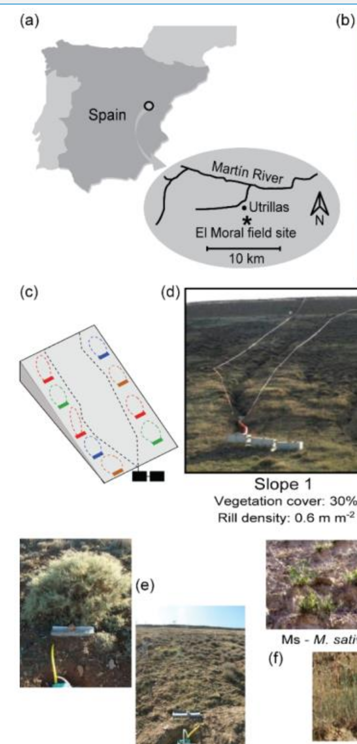


Figure 1. The Utrillas field site: (a) location map; (b) frontal view of the three experimental slopes (40º steep, berm sections located at the top of Slopes 1 and 2 are highlighted in red); (c) schematic representation of the experimental layout in the slopes (a hierarchical, scaled approach with patch- and hillslope-scale runoff/erosion plots, all naturally delimited); (d) frontal view of the hillslope-scale plots (catchment plots) and their general characteristics (vegetation cover and rill density); (e) detailed view of the seven surface types (vegetation communities) identified in the experimental slopes by Merino-Martin et al. (2012a); (f) an example of patch-size plot showing a small detail (right picture) of the Gerlach trough runoff/sediment collection systems. Names of the dominant plant species for the surface types: Ms, *Medicago sativa*; Sch, *Santolina chamaecyparissus*; Dg, *Dactilis glomerata*; Tv, *Thymus vulgaris*; Lp, *Lolium perenne*; Br, *Brachypodium retusum*; Gs, *Genista scorpius*.



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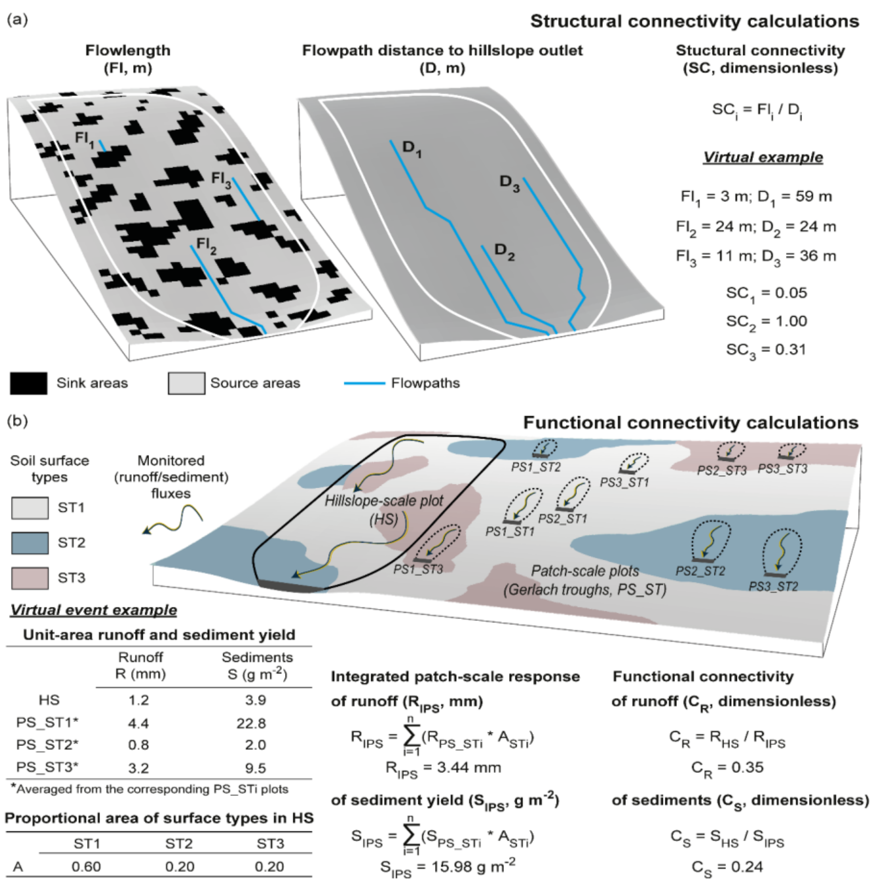


Figure 2. Schematic representation and virtual examples of the calculations for the quantification of (a) structural connectivity (SC) and (b) the functional connectivity of both runoff (C_R) and sediments (C_S). Structural connectivity for any location in the hillslope (SC_i) is calculated as the ratio of flowlength (Fl_i, length of the runoff path until a sink is reached downslope of the hillslope location) to the (topography-based) flowpath distance of the location to the hillslope outlet (D_i). For each precipitation event, functional connectivity of runoff, C_R (of sediments, C_S), is calculated as the ratio of hillslope-scale runoff, R_{HS} (sediment yield, S_{HS}), to the integrated (i.e., area-weighed) patch-scale production of runoff, R_{IPS} (of sediments, S_{IPS}).

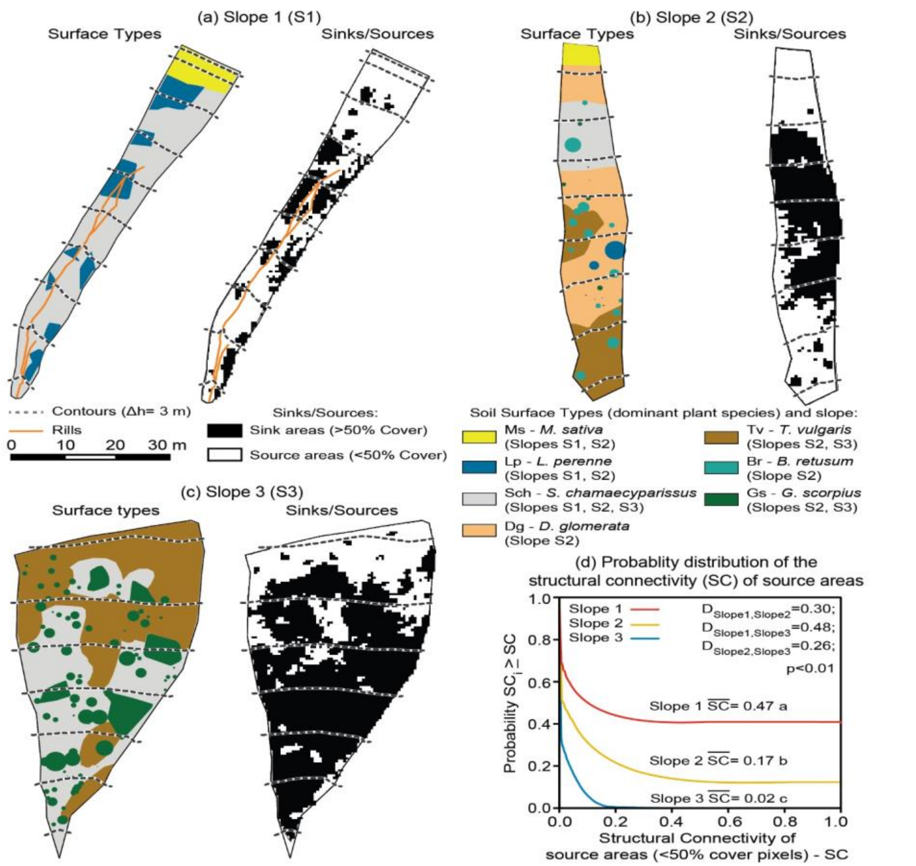
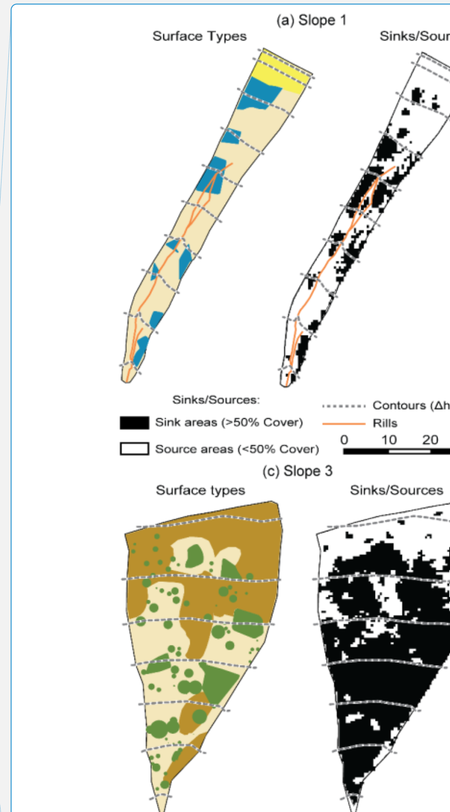


Figure 3. Structural connectivity: (a-c) spatial organization of surface types (vegetation communities) and sink/source areas (i.e., areas with above/below 50% vegetation cover) in the experimental slopes; (d) cumulative probability distribution function (CDF) of the structural connectivity (SC) metric of source areas for the experimental slopes (mean structural connectivity values, $\overline{SC}$, are provided for each slope system). Surface type maps and digital elevation data were derived from a field tachometry campaign (Merino-Martin et al., 2015). Binary maps (0.5 m pixel resolution) of sinks and sources are derived from a multispectral aerial picture (Spanish National Plan for Aerial Orthophotography, PNOA). Different letters in $\overline{SC}$ values displayed on graph (d) indicate significant differences at α=0.05. Tested using two-sample Kolmogorov-Smirnov tests (D statistics and p levels are shown in the graph).



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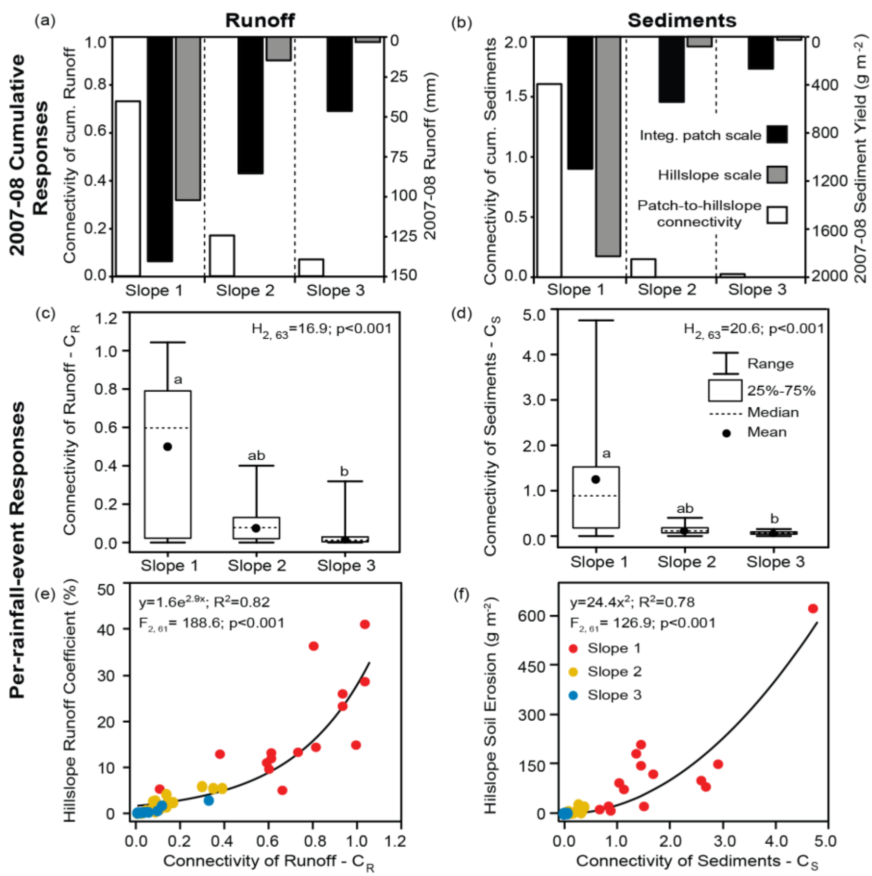

Figure 4. Functional connectivity: (a-b) 2007-08 cumulative and (c-d) per-rainfall-event connectivity of (a, c) runoff (C_R) and (b, d) sediments (C_S) in the experimental slopes; (e-f) relationship between the (per-rainfall-event) connectivity of runoff and sediments and hillslope-scale runoff coefficient and soil erosion. Connectivity of runoff/sediments across scales is represented as the ratio of hillslope to patch-scale runoff/sediments (white bars). Runoff and sediment yield at both the hillslope scale (grey bars) and the integrated (i.e., area-weighed) patch scale (black bars) are provided for the 2007-08 cumulative metrics (graphs (a) and (b), secondary vertical axis). Different letters in bars of graphs (c) and (d) indicate significant differences for the three slopes at α=0.05. Tested using Kruskal-Wallis ANOVA (H statistics and p levels are shown in the graphs).

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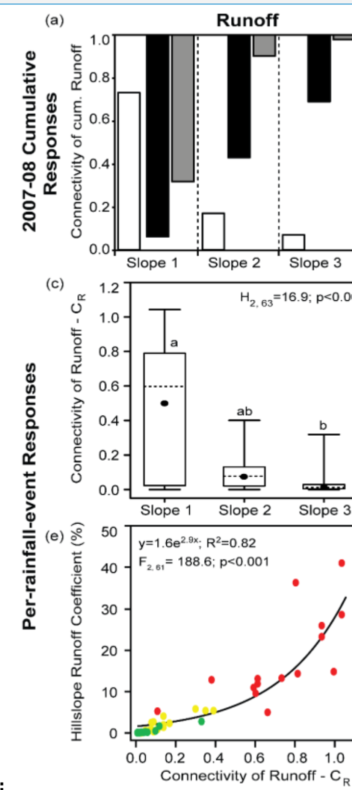

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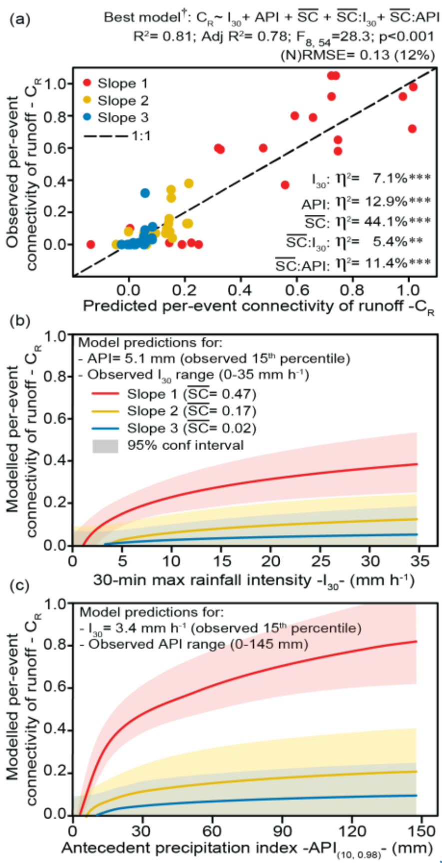

Figure 5. Structural and dynamic control of patch- to hillslope-scale runoff connectivity: (a) best-supported model of runoff connectivity and corresponding observed versus predicted runoff connectivity values; (b) modelled I_{30} and $\overline{SC}$ effects on runoff connectivity (API is fixed at 5.1 mm, 15th percentile of observed API values); (c) modelled API and $\overline{SC}$ effects on runoff connectivity (I_{30} is fixed at 3.4 mm h^{-1}, 15th percentile of observed values). The structure, R^2, Adj R^2, F statistic, p value and (normalized) root-mean-square error of the best supported model are detailed on top of the graph; η^2 values within the graph indicate the % variance explained by the direct and interaction terms of the model. Sig. codes: '***' p<0.001; '**' p<0.01; '*' p<0.05; 'ns' not significant at α=0.05. Notes: †, the model takes log-transformed values for the co-variables I_{30} and API; the graphs (b) and (c) show back-transformed I_{30} and API values for the modelled relationships.

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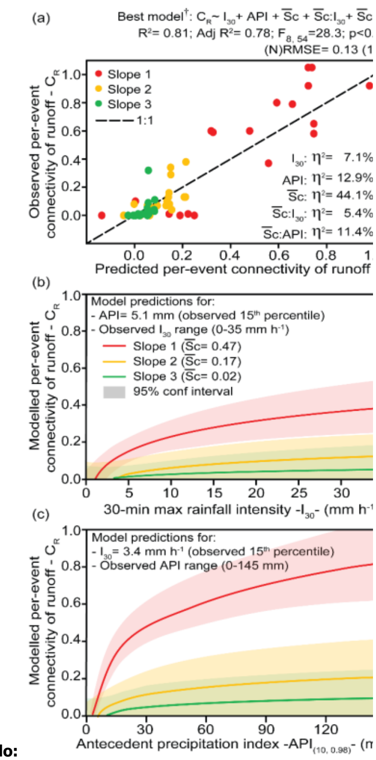

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Eliminado: $\overline{S}c$

Eliminado: Abbreviations: C_R, per-rainfall-event functional connectivity of runoff; $\overline{S}c$, mean structural connectivity of "source areas" in the experimental slopes; I_{30}, 30-min maximum rainfall intensity; API, antecedent precipitation index; ':', interactions between $\overline{S}c$ and the co-variables; (N)RMSE, (normalized) root-mean-square error; η^2, eta-squared statistic (effect size).

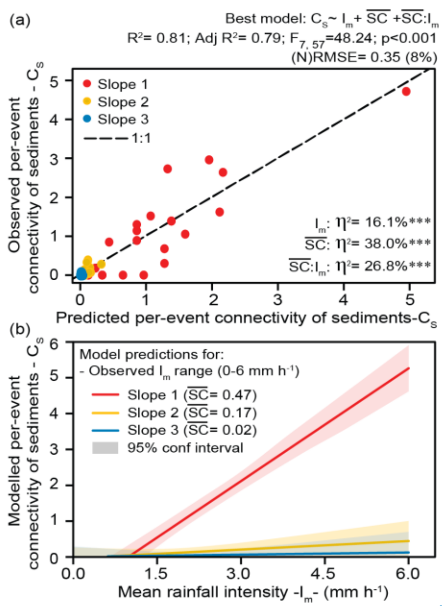
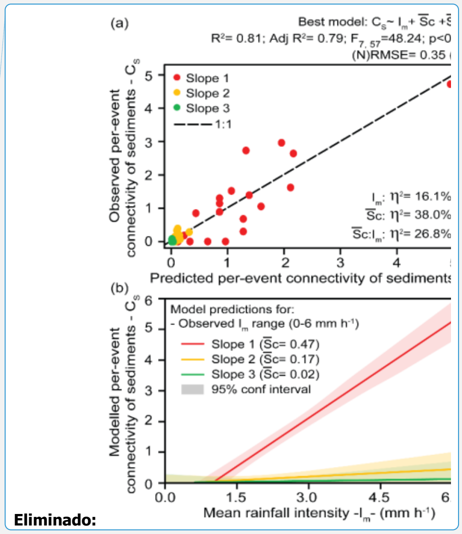


Figure 6. Structural and dynamic control of patch to hillslope-scale sediment connectivity: (a) best-supported model of sediment connectivity and corresponding observed versus predicted sediment connectivity values; (b) modelled Im and $\overline{SC}$ effects on runoff connectivity. The structure, R^2, Adj R^2, F statistic, p value and (normalized) root-mean-square error of the best supported model are detailed on top of the graph; η^2 values within the graph indicate the % variance explained by the direct and interaction terms of the model. Sig. codes: '***' p<0.001; '**' p<0.01; '*' p<0.05; 'ns' not significant at α=0.05.



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Eliminado: (the structure, R^2, Adj R^2, F statistic, p value and root-mean-square error of the model are detailed on top of the graph; η^2 values within the graph indicate the % variance explained by the direct and interaction terms of the model)

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Con formato: Fuente: Sin Cursiva

Eliminado: Abbreviations: C_S, per-rainfall-event functional connectivity of sediments; $\overline{S}$c, mean structural connectivity of "source areas" in the experimental slopes; Im, mean rainfall intensity; ':', interactions between $\overline{S}$c and the co-variables; (N)RMSE, (normalized) root-mean-square error; η^2, eta-squared statistic (effect size).