Hydrol. Earth Syst. Sci. Discuss., 9, 7877–7918, 2012 www.hydrol-earth-syst-sci-discuss.net/9/7877/2012/ doi:10.5194/hessd-9-7877-2012 © Author(s) 2012. CC Attribution 3.0 License.



This discussion paper is/has been under review for the journal Hydrology and Earth System Sciences (HESS). Please refer to the corresponding final paper in HESS if available.

Scale effect on overland flow connectivity at the plot scale

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Received: 5 June 2012 - Accepted: 8 June 2012 - Published: 25 June 2012

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Published by Copernicus Publications on behalf of the European Geosciences Union.





Abstract

A major challenge in present-day hydrological sciences is to enhance the performance of existing distributed hydrological models through a better description of subgrid processes, in particular the subgrid connectivity of flow paths. The relative surface connection function (RSC) was proposed by Antoine et al. (2009) as a functional indicator of runoff flow connectivity. For a given area, it expresses the percentage of the surface connected to the outflow boundary (*C*) as a function of the degree of filling of the depression storage. This function explicitly integrates the flow network at the soil surface and hence provides essential information regarding the flow paths' connectivity. It

- ¹⁰ has been shown that this function could help improve the modeling of the hydrogram at the square meter scale, yet it is unknown how the scale affects the RSC function, and whether and how it can be extrapolated to other scales. The main objective of this research is to study the scale effect on overland flow connectivity (RSC function). For this purpose, digital elevation data of a real field (9 × 3 m) and three synthetic fields
- $(6 \times 6 \text{ m})$ with contrasting hydrological responses were used, and the RSC function was calculated at different scales by changing the length (/) or width (*w*) of the field. Border effects, at different extents depending on the microtopography, were observed for the smaller scales, when decreasing / or *w*, which resulted in a strong decrease or increase of the maximum depression storage, respectively. There was no scale effect
- on the RSC function when changing w. On the contrary, a remarkable scale effect was observed in the RSC function when changing /. In general, for a given degree of filling of the depression storage, C decreased as / increased. This change in C was inversely proportional to the change in /. This observation applied only up to approx. 50–70 % (depending on the hydrological response of the field) of filling of depression storage,
- ²⁵ after which no correlation was found between *C* and *I*. The results of this study help identify the minimal scale to study overland flow connectivity. At scales larger than the minimal scale, the RSC function showed a great potential to be extrapolated to other scales.





1 Introduction

The concept of connectivity, applied in many disciplines, aims at characterizing the behavior of heterogeneous systems according to the intrinsic organization of the heterogeneities. In the context of landscape connectivity, connectivity can be defined as

- the degree to which the landscape facilitates or impedes movement between resource patches (Taylor et al., 1993). In hydrology there is still no consensus in the definition of hydrological connectivity (Braken and Croke, 2007; Ali and Roy, 2009). However, by analogy with the concept of landscape connectivity, overland flow connectivity can be defined as the degree to which the surface morphology facilitates or impedes overland
- flow. This definition, as well as the landscape connectivity concept, integrates two subconcepts, structural and functional connectivity (Tischendorf and Fahring, 2000). Structural connectivity describes the extent to which the surface morphology units, such as depressions, are linked to each other. It can be derived from topographical information. Functional connectivity describes the effect produced by the surface morphology on
- the process of overland flow. Functional connectivity must therefore be derived from a combination of topographical information and hydrological modeling.

Overland flow is a spatially distributed process affected by both the macro (meters) and micro (millimeters) scales. As the scale of study changes, different features of the surface become relevant and govern the hydrological response of the area of study.

- At the finest scale, soil roughness plays an important role through its effect on flow velocity. This effect, extensively studied, is incorporated in hydrological models as a friction factor. As the scale increases, the surface morphology has a greater influence on overland flow (Darboux et al., 2002b). At this scale, the spatial configuration of the system, formed by water-contributing sources (high areas), water-accepting sinks
- (depressions) and connecting links (rills), determines the hydrological response of the system. The study of the spatial configuration by geostatistics (e.g. the semivariogram) or landscape metrics allows comparison and classification of dominant processes and





explain the hydrological response. However, it is not adequate for predictive purposes in terms of hydrological response and connectivity (Van Nieuwenhuyse et al., 2011).

Distributed hydrological models frequently use "plot size" (100–10000 m²) gridcells allowing for an explicit analysis of overland flow connectivity at the watershed-scale.

- ⁵ However, such watershed-scale hydrological models do not explicitly treat overland flow connectivity below gridcell size. Overland flow processes in each gridcell are generally represented by two effective parameters, the maximum depression storage (i.e. maximum volume of water that the soil is able to store in surface depressions) and the friction factor (i.e. resistance to flow) (Singh and Frevert, 2002; Smith et al., 2007).
- ¹⁰ These two factors are generally obtained either by calibration, which suffers from equifinality (Beven, 1992) or by relating them to geostatistics indices (e.g. random roughness), which may be not able to discriminate between different hydrological responses (Antoine et al., 2009) or by empirical equations, such as Darcy-Weisbach, Chézy and Manning equations, which were designed for 1-D pipe-flows that do not reflect the overland flow conditions (Smith et al., 2007).

Generally, hydrological models assume that the generation of overland flow only starts after the maximum depressions storage is reached (Singh and Frevert, 2002). However, this assumption underestimates the surface connected and hence the volume of runoff generated before the complete filling of depressions (Antoine et al.,

- 20 2011). Conversely, depressions progressively overflow and water flows either to nearby depressions, or to the outflow boundary (Onstad, 1984; Darboux et al., 2002b). As depression storage increases, a larger area of the field become connected and contributes to the overland flow generation. This gradual process delays the initiation of the overland flow, and hence of the hydrograph. The understanding of this process
- of connectivity, which drives the hydrological response of a system at different scales (Lexartza-Artza and Wainwright, 2009), can potentially improve the current hydrological modeling and runoff prediction (Western et al., 2001; Mueller et al., 2007).

In order to fully take into account overland flow connectivity at the watershed scale, it would be necessary to provide hydrological models with subgrid microtopographical





information. The use of a high resolution DEM (cm–mm resolution) in hydrological models would strongly increase the input data and the computation time requirements. Yet even more problematic would be the acquisition of such data over large areas. Hence, subgrid connectivity functions, able to characterize different surfaces morphologies with

different hydrological responses, must be developed in order to improve the prediction of flows at the watershed scale without critically increasing computation time and data requirements of distributed hydrological models.

As the subgrid connectivity is expected to be scale-dependent, extra attention must be paid in order to select an appropriate size of the gridcell. Some studies have re-

- ¹⁰ ported the existence of a representative elementary area (Wood et al., 1988) or length scale (Julien and Moglen, 1990) that could serve to determine the gridcell scale in hydrological models. Firstly, it must be sufficiently large to be representative of the process of overland flow connectivity at the plot scale, i.e. all the components and the relationships between them must be represented (Ali and Roy, 2009). Secondly, it must
- ¹⁵ minimize border effects so as to neither miss nor modify some of these components. In addition, slope length has been observed to influence the response of the overland flow showing a lower runoff coefficient (*C*) with increasing scales (Van de Giessen et al., 2000; Cerdan et al., 2004). It has generally been assumed that this results from the spatial variability of rainfall and infiltration capacity (Yair and Lavee, 1985). Yet this effect
- has also been observed on homogenous hillslopes, in which case it was attributed to a change in residence time (Stomph et al., 2002). According to the definition of overland flow connectivity mentioned above, connectivity is expected to decrease with increasing slope lengths, since the probability for the water flow to encounter depressions is higher. However, the relation between overland flow connectivity and the decrease of the runoff coefficient with increasing lengths is still unclear.

This study focuses on the hydrological connectivity at the plot scale considering no interferences from infiltration, i.e. the infiltration capacity of the soil is assumed to be spatially homogeneous and lower than the rainfall intensity. In this manner, the effect of the surface morphology on the overland flow can be more easily studied. In order to





analyze and quantify the overland flow connectivity, a functional connectivity indicator was selected, the so-called Relative Surface Connection (RSC) function (Antoine et al., 2009). It expresses the percentage of the surface connected to the outflow boundary of a grid element as a function of the degree of filling of the depression storage. This

- ⁵ function explicitly integrates the flow network at the soil surface and hence provides essential information regarding the flow paths' connectivity. It can be calculated much faster than the full resolution of the St Venant equations and it has shown good results in capturing runoff-relevant connectivity properties compared to other connectivity indicators (Antoine et al., 2009). The RSC function showed very promising results at the square meter scale but, as a functional connectivity indicator, it may be dependent on the border effects and on the scale. However, it is unknown how these affect the RSC
 - function and whether and how it can be extrapolated to other scales.

The objective of this study is twofold. The first objective is to study the effect of changing scale on the RSC function for scales ranging from 0.18 m² to 36 m². And the second objective is to investigate the potential of the RSC function to be extrapolated to larger scales. For that purpose, the RSC function will be calculated and compared at differ-

ent scales and microtopography types. Comparison of the averaged RSC functions obtained will allow us find a relationship between scale and overland flow connectivity.

2 Materials and method

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20 2.1 Characteristics of the microtopographies

Two types of DEMs were used, real and synthetics. First, we used the DEM from a field located near Fort Collins, Colorado (USA) and obtained by laser scanning (courtesy of the USDA-ARS Agricultural Systems Research Unit in Fort Collins). The field had been under grassland but the grass had been killed chemically and left to decay before scanning. The total size of the DEM is 9.5×4.8 m, the spatial x-y resolution is 1.5 mm and the vertical resolution is 0.5 mm. The natural slope of the field is 6.6%. In order





to avoid border effects that may have been generated during the process of obtaining the DEM, this study focuses on the central area, with a size of 9×3 m. This was also guided by the need to have three square replicate areas of the largest possible size (in this case, 3×3 m). For computational reasons, the spatial x-y resolution of the DEM was reduced to 3 mm. The semi-variograms of the three replicates had a range of approximately 600 mm and a sill of 80–110 mm² (Table 1).

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Secondly, in order to evaluate the scale effect in scenarios with different hydrological characteristics and connectivity patterns, synthetic fields with contrasting microtopographies were generated using a method developed by Zinn and Harvey (2003),

- and adapted by Antoine et al. (2009). These fields present identical statistics in terms of mean elevation, standard deviation and semivariogram. However, they have different connectivity patterns in the sense of how the depressions get connected to each other. This method also allowed us to study the scale effect at larger scales compared to the real field case, yet the size of the fields was nevertheless limited for computational rea-
- sons. Three different types of micro-topographies were generated using this method:
 (a) River, (b) Crater and (c) Random type (Fig. 1; Antoine et al., 2009). The River type microtopography presents high areas connected by a system of rills. On the other hand, the Crater type, which is the reverse of the River type, presents a system of crests that isolate the depressions from each other. The Random type micro-topography is an
- intermediate scenario represented by a standard multi-Gaussian synthetic field. The three synthetic fields are characterized by values of sill (100 mm²) and range (100 mm) of the semivariogram observed in real fields (Vidal Vazquez et al., 2005) and experimental plots (Darboux et al., 2002b). In order to maintain the range of the semivariogram after the normalization of the river and crater patterns, a scale factor of 1.86 was
- applied since this value can preserve the spatial correlation (Zinn and Harvey, 2003).
 A slope equal to the natural slope (6.6%) of the real field was also added.





2.2 Filling algorithm and Relative Surface Connection (RSC) function

A filling algorithm (Antoine et al., 2009) was used to evaluate the overland flow connectivity. This method calculates a simplified hydrograph in which the velocity of the water is infinite and infiltration is not considered. A uniform rainfall is applied over the Digital

- ⁵ Elevation Model (DEM) of the study area. At every time step, a certain volume of water is applied in every pixel of the DEM. These volume of water "walks" over the DEM to the lowest pixel selected by an 8-neighbour scheme until they reach a depression or the outflow boundary. In a depression, this volume of water is stored as depression storage. Once the depression overflows, any excess of water flows to the next depres-
- sion or to the outflow boundary Since the water velocity is infinite, surface detention, i.e. water that is not trapped in depressions, is removed at every time step. When a drop reaches the outflow boundary it is added to the hydrograph. Since both the infiltration and the time transfer are null, the ratio of instantaneous outflow compared to the instantaneous inflow (Runoff Coefficient, *C*) corresponds to the percentage of the
- total area connected to the outflow boundary. Thus, this ratio will be equal to 1 when the 100% of the surface of the study area is connected to the outflow boundary. At that point, depression storage reaches its maximum value, i.e. the dead storage zone is completely filled.

The relative area connected to the outflow boundary can be represented in a sim-²⁰ plified hydrograph as a function of the cumulative input of water. In this case, the area under the simplified hydrograph is equal to the cumulative volume of outflow $[m^3]$ and the area between C = 1 and the simplified hydrograph corresponds to the MDS (Maximum Depression Storage). Based on this, we can represent *C* as a function of the depression storage (Fig. 2). This is known as the Relative Surface Connection (RSC)

²⁵ function, which is a functional connectivity indicator that is able to discriminate well among surfaces with differing levels of connectivity and that can potentially be implemented in hydrological models (Antoine et al., 2009).





2.3 Process of fragmentation and calculation of the RSC function

Two different scale effects were considered, i.e. changing the width of the plot area and changing the length of the plot area. Therefore, the area was first divided into narrower areas (from 1/2 up to 1/32 of the initial width) keeping the initial length constant,

and secondly the area was divided into shorter areas (from 1/2 up to 1/32 of the initial length) keeping the initial width constant (Fig. 3). The process of fragmentation of the areas and the calculation of the RSC function was exactly the same for all the fields. After the plot areas were divided, the Filling Algorithm was run in each of these sub-areas in order to obtain their RSC function. Finally, for a given scale, the RSC functions obtain their area were averaged in order to compare overland flow connectivity at different scales.

3 Results

3.1 Real field

3.1.1 Scale effect produced by changing only the width

- ¹⁵ When representing the average RSC function for each scale in the same graph (Fig. 4a), a gradual shift of the RSC function to the right is observed, i.e. a gradual increase of the MDS. This increase, as a function of the width (Fig. 4b), shows an exponential increase of the maximum depression storage as the width decreases and it can be fitted by an exponential curve represented in Fig. 4b as a dotted line.
- ²⁰ The fitted exponential curve is defined by:

$$MDS(w) = 0.001 \left(\frac{1}{1 - e^{-\frac{w}{k}}}\right) + v$$
(1)

where MDS is the maximum depression storage [mm], w is the width of the plot [m], k is a constant (Table 2) whose value reflects the magnitude of the asymptotic decrease





of the MDS when increasing the width of the plot area and v is another constant that represents the horizontal asymptote of the equation, i.e. the value of MDS when wtends to infinity. Therefore, v can be interpreted as the absolute value of MDS (AbsMDS). The factor 0.001 is a scale factor that makes the fitting better as this factor approximates to 0, e.g. when width tends to infinity MDS = 0.001 + v. The value 0.001 is assumed to be low expected in order to go d fitting

is assumed to be low enough in order to get a good fitting.

A limit in the variation of the MDS, corresponding to the AbsMDS + 10 % and represented in Fig. 4b as a dashed line, will be used to quantify and compare the scale effects between the four microtopography types. This value will be known as the "representative" width. Below this value, the variation of the MDS will be considered as negligible.

In order to compare the shape of the different RSC functions, the depression storage was normalized by the value of the maximum depression storage for each scale (Fig. 5). This way of representing the RSC function shows that the shape is little affected except for the two smallest scales (width = 0.188 m and 0.09 m), which present a strong deviation in the last third of the function (relative depression storage approximately > 2/3) (Fig. 5). These two curves show a displacement to the left, i.e. for the same value of relative depression storage the connectivity is lower for the two smallest scales.

20 3.1.2 Scale effect produced by changing only the length

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For the second case, when changing the length for a constant width of 3 m, the average RSC functions show the opposite effect compared to when changing the width. The RSC function shows a gradual shift to the left as the plot length decreases (Fig. 6a), i.e. a gradual decrease of the MDS. This decrease can also be fitted by the exponential curve defined by Eq. (1) with *I* instead of *w* (Fig. 6b).

A limit in the variation of the MDS, corresponding to the AbsMDS – 10% and represented in Fig. 6b as a dashed line, will be used to quantify and compare the scale effects between the four microtopography types. This value will be known as the





"representative" length. Below this value, the variation of the MDS will be considered as negligible.

As opposed to what was observed when changing with, changing length not only changes the MDS but also to the shape of the RSC function (Fig. 7). The shorter the slope length, the higher the connectivity for the same value of relative depression storage. The RSC function tends from a concave shape for the largest plot lengths to a straighter or even convex shape, especially for the smallest scales (length = 0.1875 m and 0.09 m).

3.2 Synthetic fields

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10 3.2.1 Scale effect produced by changing only the width

As for the real field, when decreasing the plot width, a gradual shift of the RSC function to the right is observed (Fig. 8), i.e. a gradual increase of the MDS. When representing the MDS as a function of the width (Fig. 9), the graph also shows an asymptotic decrease of the MDS as the width increases. This variation of the MDS as a function of the plot width can also be fitted by the Eq. (1) showing different values of *k* and *v*

(AbsMDS) for the different synthetic fields (Table 2).

The shape of the RSC function, like for the real field, is little affected by the change of width, except for the two smallest scales (width = 0.375 m and 0.188 m) which deviate considerably in the last third of the function (relative depression storage approximately > 2/3) (Fig. 10).

3.2.2 Scale effect produced by changing only the length

When reducing the length and keeping the initial width (6 m), the average RSC functions show the opposite effect compared to when changing the width, just like the real field. Again, there is a gradual shift to the left the RSC (Fig. 11), i.e. an exponential





decrease of the MDS as the length decreases (Fig. 12) which can be fitted by the Eq. (1) with / instead of w and different values of k and v (AbsMDS) (Table 3).

Likewise the real field, the reduction of the length causes a variation in the shape of the RSC functions. For the same value of the relative depression storage a regular in-

⁵ crease of connectivity is observed as the length decreases (Fig. 13). The RSC function tends from a concave shape for the largest plot lengths to a straighter or even convex shape, especially for the smallest scales (length = 0.375 m and 0.188 m).

4 Discussion

4.1 Scale effect on the MDS

- In all the cases studied, a gradual variation of the MDS has been observed when either the width or the length was reduced. This can be explained by the increasing influence of the lateral and bottom boundaries when reducing the scale, i.e. two border effects. On the one hand, the reduction of the width causes the interruption of the connecting paths between depressions (Fig. 3). At a certain scale, assumed to correspond to the value of AbsMDS + 10%, the variation of MDS starts to be considerable. Below this scale, the area between these virtual lateral boundaries is not able to represent all the components involved in the functional connectivity process. The connections between depressions are not completely included in this area and consequently water has to find new paths to reach the outflow boundary. These new paths require higher levels
- of stored water, i.e. the depth of water needed to overflow the depressions gets higher, and consequently the value of MDS increases. On the other hand, with the reduction of the plot length below a certain scale, assumed to correspond to the value of AbsMDS 10% (Fig. 12), the resulting area becomes less and less representative of all the components that cause the accumulation of water in the depressions (i.e. barriers in the direction of flow). In other words, as the length decreases, a larger proportion





of depressions get crossed by the virtual outflow boundary and hence, they get more easily connected to it.

These two border effects affect to all the microtopography types similarly in a qualitative way but differently in a quantitative way. In order to quantify and compare these
effects between the different microtopography types, a "representative" scale (AbsMDS ± 10%) (Fig. 4b, 6b, 9 and 12) will be used. This scale is assumed to represent the width or length below which the border effect starts to be considerable, i.e. the plot is not either long or wide enough to be representative of the process of overland flow connectivity occurring at larger scales. This representative scale provides a measure
of the sensitivity of the different microtopographies to these two border effects. It is calculated using the Eq. (1) (Tables 2 and 3) and when plotted as a function of the AbsMDS (Fig. 14a and b) allows comparing the extent of this sensitivity between the

four microtopography types.
 On the one hand, Fig. 14a shows a decrease of the representative width as the
 AbsMDS increases. This decrease seems to follow a linear trend except for the River microtopography whose representative width is approximately double of the Real microtopography, even though they both have approximately the same value of AbsMDS. This shows a higher sensitivity of the MDS to changes in width for the River microtopography compared to the other microtopographies. On the other hand, Fig. 14b shows an

increase of the representative length as the AbsMDS increases. This increase seems to be linear and contrarily to the width border effect, the length border effect shows a higher sensitivity to the changes in length for the Crater microtopography and a lower sensitivity for the River one.

These differences between the width and the length border effect and between different microtopographies can be explained by the preferential directions of flow and the different mechanisms of overland connectivity. Since we have applied a slope (6.6%) to all the microtopographies, the preferential direction of flow is expected to follow the maximum slope direction, parallel to the lateral boundaries, until the bottom boundary. However, connection paths in the perpendicular direction to the lateral boundaries may





also be important for the overland flow connectivity. This is the case of the River microtopography, which is the most sensitive to the width border effect. The mechanism of overland connectivity in this microtopography type is based in the connections by a system of rills which do not follow a preferential direction. When these rills are blocked

- ⁵ by the virtual lateral boundaries, water must overflow higher areas of the plot to flow either to other rills or up to the bottom boundary. As a consequence, the mechanism of connectivity through rills changes to an overflow mechanism as width decreases, causing a higher storage of water inside of these disconnected areas, i.e. an increase of the MDS. Contrarily, connectivity in the Crater microtopography, which is the less sensitive
- to the width border effect, is already based in an overflow mechanism, i.e. water stored in depressions must overflow the system of crests to flow to either other depressions or to the outflow boundary. In this case water overflows the rills located at the lower part of the depressions, thus overland flow tends to follow the maximum slope direction which is parallel to the lateral boundaries. Since water tends to flow parallel to 15 the lateral boundaries they are less likely to block connections between depressions
- and as a consequence, the width border effect has therefore a lower influence in the connectivity process and in the MDS.

Conversely to the width border effect, the border effect when reducing length generates new connections in the areas crossed by the new outflow boundaries. In the

- ²⁰ Crater microtopography, which is the most sensitive to the length border effect, the depressions crossed by the outflow boundary get directly connected since water does not need to overflow the system of crests. As length decreases the mechanism of connectivity becomes less based on the overflow of depressions since a larger proportion of depressions get crossed by the outflow boundary and as a consequence, the
- MDS gradually decreases. Differently, in the River microtopography, which is the less sensitive to the length border effect, overland flow from higher areas is stored in the system of rills. This mechanism of connectivity stores a very low volume of water since most of rills are interconnected and only disconnected areas, which need to overflow to get connected, stores a considerable volume of water. Therefore, the length border





effect is considerable when the new outflow boundaries cross a great part of isolated areas. This only occurs when the length of the generated plots decrease considerably (300 mm for the "River" microtopography).

- For the two other microtopography types, Real and Random, as shown in Fig. 14a and b the sensitivity to the two border effects is, as expected, between the two extreme cases, River and Crater. Figure 14a shows that the width border effect affects the Real and Random types at an extent slightly higher than the Crater type but considerably lower than the River type. From this it can be interpreted, as for the Crater type but at a smaller extent, that the preferential direction of flow is parallel to the lateral boundaries and the connections in the perpendicular direction have a low importance. From Fig. 14b, it may be interpreted that the connectivity mechanism for the Real and Random microtopographies is intermediate between the overflow of depressions and the connection through rills. But since the representative length of the Real microtopogra-
- phy is closer to the River type, it may be interpreted that its connectivity mechanism is predominately based on rills connections rather than the overflow of depressions.
 - As shown above, the sensitivity to border effects depends on the preferential direction of flow and the hydrological response of the field. Even microtopographies with the same statistics (Table 1) in terms of mean, standard deviation and semivariogram, showed different sensitivities to border effects and representative scales. This is ex-
- ²⁰ plained by the fact that these statistics can be considered as structural indicators whereas the RSC function is a functional indicator. Structural indicators such as the semivariogram can be useful to describe the spatial heterogeneity (Western et al., 1998), and as a heterogeneity index it can be interpreted as a link between pattern and process (Gustafson, 1998). Connectivity, as a process, changes in time and space
- however, structural indicators, such as the range of the semivariogram, are not able to reflect this change and hence, may not be good indicators of the sensitivity of a surface to border effects. Whereas, functional indicators, such as the RSC function, are able to reflect the evolution of the connectivity process since it integrates both topographical data and hydrological modeling. As it has been shown, the study of the RSC function





and how it is affected by the border effect cannot only help identify the sensitivity to border effects but also help understand the connectivity process and identify different mechanisms of connectivity.

4.2 Scale effect on overland flow connectivity produced by changing only the width

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Apart from the border effect on the MDS when changing width, the shape of the RSC function does not seem to be considerably affected (Figs. 5 and 10). Only when the width of the sub-areas of study is less than a certain scale (0.1875–0.375 m) border effects get more noticeable and they not only have an effect on the MDS but also a considerable impact on the shape of RSC functions. As width increases this border effect becomes less and less noticeable on both the MDS and the shape of the RSC function. Therefore, regions of a field wider than the minimal representative width may be potentially representative of the functional connectivity of the whole field.

4.3 Scale effect on overland flow connectivity produced by changing only the length

When length decreases, it not only produces a decrease in the MDS but also a considerable increase of the connectivity when comparing the normalized RSC functions (Figs. 7 and 13). In order to quantify the change in shape of the normalized RSC function, the connectivity of the largest field C(/ref), taken as a reference, is divided by the C(I) of the other scales for each value of relative depression storage (Figs. 15a and 16a). For the first part of the graph (relative depression storage < 0.5–0.7), the ratio of connectivity does not show a clear trend of increase or decrease of the values of C, which seem to oscillate around their mean value. In this interval the separation between the different curves remains approximately constant, whilst for the last part, the ratio of C shows a clear increase and the distance between curves progressively





decreases until they all meet when the field is completely connected (relative depression storage = 1).

Since for a given scale the ratio C(/ref)/C(/) of connectivity seems to oscillate around their mean value in the first part of the function (relative depression storage < 0.5-0.7) the values of *C* for this part of the function were averaged and compared to the ratio ///ref, where /ref = 3 m for the real field (Fig. 15b) and /ref = 6 m for the synthetic fields (Fig. 16b). In this interval, both ratios showed an inverse correlation, i.e. the rate of change of connectivity (dC(/)/dC(/ref)) is inversely proportional to the rate of change of length (d//d/ref). Since connectivity is the ratio of area connected to the outflow boundary and it increases with the same rate as the length decreases, the

- size of the area connected (in absolute units, m²) is approximately the same for all the scales (Fig. 17). This can be explained as follows. For the first part of the RSC function, which represents the first stage of the depression filling process, the depressions that are more likely to be already connected are the ones located closer to the bottom
- ¹⁵ boundary. These depressions that cover a specific area behave independently with regard to the rest of the depressions, further from the bottom boundary. This connected area keeps the same size independently of the plot length except for plots shorter than this area (Fig. 17). Therefore, the connectivity *C* gets higher when decreasing the plot length since the total area of study decreases.

After this first stage of the depression filling process (relative depression storage < 0.5–0.7), a quick process of connection of the depressions starts and depressions located further from the outflow boundary get connected. This "jump" or sharp threshold in the RSC function, which has been observed in the four microtopographies simulated, is more noticeable for the longer plots (> 3 m) (Fig. 17). This is consistent with

the percolation theory (Berkowitz and Ewing, 1998), whose applicability on overland flow was demonstrated by Darboux et al. (2002a) and Lehman et al. (2007). It relies on the existence of a threshold relationship between rainfall and overland flow, caused by variations in the storage capacity and connectivity. Below this threshold, preferential pathways that go from the top to the bottom boundary are still not connected and the



overland flow remains very low. But when this threshold is exceeded, the pathways become connected and a sharp increase in the overland flow occurs. In addition, making the assumption that at this stage of the RSC function only the depressions close to the bottom boundary are connected, this stage will help identify characteristics of the

5 structural connectivity of the field, such as the average size the depressions (puddles). Or vice versa, measuring, for instance, the average size of the depressions will help predict this first stage of the RSC function.

These results show a great potential for the RSC function to be extrapolated to larger scales. At scales larger than the minimal representative scale, once the percolation
threshold is identified and predicted, we can divide the RSC function in two parts. The first one, before the percolation threshold, as it has been shown, can be directly extrapolated applying the inverse correlation between length and connectivity. The second part, after the percolation threshold, in which no correlation between scales has been found, may be obtained assuming a linear relationship between depression storage and connectivity. However, further research is needed to assess and confirm this hypothesis.

5 Conclusions

In this study we investigated the behavior of the RSC function, and hence the overland flow connectivity, when changing the scale of the area of study. The results of this study

- have reveal that both scale effects and border effects affect overland flow connectivity at the plot scale. A similar behavior of the RSC function with scale has been shown for different surfaces with different microtopography patterns. However, the magnitude of the scale and the border effects was different depending, not on the statistics (e.g. the semivariogram) but on the hydrological response of the microtopography.
- ²⁵ On the one hand, no scale effect but border effect was observed when changing the width of the plots hence, regions of a field with shorter widths may be potentially representative of the functional connectivity of the whole field. The study of the sensitivity of





the RSC function to width and length border effects helps identify preferential direction of flows and different predominant mechanisms of connectivity on different microtopography types. This sensitivity to border effects also allows determining the minimal representative scale (width or length) to study the overland flow connectivity, in this study between 0.3 m and 2.5 m depending on the microtopography type.

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On the other hand, a remarkable scale effect was observed in the RSC function when changing the length of the plots. At scales larger than the minimal representative scale, the RSC function showed a great potential to be extrapolated to other scales. For a given degree of filling of the depression storage, connectivity (C) decreased as the plot

- ¹⁰ length increased and the rate of this change of connectivity was inversely proportional to the rate of change in length. This latter observation applied only at the first stage of the RSC function (up to approx. 50-70% of filling of depression storage, depending on the hydrological response of the field), after which no correlation was found between *C* and length.
- At this first stage of the RSC function it has been observed that only the depressions close to the outflow boundary are connected. After this first stage, the RSC function shows a percolation threshold relationship between the depression storage and the connectivity of the field. This two differentiated stages can potentially not only help extrapolate the whole RSC function but also to obtain information about the structural connectivity of the field.

For all of this, further research is needed in order to obtain a method to predict the percolation threshold and to extrapolate the whole RSC function to other scales and to which extent it can be extrapolated. In order to do so, a larger number of DEMs obtained from a greater variety of real soils and synthetic fields with larger sizes, dif-

²⁵ ferent boundary conditions and connectivity characteristics must be studied in order to contrast the results obtained in this study.





Acknowledgements. The DEM of the Real microtopography type was acquired by the USDA-ARS Agricultural Systems Research Unit in Fort Collins, Co (Jim Ascough and Timothy R. Green) with the support of the USDA-ARS National Soil Erosion Research Laboratory (F. Darboux, C. Huang, S. McAfee).

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 Table 1. Characteristics of the microtopographies.

		Real field	Synthetic Fields		
			River	Random	Crater
Size [m × m]		3 × 3	6×6	6×6	6 × 6
Spatial Resolution	3	10	10	10	
Slope [%]	6.6	6.6	6.6	6.6	
Standard deviation of elevation [mm]		1.8	1.3	1.3	1.3
a	Sill [mm ²]	80–110	100	100	100
Semivariogram	Range [mm]	600	100	100	100
Depression Storage [mm]		0.53	0.5	1.275	2.55





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Table 2. Parameters of the fitting curve (Eq. 1 when changing w), goodness of fit represented by the sum of squares (SS) and width.

	MDS [mm]	k	v	Sum of squares [mm ²]	Representative width [mm]
Real	0.53	59561.18	0.51	0.00036	1200
River	0.50	120254.54	0.48	0.02115	2500
Random	1.28	128950.14	1.26	0.00102	1100
Crater	2.55	221946.09	2.52	0.00145	900

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Table 3. Parameters of the fitting curve (Eq. 1 when changing /) and goodness of fit represented by the sum of squares (SS).

	MDS [mm]	k	V	Sum of squares [mm ²]	Representative length [mm]
Real	0.53	-22510.91	0.54	0.00059	400
River	0.50	-15811.89	0.50	0.00009	300
Random	1.28	-70932.76	1.29	0.00026	600
Crater	2.55	-237168.2	2.57	0.00385	950







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Fig. 2. RSC function and connectivity evolution (connected areas in black).







Fig. 3. Division pattern when changing (a) width and (b) length of the plots.







Fig. 4. Real field – (a) Effect of plot width on the RSC function and (b) on the maximum depression storage (n indicates the number of plots averaged; the associated standard deviations are represented by vertical lines; the arrow represents the "representative" width; all the plots are 3 m long).







Fig. 5. Real Field - Effect of plot width on the normalized RSC function (Depression storage (x-axis) scaled by the maximum depression storage; all the plots are 3 m long).

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Fig. 6. Real field – Effect of plot length on the RSC function (a) and on the maximum depression storage (b) (*n* indicates the number of plots averaged; the associated standard deviations are represented by vertical lines; the arrow represents the "representative" length; all the plots are 3 m long).







Fig. 7. Real Field – Effect of plot length on the normalized RSC function (Depression storage (x-axis) scaled by the maximum depression storage; all the plots are 3 m wide).















Fig. 9. Synthetic Fields – Effect of plot width on the maximum depression storage for the "River", "Random" and "Crater" type micro-topographies (the associated standard deviations are represented by vertical lines; arrows represent the "representative" width; all the plots are 6 m long).







Fig. 10. Synthetic Fields – Effect of plot width on the normalized RSC function (Depression storage (x-axis) scaled by the maximum depression storage; all the plots are 6 m long).



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Fig. 11. Synthetic Fields – Effect of plot length on the RSC function for the "River", "Random" and "Crater" type micro-topographies (all the plots are 6 m wide).



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Fig. 12. Synthetic Fields – Effect of plot length on the maximum depression storage for the "River", "Random" and "Crater" type micro-topographies (the associated standard deviations are represented by vertical lines; arrows represent the "representative" length; all the plots are 6 m wide).







Fig. 13. Synthetic Fields – Effect of plot length on the normalized RSC function (Depression storage (x-axis) scaled by the maximum depression storage; all the plots are 6 m wide).







Fig. 14. (a) Representative width as a function of the Absolute MDS for the four microtopography types and **(b)** representative length as a function of the Absolute MDS for the four microtopography types.







Fig. 15. Real Field – Scale effect when changing the length: **(a)** Ratio of connectivity at different scales at the first two thirds of the RSC function. **(b)** Correlation between the ratio of scale and the ratio of connectivity at the first two thirds of the RSC function (the associated standard deviations are represented by vertical lines; all the plots are 3 m wide).







Fig. 16. Synthetic Fields – Scale effect when changing the length: **(a)** Ratio of connectivity at different scales at the first two thirds of the RSC function. **(b)** Correlation between the ratio of scale and the ratio of connectivity at the first two thirds of the RSC function (the associated standard deviations are represented by vertical lines; all the plots are 6 m wide).









Fig. 17. Surface of the area connected to the outflow boundary, in absolute units (m²), in function of the relative depression storage.