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Influence of the gully erosion on connectivity patterns in a small semiarid catchment area

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Summary

For centuries, land in the North East of Brazil has been overexploited, which has brought a large area to a high degradation level, vulnerable to erosion. Ephemeral gullies emerge with increasing frequency. Among the potential impacts of gully erosion, there is the change in connectivity patterns, which might influence the sediment delivery ratio and therefore, the rates of sediment transfer from the hillslopes into the lower parts of the catchment area.

The purpose of this research is to point out how gully erosion changes sediment connectivity patterns in a small-scale catchment area in the Brazilian semiarid region. This change can enhance rates of soil losses, river and reservoir silting and pollutant transfer, among others.

Two small gully erosion watersheds in the Madalena catchment area are researched to compute the impacts of the gullies on the soil loss, the connectivity and the sediment delivery ratio (SDR).

The Universal Soil Loss Equation (USLE) is used to compute the soil loss based on the erosivity factor (R), the erodibility factor (K), the slope (S) and slope length factor (L), the cropping factor (C) and the conservation practice factor (P) of the watersheds. The connectivity is determined by making use of the Connectivity index of Cavalli taking the downstream and upstream characteristics of the water flows into account. A high connectivity implies a faster and more regular discharge of the sediment. The SDR is computed by making use of the Maner method including the maximum length of the watershed parallel to the biggest gully and the elevation of the area.

According to the USLE the average soil loss is 761 tons/ha/year with the gullies and 744 tons/ha/year without the gullies for site 1 and 454 tons/ha/year with the gullies and 448 tons/ha/year without the gullies for site 2 for the dry season. The main changes in soil loss are only visible in the area where the gullies are eliminated. Focussing on the gully erosion area itself reveals a decline of the soil loss of 34,2 % and 32,9 % respectively for site 1 and site 2.

The connectivity with the gullies is higher than the connectivity without the gullies. Not only a change in connectivity in the area where the gullies are eliminated was visible, but also the connectivity in the streamlines upstream was affected by the gullies. The connectivity of the upper streamlines is higher with the presence of the gullies in the watershed.

The SDR is 100% and 50% for respectively site 1 and site 2. The method of Maner does not include changes in the topography in the computation of the SDR, so this ratio stays the same with or without gullies. However the Forest Service Model indicates the changes of the presence of a gully and might be a good method to use in the future.

The conclusions are that the occurrence of gullies will increase the soil loss and connectivity resulting in a higher discharge of sediment. This sediment could enhance river and reservoir silting, polluted water and rates of soil losses.

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1. Introduction

1.1 Problem context

Gully erosion is the process of soil loss mainly caused by the surface water flow induced by precipitation. The preliminary stages of gully erosion are sheet-and rill erosion (Figure 1). Sheet erosion is mainly caused by raindrop impact and consequently by the surface flow of these gathering raindrops. Some of the fine soil particles are trapped, but this type of erosion is hardly visible. Rill erosion is the next stage and is caused by concentrated water run-off inducing small drainage lines (maximum 30 cm deep). The last stage is the gully erosion. Gullies are deep width channels which continue to develop to greater proportions which results in a higher amount of soil loss.

The soil loss causes siltation of the small lakes and reservoirs, which are constructed to manage the water suply. The storage capacity and the life time will decrease in case of a high siltation rate (Lima Neto, Wiegand, & de Araujo, 2011). Another problem is the reduction of available farmlands, because the soil is flushed away.

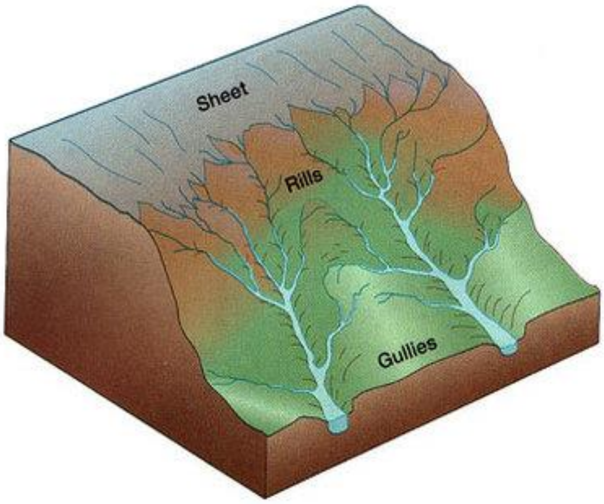

Figure 1: Gully erosion (Pinto, 2009)

The amount of soil loss depends on the interaction between land use, precipitation, topography, soils and lithology (Jiuchun, 2017). The topographic factors elevation, slope and slope aspects do have the biggest influence on the arise of gullies (Wang, 2016). Indices of gully erosion regionalization are the stream power index (SPI), the land use type and the population intensity. Combining these factors can reveal the development of the gully erosion according to Jiuchun. The soil loss per unit area could be expressed by the Universal Soil Loss Equation. The equation includes the influence of the rainfall erosivity, the soil erodibility, the topography, the land use and the land slope.

The occurrence of gullies will change the topography of an area which also could enhance a change in connectivity patterns. The sediment transport without gullies towards rivers is characterized with the following connectivity: the water flow towards the river contains soil particles which might reach the water in the river and gets drained from the area. However not all particles will reach the water in the river and are left behind in the river bed. A high connectivity means that many soil particles reach the water in the river and are discharged from the area (Figure 3). Due to a low water level many soil particles will be left behind in the river bed and are only discharged during a peak water flow which will occur in the rain season. Figure 2 shows the sediment bulks (red circle) in a gully, waiting to get discharged by a high water flow. In case of a drought, the peak water flow will take place after a few years. A Lot of sediment is discharged from the river bed in that case and flows to the reservoirs. However this will not result in more siltation of the reservoirs, because the soil particles present in the water will flow behind the dam. The relation between the water discharge and the suspended sediment load is linear (Lima Neto, Wiegand, & de Araujo, 2011).

Therefore, gullies will affect the connectivity and will provide a steady flow of soil particles, due to the connection with the river. The soil particles, which are discharged only during peak water flows, will be discharged on a regular basis. A higher connectivity leads to a higher percentage of sediment in the water. The change in connectivity patterns can enhance rates of soil losses, river and reservoir silting, and pollutant transfer, among others.

Figure 2: Geomorphometric connectivity gully erosion site Gilbués Brazil

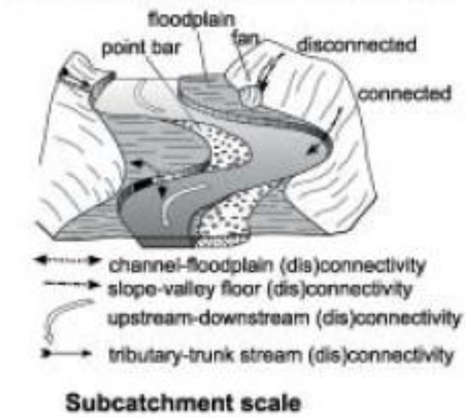

Figure 3: Geomorphometric connectivity

1.2 Problem description

For centuries, land in the NEB has been overexploited, which brought a large area to a high degradation level, vulnerable to erosion. Previous studies show that, in the region, inter-rill erosion prevails (Lima Neto, Wiegand, & de Araujo, 2011). However, as anthropogenic actions intensify, ephemeral gullies emerge with increasing frequency. Ephemeral gullies have a length of several decametres, a maximum width and a maximum depth of a few meters. Among the potential impacts of gully erosion, there is the change in connectivity patterns, which might influence the sediment delivery ratio and therefore, the rates of sediment transfer from the hillslopes into the lower parts of the catchment area. This change can enhance rates of soil losses, river and reservoir silting and pollutant transfer, among others. These processes may have relevant consequences for the rural communities in the region, mainly considering that 90% of the water demanded by these communities rely on the small dams, located on the outlet of such small watersheds (de Araújo, Güntner, & Bronstert, 2006).

1.3 Relevance

The Northeast of Brazil contends with drought, because of the small precipitation compared to the potential evaporation. The average rainfall in Northeast Brazil is less than 800 mm per year (Paredes-Trejo, Barbosa, & Kumar, 2016) and the rainy season occurs from February to May (Barbosa & Kumar, 2016). As stated in the problem description the rural communities rely on the dams to regulate the water supply for downstream located water users, because over 75% of the precipitation occurs in the rainy season. So it is very important that the reservoirs in front of the dams can store enough water. Silting of the lakes because of sediment transport will occur regardless of its purpose. The enlargement of the river width and the slowdown of the water flow are suitable conditions for siltation (de Almeida, Figueiredo, & Oliveira, 2016). Siltation reduces the storage of the lakes and therefore the water availability and the reservoir morphology changes to a more open geometry resulting in a higher evaporation rate if the storage stays the same (de Araújo, Güntner, & Bronstert, 2006). This might be a problem in the future, especially when the gully erosion plays a big part in the sediment delivery rate.

Another aspect of relevance is the waste of land (soil), due to the erosion and the occurrence of the gullies. Soil erosion is a threat to humanity, because the soil could not be productively used of its full capacity, while it is needed for food supply. The removal of topsoil and an increased water runoff negatively affect the useable soil (García-Ruiz, 2016).

The water quality is badly affected if the percentage of sediment in the water gets too high and the water gets cloudy, preventing fish to recognize their food. The turbidity of the water also destroys the habitat of the smallest stream organism causing that the population of some fish species will be shorten or might extinct in the rivers and basins in the worst case (Sattison, 2015). Also less vegetation will grow in the rivers, which could lead to more erosion, because the roots provide solidity of the soil.

Besides the decline of animals and vegetation, polluted water is also more expensive to purify to function as drink water. A study on the monetary costs of agricultural and water quality performed for 32 countries all over the world showed the high costs induced by the pollution of water. The water pollution in the United States of America for example costs 1.5 billion euro, of which 556 million euro is used for treatment of the drinking water (Agriculture and the Environment of the OECD´s Committee for Agriculture and the Environment Policy Committee, 2010). So it is really important to maintain the water quality if possible.

In this research an assessment is made of the influences of gullies on a watershed and eventually on the whole catchment. In order to evaluate the influences of gullies a comparison between an area with and without gully erosion is made. To keep as many fixed parameters as possible, the exact same area is chosen to compare the site with and without the gully erosion. The topography of the current site is used as the reference for a gully erosion site and the topography of the site before gully erosion occurred is used as the reference for a gully erosion free area. Two gully erosion areas are chosen of a small size (<1 ha) to get to the bottom. The assumption was made that the area without the gully erosion is exact the same as the topography nowadays except for the gullies.

The main objective is to assess how the gullies affect the connectivity of the watershed. A change in connectivity does not only affect the watershed itself but also has consequences for the sequence drainage systems, like the rivers and reservoir. A raindrop probably contacts the soil in the watershed first and got drained all the way to the ocean. A change in the composition of the water at the first stage (watershed) due to a higher percentage of sediment will affect the remaining drainage systems. A higher connectivity in the watershed will result in a higher percentage of sediment in the water, because more soil is discharged from the watershed. So it is very important to evaluate the influences of the gullies on the connectivity, as this might not only affect the watershed, but also the whole natural drainage system.

Studies performed on the connectivity usually include enormous areas (multiple square kilometres) and do not focus on small streamlines like gullies. The high focus level of this research makes it unique and creates the possibility to get to the bottom of the effects gully erosion has on the connectivity and in the end on the rest of the drainage systems. Finally the results could draw more attention to the gully erosion problem and a better understanding of the effects gullies have on a watershed could be obtained.

In this study the change in connectivity patterns due to the occurrence of gullies is researched. After completing the research a better understanding of the effects gullies have on the soil loss, the connectivity and the sediment delivery ratio will be obtained.

1.4 Study area

The study area was a small watershed within the Madalena basin in the state Ceará in Brazil (Zhang, et al., 2016)(Figure 4). The Northeast of Brazil (NEB) is a semiarid region of 1 million km² and 25 million inhabitants in the Caatinga biome Within the Madalena basin two small areas are studied to get to the bottom of the gully erosion. The chosen areas show signs of ephemeral gullies occurred roughly over the last 60 years. The size of the areas differ from 100 m^2 till 1000 m^2 and are located relatively nearby each other.

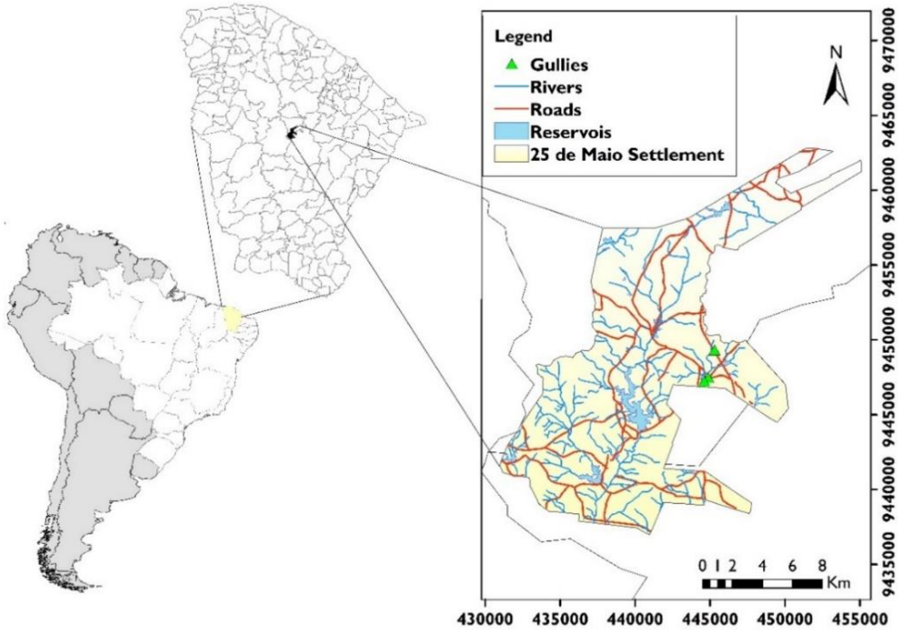

Figure 4: Study area Madalena catchment

Climate

The study area is characterized by a tropical semiarid climate and an average rainfall over the last 60 years measured by two weather stations located nearby the gully erosion sites of 800 mm a year (Climate Data, 2017). Almost all the rainfall takes place in the rain season from February till May (Barbosa & Kumar, 2016). The uncertainty in the amount of rainfall each year and the high evaporation rate (could reach up-to 3000 mm a year (Silva, 2001)) in the area results in periods of drought. The temperatures vary from 21 to 32 degrees Celsius over the year with an average of 26 degrees Celsius.

Geology

The soil present in the Madalena catchment mainly consists of Fluvic Neosols, Vertisols, Luvisols and Litholic Neosols (Figure 5) (Lopes, 2013). Results of the soil research of the first two gully erosion sites are visible in Table 1. Samples of three different depths are taken to obtain the average composition of the soil types.

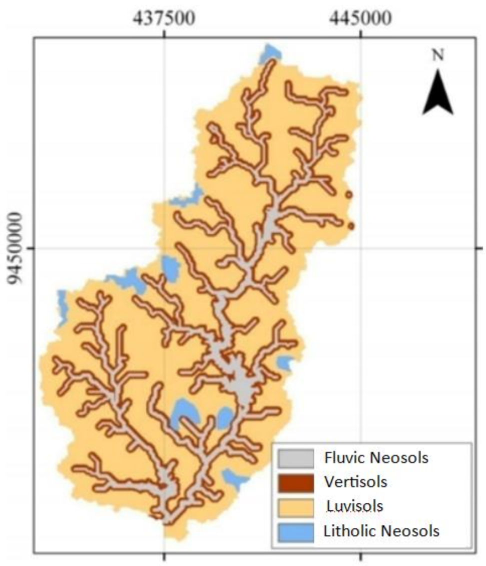

Figure 5: soil types Madalena

2. Objectives

The main objective of this research is to assess how gully erosion changes sediment connectivity patterns in a small-scale catchment area in the Brazilian semiarid region. Goals of the research is to create a better understanding of the change in connectivity patterns and the causes it has. In particular the outcomes of the connectivity pattern; (1) without gully erosion, (2) with gully erosion are interesting. With this information it is possible to model gully erosion in other areas where gully erosion might appear in the future and study the effects a change in connectivity patterns will have on the catchment area. After that a suitable approach to counteract the gully erosion could be conceived in case the effects on the sediment delivery ratio induced by a change in connectivity patterns are of significant proportions.

2.1 Research questions

The following questions are derived to reach the goal:

1. How does gully erosion affect the soil loss of a watershed?
2. How did the occurrence of gullies affect the connectivity patterns of the watershed?
3. What is the difference in the sediment delivery rate comparing an area without the presence of gully erosion and a further developed area of gully erosion?
4. Is there a relationship between the connectivity and the sediment delivery ratio?

3. Methodology

In order to assess how gully erosion changes sediment connectivity patterns in a small-scale catchment area in the Brazilian semiarid region a comparison is made between sites before and after gully erosion occurred. The first stage of the gully erosion is the shift from rill erosion to gully erosion and is assumed to be in 1958. This date was selected because it was indicated by dozen of questionnaires. The reason therefore was the construction of the country road. The first stage of the gully erosion is compared to the stage nowadays with a development of gullies of nearly 60 years (2017). The soil loss of the area with and without gully erosion is computed with the Universal Soil Loss Equation (USLE). In order to compute the connectivity of the watershed the connectivity index of Cavalli is used (Cavalli, Trevisani, Comiti, & Marchi, 2013). In the end the sediment delivery ratio (SDR) is computed with the Maner method (Maner, 1958). First of all the data needed for the research is presented with the corresponding data collection method used.

3.1 Data available

The detailed data of three of the largest gullies surveyed is available for the research at the moment. A digital elevation model (DEM) of each site represents the topography with a resolution of 4x4 cm^2. In the Data collection section the approach of the measurements is elaborated. The data of the fourth gully erosion site is not available, so that area will be measured during the research. The area is located a couple of kilometres east from the city Madalena.

Apart from the topography of the study area other input parameters are needed. The amount of rainfall, interception, evaporation, infiltration, surface and subsurface runoff, transpiration and groundwater recharge are available from the first year the gully erosion occurred (1958) till 2013 for the whole Madalena catchment area. Also samples of the soil layers are available till a depth of 0.6 m, so the grain size of the soil could be determined.

During the research it became clear that the measured topography by UAV of one of the gully erosion areas is not suitable for the research, because there is too much vegetation present in the area. Removing all this vegetation will result in a topography raster with high uncertainties in the elevation. For that reason this data is not used in the research.

Gully erosion sites

The locations of the two gully sites are displayed in Figure 6 and Figure 7. The black lines indicate the gullies occurred in the last 60 years.

Figure 6: Gully erosion site 1

Figure 7: Gully erosion site 2

Precipitation

The data of the located weather station in Madalena, nearby the gully erosion sites, is used as the precipitation of the sites (Figure 8).

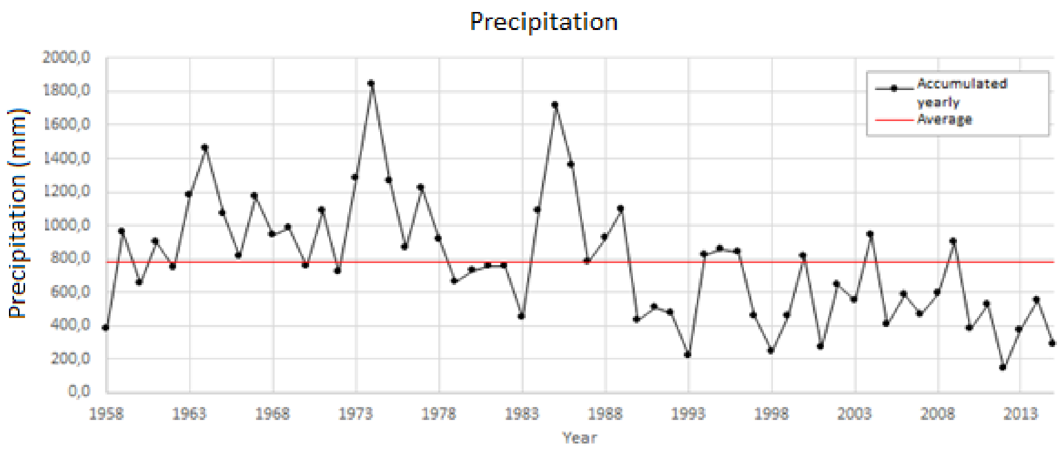

Figure 8: Precipitation 1958-2013 Madalena

Soil classification

Soil samples are available of the two sites, so the composition of the present soil could be determined. The soil samples are taken from three different depths of 10, 30 and 50 cm respectively representing the layers 0-20,20-40 and 40-60 cm. Table 1 shows the compositions of the layers based on the grain size with the average percentage of each soil type.

Table 1:Soil classification soil samples

USDA soil classification	Site 1- 10 cm	Site 1- 30 cm	Site 1- 50 cm	Site 1 average	Site S2- 10 cm	Site S2- 30 cm	Site S2- 50 cm	Site 2 average
>4,8 mm (gravel)	9%	3%	2%	5%	13%	5%	1%	6%
4,8 - 2 mm (fine gravel)	5%	3%	2%	3%	3%	3%	1%	2%
2 - 0,42 mm (coarse sand)	15%	19%	22%	19%	12%	13%	15%	13%
0,42 - 0,074 mm (medium sand)	35%	32%	46%	37%	26%	19%	27%	24%
0,074 - 0,005 mm (fine sand)	25%	23%	21%	23%	26%	19%	26%	24%
<0,005 mm (silt, clay)	12%	20%	7%	13%	19%	42%	29%	30%

3.2 Data collection

The following tools are used to obtain the needed data:

UAV (Unmanned Aerial Vehicle)

The resolution of the satellite imagery is not good enough to map the ephemeral gullies in detail. Therefore an UAV will be used to obtain the dimensions of the gullies in more detail.

The Inspire 1 equipped with a ZENMUSE X5 camera (16 MP resolution and a field of view of 94 degrees), created by DJI Innovations, functioned as UAV (Dji, 2017) (Figure 9). The vision positioning system identifies the position by making use of sonars and image data obtained with the camera combined with the GPS information. A stabilization mechanism prevents big distortions during flight in the measurements.

Figure 9: The Inspire 1 UAV

The flight settings (speed, height and path) are set with the software Litchi, so the UAV can fly autonomously. A frontal overlap of 80% and a side overlap of 60% between the images is used with a height of 30 meters. This is sufficient overlap to get accurate results (Pix4D, 2017).

Four ground control points for each gully site are used to georeference the images obtained during the flight. The coordinates are obtained with a Trimble R4 GNSS System (Trimble, 2017).

In the end the digital elevation model (DEM) could be derived from the images and the coordinates with a density ranging from 520 to 600 pixels per square meter.

On-site surveys

The main aim of the on-site surveys is to validate the UAV images and get a clear view of the concerned area. The bathymetry (width and depth of the gullies), grain size of the sediment and the slope of the gullies are the most important factors to be measured/determined. Furthermore an indication of the type of land use and vegetation cover is useful to solve the Universal Soil Loss Equation. The equipment needed for the on-site survey basically consists of the total station. This tool is an electronic theodolite combined with an electronic distance measurement and an on-board computer collecting the topographic data needed.

3.3 Modelling process DEM

The DEM of year 2016 is available for the three gully erosion sites and would be obtained for the fourth one. The DEM of 1958 (the reference of the area without gullies) is not available so the current DEM should be adjust to reconstruct the surface area. Assumed is that the only difference between the DEM´s is the occurrence of the gullies.

3.3.1 Reconstruction of the DEM without gullies

In order to obtain the DEM without gullies the cross sections of the gullies should be eliminated by filling them. The elevation of the points in the cross section should be raised to the surface level of roughly 60 years ago (the reference of the area without gullies). Assumed is that the surface near the gully has kept the same shape/elevation and only the occurred gullies have changed the surface. To fill the gully in a most natural way a cubic spline is constructed to obtain a smooth flow from the boundaries of the cross section. This spline method does not have big fluctuations in the curve like other spline methods. Two reference points near each side of the cross section are pointed out and used to fit a function through. Following Bartels et al. (1998) the ith part of the spline is represented by the following function:

$Y_i(t) = a_i + b_1 t + c_i t^2 + d_i t^3$ (Equation 1)

(Bartels, Beatty, & Barsky, 1998)

The cubic splines produce an interpolated function which is continuous through the second derivative. Splines are suitable to obtain a function without big amplitudes and a smooth line.

In this way the surface area is reconstructed as it most likely was before the occurrence of the gullies (Figure 10). Appendix C: Reconstruction surface without gullies shows a cross section obtained by making use of the cubic spline.

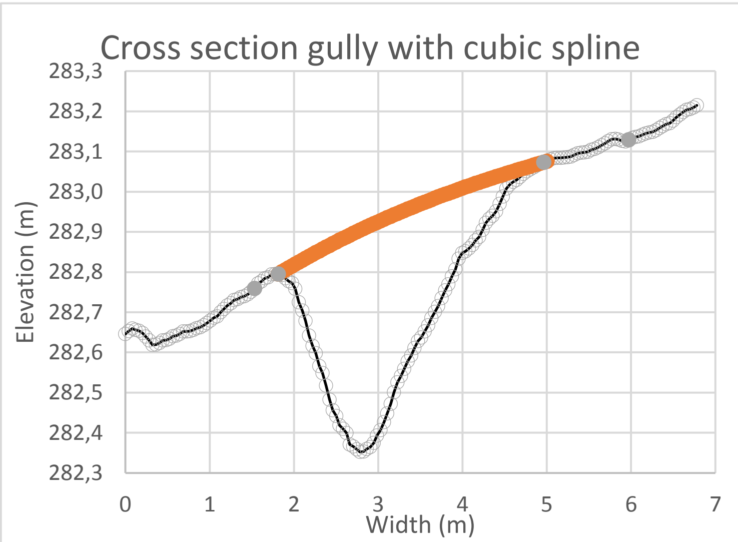

Figure 10: Cross section gully with cubic spline

3.3.2 Remove vegetation cover

The obtained DEM from drone survey contains small vegetation covers within the watershed. The vegetation disturbs the elevation measured by the drone resulting in unrealistic values of the surface elevation which affect the hydrological characteristics of the area. So at some places in the watershed the vegetation needs to be eliminated to obtain an approximation of the surface elevation.

First of all the big areas of vegetation are surrounded by a couple of points containing the xyz coordinates of the DEM. These are the reference points used to fit a spline through to create a surface to replace the elevation data of the DEM. Afterwards the smooth surface is replaced by a rough surface. In the end the new surface is added to the DEM and replace the lower elevation points (Appendix D: Remove vegetation cover ArcGIS).

3.4 Universal Soil Loss Equation (USLE)

The soil loss with and without the gullies is computed by making use of the Universal Soil Loss Equation. All input parameters of this methodology could be computed with the available data which makes this method suitable for this research. The main goal for this assessment is to see the difference between the soil loss with and without gullies in the area.

The Universal Soil Loss Equation includes the influence of the rainfall erosivity, the soil erodibility, the topography, the land use and the land slope to compute the soil loss per unit area. The rainfall erosivity factor R is based on the erosive force of rainfall (MJ mm/ha/h per year). Raindrops splash soil a couple of feet away, but stay in the field. However they will obstruct the surface pores reducing the water infiltration. This will increase water runoff and a higher rate of soil erosion because less water is absorbed into the soil (Helmers & Al-Kaisi, 2008). The soil erodibility factor K is based on the soil granulometry and distinguishes different soil erosion rates for different types of soil considering constant conditions (Stewart, Woolhiser, Wischmeier, Caro, & Frere, 1975). The topographic factors are subdivided in the slope length L and the slope S. Bigger slopes will produce a higher runoff velocity which will increase the soil erosion. As mentioned before the land use also plays an important role in gully erosion. The cropping management factor C includes the type of land use and the factor P includes the slope of the land. These factors multiplied will result in the soil loss per unit area (Figure 11):

$$A = R\,K\,L\,S\,C\,P$$

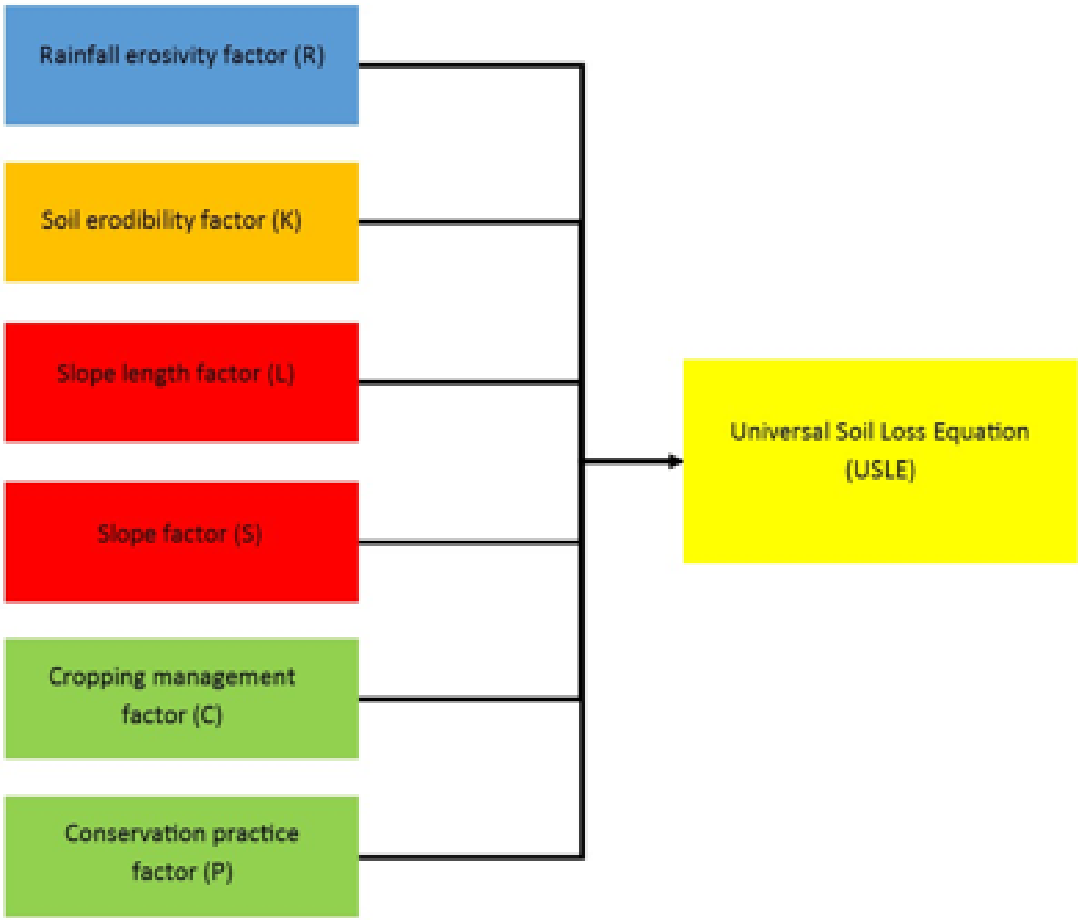

Figure 11: USLE

The factors mentioned above are described in more detail in the following section:

3.4.1 Erosivity factor (R)

The erosivity factor includes the effects of the rainfall events on the soil erosion. A linear relation between the storm energy times the rainfall intensify (EI) is found to compute the R- factor (Wischmeier & Smith, 1978).

$$R_j = \sum_1^{12} (E_c I_{30})_j \text{ (Equation 2)}$$

$$E_c = 12{,}14 + 8{,}88 \log I_m \text{ (Equation 3)}$$

I_{30}= the maximum intensity in 30 minutes (mm/h)

E_c= Energy of the rainfall (MJ/ha)

I_m= the average rainfall intensity (mm/h)

An intensive rainfall event with the same energy of a rainfall event less intensive will do more harm to the soil and will increase the soil erosion. However the data concerning the duration of a rainfall event is not available, so another approach is used to compute the erosivity factor. The erosivity factor could also be computed based on the monthly precipitation and the overall average with the following formula's (Bertoni & Neto, 1990):

$$R_j = 67{,}355 * \frac{P_m^2}{P_a}^{0{,}85} \text{ (Equation 4)}$$

$$R = \sum_1^{12} R_j \text{ (Equation 5)}$$

P_m=the monthly precipitation (mm)

P_a=the average precipitation of all years (mm)

The equations from Bertoni & Neto (1990) are applied for seven basins in the state Ceará obtaining very accurate results (de Araújo, Fernandes, Júnior, Oliveira, & Sousa, 2003).

3.4.2 Erodibility factor (K)

The soil composition of the surface layer affects the erosion rate of the area. Samples of the soils are taken to determine the composition of the soil. According to the United States Department of Agriculture (USDA) the soil is characterized by three different kind of soil types. Sand, silt and clay are distinguished from the soil sample (United States Department of Agriculture, 2017). The amount of organic matter is also determined as this might be of importance to determine the K-factor based on the composition of the soil.

Wischmeier and Smith presented a table of roughly twenty different soil compositions with the corresponding K-values. However it hard to just pick one K-value to use based on the soil types which represent the soil composition the best (Wischmeier & Smith, 1965).

Williams presents equations to compute the K-value only based on the percentages of soil types and the organic carbon present in the sample without taking the soil structure index and the permeability factor into account (Williams, 1995). This method is used to compute the K-factor due to a lack of information about the structure and the permeability and in the end the values are validated with the values from the tables of Wischmeier and Smith.

The organic carbon percentage is not known, but could be determined based on the amount of organic matter. The percentage of organic carbon of the organic matter is assumed to be 58% (Bianchi, Miyazawa, Oliveira, & Pavan, 2008).

3.4.3 Slope (S) and 3.4.4 slope length (L)

The slope is computed from the DEM of the gully erosion sites. The cell size is very small (4×4 cm^2) resulting in high slope percentages, because the surface area is not smooth. Disturbances of small soil bulks cause an unreliable percentage of the slope parameter. To avoid an overestimating of the slope and the sediment delivery ratio, the slope of a bigger area is computed (cell size of 1×1 m^2). In this way the small disturbances of the roughness of the surface do not affect the slope calculation.

The slope length could be computed by making use of the flow accumulation tool in ArcGIS and the slope. In advance the flow direction raster should be modelled in order to obtain the flow accumulation raster. The flow accumulation raster displays the amount of flows from cells into each downslope cell. The high flow accumulation cells are probably stream channels because the concentration of flows is high.

The LS factor could be calculated in ArcGIS according to the following formula:

*Power (flowacc * cell resolution / 22.1, 0.4) * Power (Sin (slope * 0.01745) / 0.09, 1.4) * 1.4*

(Equation 6)

(Pelton, Frazier, & Pickilingis, 2016)

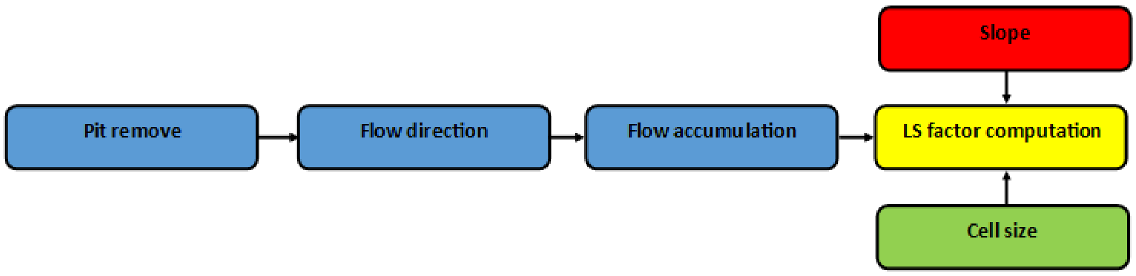

Figure 12: Slope and slope length computation (LS)

Pit remove, flow direction and flow accumulation

Pits are areas with a lower elevation level than the surrounding terrains. The pits will interfere with the water flow across the DEM. The elevation of the pits is increased to the same level of the surrounding terrain so the water could drain away. The flow direction of the water is based on the steepest descent of each grid cell. The flow accumulation represents the amount of flows from cells into each downslope cell based on the flow direction (Figure 13).

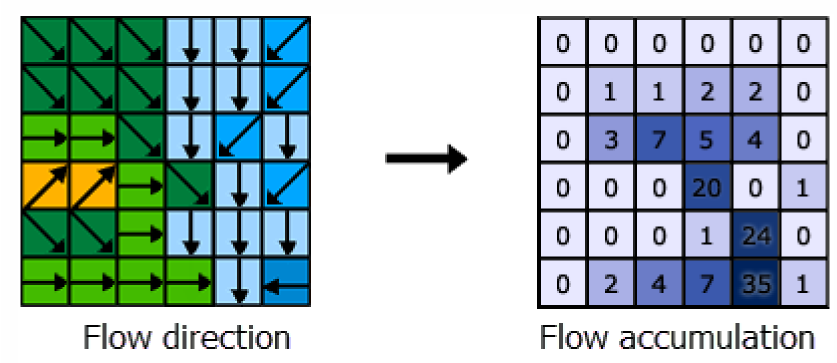

Figure 13: Flow direction to flow accumulation

3.4.5 Cropping factor (C)

The vegetation cover of the area could vary over the year. On the DEM there is no vegetation cover except for some small areas with a tree. However in the rain season plenty of water is available to provide plants to grow.

The C factor is 1 in case of no vegetation and could range to 0.01 for soil which has a high protection rate against erosion.

3.4.6 Conservation practice factor (P)

The P factor represents the effects of practices of the land on the amount of erosion. Displayed in Table 2 below are some common P values for each kind of support practice.

Table 2: Support practice factor (Stone, 2015)

Support Practice	P Factor
Up & down slope	1.0
Cross slope	0.75
Contour farming	0.50
Strip cropping, cross slope	0.37
Strip cropping, contour	0.25

3.5 Connectivity index (IC)

The connectivity is used to describe the internal linkages between runoff and storage of sediment in the upper part of watersheds (Croke, Mockler, Fogarty, & Takken, 2005). In order to compute the connectivity, a connectivity index is set to compute the connectivity for each cell so a comparison could be made in the end. A value for each cell is computed in a certain range and in the end the cells with the highest value will indicate the highest connectivity and the cells with the lowest values will indicate the lowest connectivity in the watershed.

The connectivity index is computed based on the methodology of Cavalli. This method is mainly chosen because this approach does not include the vegetation cover in the computation of the connectivity index but the roughness of the surface area. In contradiction to Borselli who includes the vegetation cover in the computation the approach of Cavalli is more suitable as the gully erosion site almost have no vegetation cover.

So the connectivity index method of Cavalli is used which is a revised method of Borselli (Cavalli, Trevisani, Comiti, & Marchi, 2013) (Borselli, Cassi, & Torri, 2008). First of all the method of Borselli is described below:

The connectivity index takes a couple of parameters into account which influence the drainage. the vegetation cover or roughness of the area

The connectivity index (IC) is computed with the following equations:

$IC = \log_{10}\frac{D_{up}}{D_{dn}}$ (Equation 7)

The upslope component (D_{up}) and downslope component (D_{dn}) are defined as (Figure 14):

$D_{up} = \overline{W}S\sqrt{A}$ (Equation 8)

$\overline{W}$ Is the weighting factor containing the vegetation cover and the land use. This factor could also be based on the Manning coefficient or on the roughness index depending on the land type.

S Is the average slope gradient in $\frac{m}{m}$

A Is the upslope area in m

$D_{dn} = \sum_i \frac{d_i}{W_i S_i}$ (Equation 9)

d_i Is the length of the flow path along the i^{th} cell according to the steepest downslope direction (m)

W_i Weighting factor of the i^{th} cell

S_i Slope gradient of the i^{th} cell in $\frac{m}{m}$

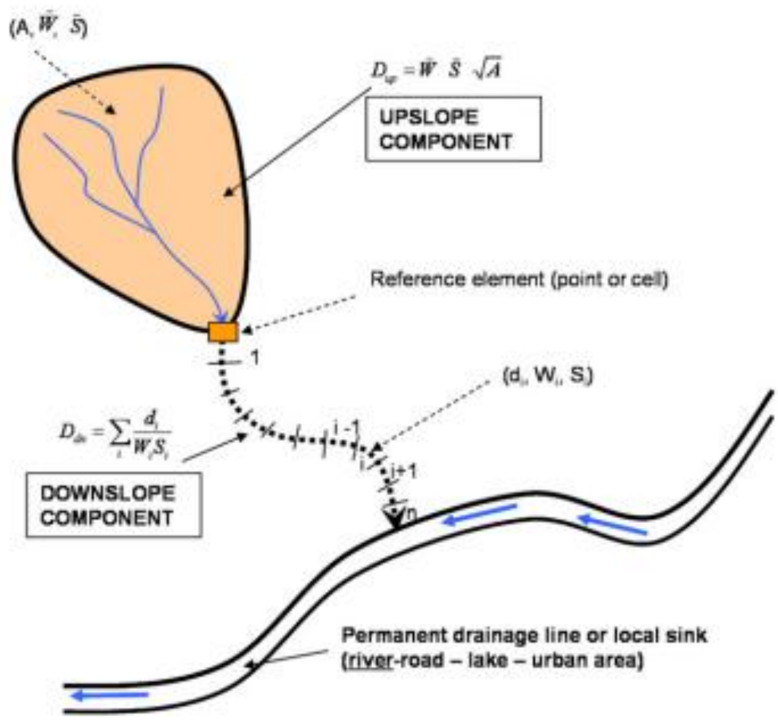

Figure 14: Connectivity index parameters

The input to compute the connectivity are the topography and the weight factor. The hydrological characteristics of the area like the flow direction, flow accumulation and contribution areas are obtained with the TAUdem toolbox. The steps taken to compute the connectivity index are displayed in Appendix E: flow chart connectivity index.

The DEM of the sites is used as an input with the removed vegetation and the filled gullies. The pits should be removed to avoid disturbances in the water flow.

Roughness index

The roughness index according to Cavalli is the standard deviation of the average DEM (smoothed version) and the DEM, calculated by the formula below.

$$RI = \sqrt{\frac{\sum_{i=1}^{25}(x_i - x_m)^2}{25}} \quad \text{(Equation 10)}$$

The weighting factor is derived from the RI with the following formula:

$$W = 1 - \left(\frac{RI}{RI_{MAX}}\right) \quad \text{(Equation 11)}$$

The range of the weighting factor reach from nearly zero to 1. To avoid that the weighting factor approaches zero the minimum value is set to 0.001. According to Cavalli the weighting factor raster is linearly scaled with the roughness index. However the roughness index contains some high values due to the small vegetation which is not eliminated from the maps. A linear scaled weighting factor including the full range of values of the roughness index will result in extremely high and extremely low values. The high values are set to 0,006 to avoid this. The average roughness is namely around 0,0025.

3.6 Sediment Delivery Ratio

The sediment delivery ratio could be computed by making use of the Maner equation (Maner, 1958):

$$Log(SDR\%) = 2{,}943 - 0{,}824. Log(L_m/F_r) \text{ (Equation 12)}$$

L_m is the maximum length of the watershed, in a straight line, measured parallel to the main stream drainage in meters.

F_r is the relief of the watershed, defined as the difference in elevation between the average elevation of the watershed divide and the outlet.

The Maner equation fits the sediment yield the best, validated for seven watersheds in Brazilian semiarid environment compared to Roehl and Williams and Berndt´s methods (de Araújo, 2003).

3.7 Forest Service Model

In contrast to the method of Maner the Forest Service Model takes the topography of the watershed into account. This method is designed to evaluate the change in the SDR after a forest fire or another natural disaster which influences the appearance of the watershed (Haan, Barfield, & Hayes, 1994). The covered area of the stiff diagram functions as the input for the x-value of the graph. The corresponding y-value determines the sediment delivery ratio (Figure 15) (Figure 16). Most likely the parameters ´ground cover´, ´surface roughness´, ´slope gradient´ and ´slope shape´ will change in case of such a disaster. The occurrence of a gully in the watershed will influence the ´surface roughness´, ´slope gradient´ and ´slope shape´. Possible changes of the parameters would be: the surface roughness gets lower because a smooth path for the water is created. The slope gradient will also increase when the gullies grow, because the gullies will become deeper with bigger slopes. The slope shape will become more concave resulting in a higher slope shape. All this factors combined will result in a larger area of the stiff diagram. Each point of each parameter combined will result in an inner area. The percentage of the inner area out of the total stiff diagram is used to determine the sediment delivery ratio. For instance, an inner area of 50% will result in a sediment delivery ratio of 0.5=50%.

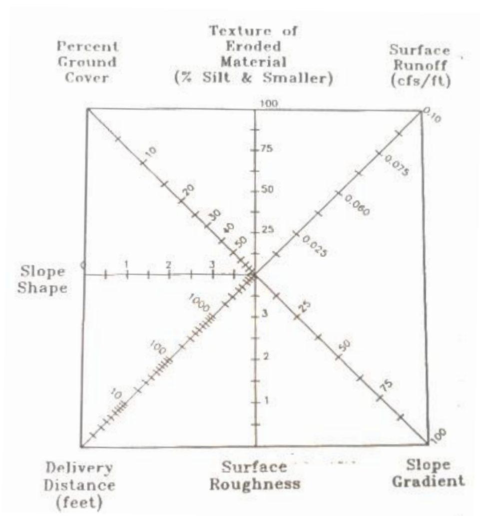

Figure 15:Stiff diagram Forest Service model

Figure 16: Sediment Delivery Index

4. Results

The outcomes of the research are computed by following the methodologies of the soil loss, the connectivity index and the SDR. The derived research questions will be answered in the Conclusion sector.

4.1 Soil loss computation USLE

4.1.1 Erosivity factor (R)

The rainfall data from 1958 until 2015 is used to compute the rainfall erosivity factor of each year, displayed in Figure 17 with an average of 6552. The average is used as the input in the USLE.

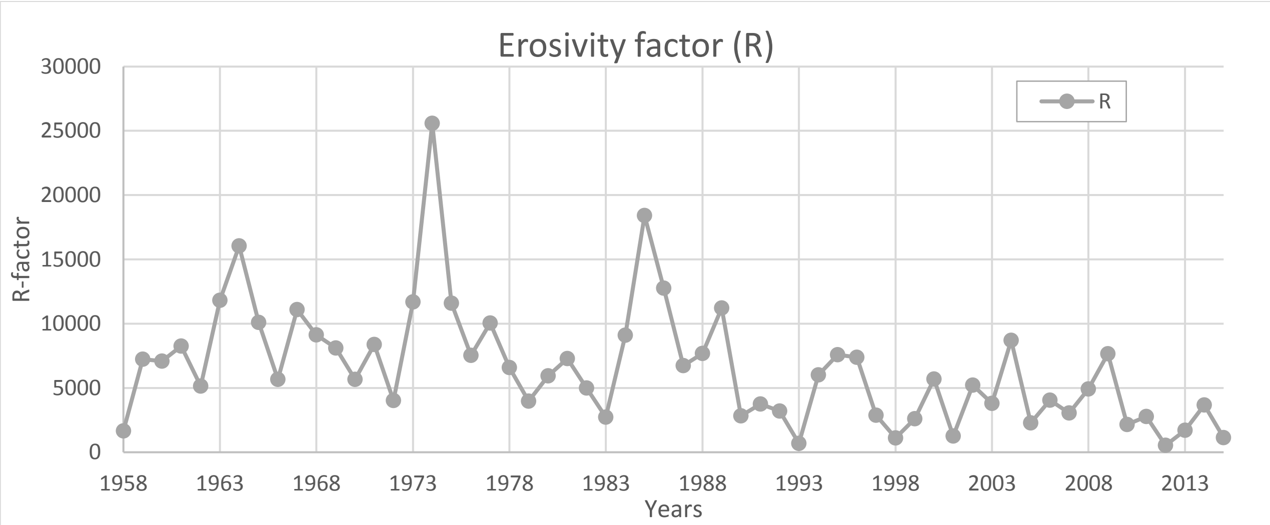

Figure 17: Erosivity factor 1958-2013

4.1.2 Erodibility factor (K)

The K-factor for the two gully erosion sites are computed by making use of the equations presented by Williams (Appendix A: Computation K-factor). The results of the K factor are displayed in Table 3.

Table 3: K-factor

	K-factor
Gully erosion site 1	0.1431
Gully erosion site 2	0.1263

4.1.3 Slope (S) and 4.1.4 slope length (L)

The slope is computed from the DEM of the gully erosion sites with the presented Equation (6). Small errors in the outcomes are avoided by setting a limitation based on the maximum possible slope and slope length (Appendix B: Computation slope (S) and slope length (L)).

4.2 Soil loss maps

The soil loss maps of the two sites computed with the Universal Soil Loss Equation are presented below. Multiplying all parameters with each other will result in the soil loss in tons/ha/year.

4.2.1 Site 1

The average soil loss of the whole area is 761 tons/ha/year with the gullies and 744 tons/ha/year without the gullies (Figure 18)(Figure 19). That is not a significant difference, probably only induced by the gully erosion area itself (Figure 20). This is because the LS factor of this gully erosion area decreased due to the change in the bathymetry of the gully. The slopes of the edges of the gullies highly increase the LS factor and when the surface become more flat this factor decrease. More interesting is the difference in soil loss of the small area instead of the whole catchment area. A polygon is drawn over the area were the gullies occurred. In Figure 21 the two graphs of the cumulative area of the amount of soil loss is visible. It is clear that there is a significant difference in soil loss between the gully erosion site and the site without erosion. A shift between a high soil loss to a minimum soil loss is visible. The average soil loss of the gully erosion site is 1076 tons/ha/year and without gullies is 708 tons/ha/year. That is a decline of 34,2 %.

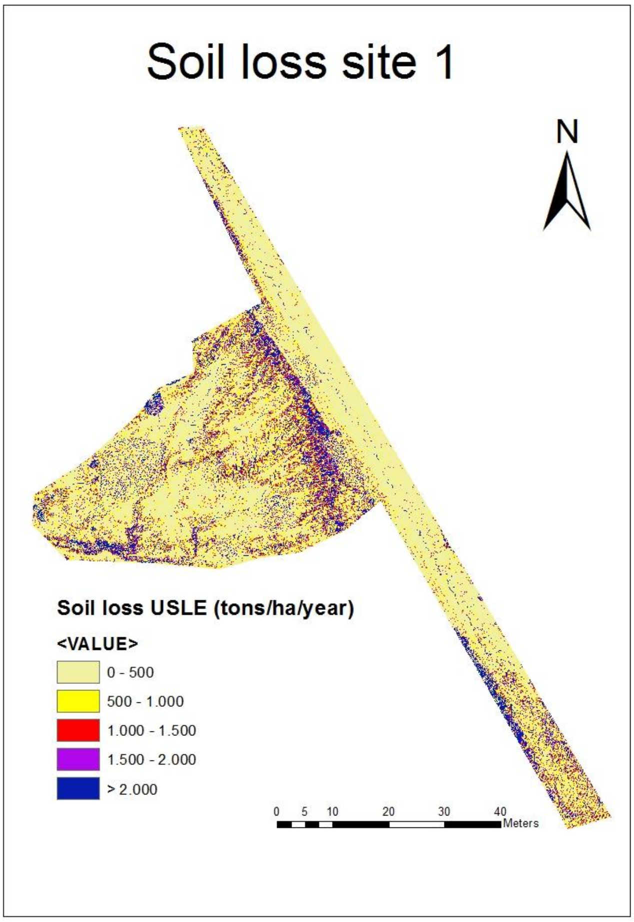

Figure 18: Soil loss site 1 gully

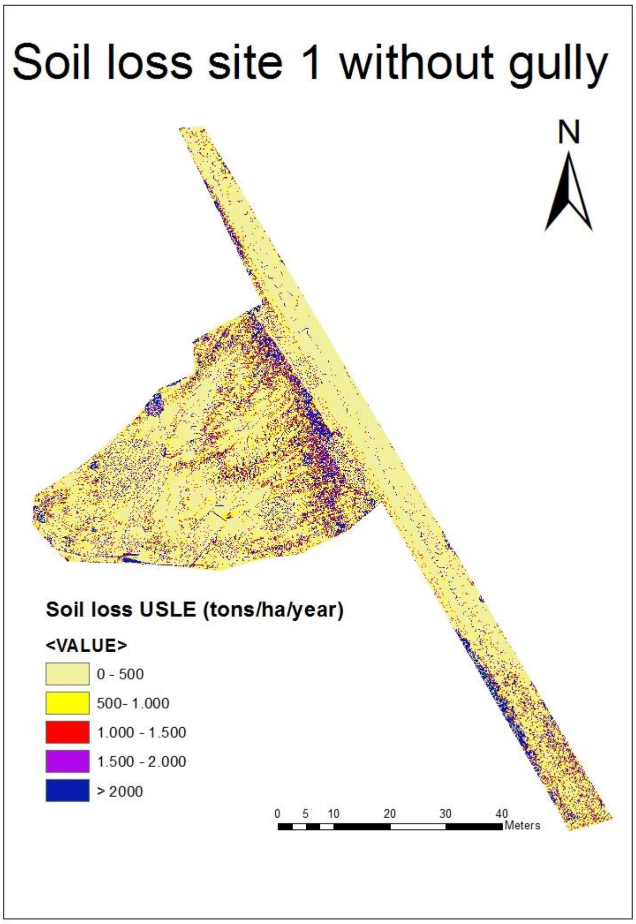

Figure 19: Soil loss site 1 without gully

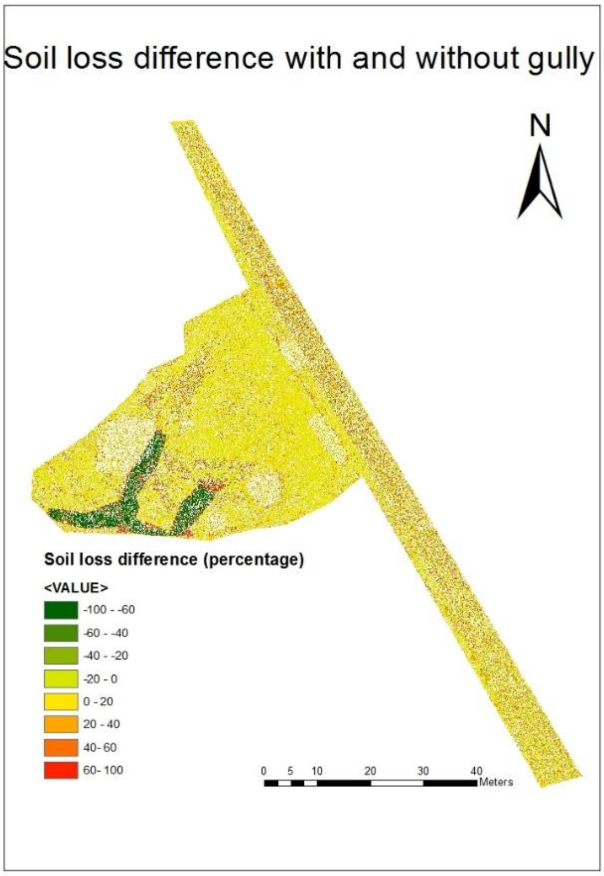

Figure 20: Soil loss difference with and without gully

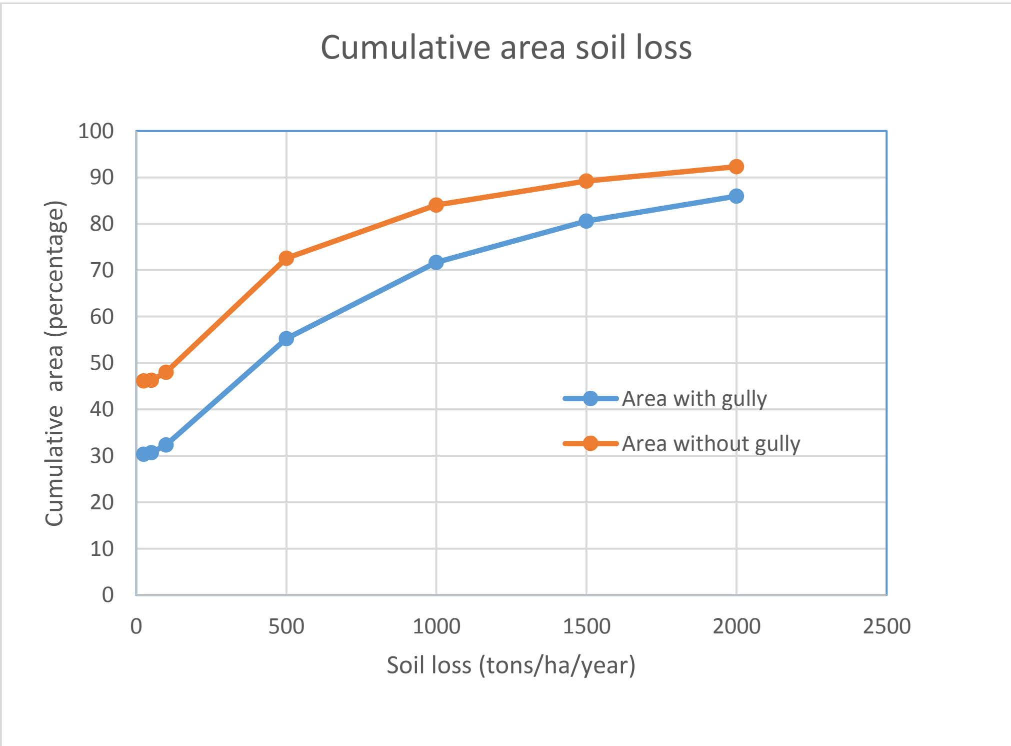

Figure 21: Cumulative area soil loss

4.2.2 Site 2

The average soil loss of the whole area is 454 tons/ha/year with the gullies and 448 tons/ha/year without the gullies (Figure 22)(Figure 23). The average soil loss of the gully erosion site is 1356 tons/ha/year and without gullies is 910 tons/ha/year (Figure 25). That is a decline of 32,9 %. Furthermore the same characteristics are visible in the area as site 1. The gully erosion area changed a lot, but the other part of the area almost stays the same (Figure 24). The main explanation therefore is that the slope does not change of this part of the area. Only the flow accumulation might change due to the elimination of the gullies. All other parameters stay the same.

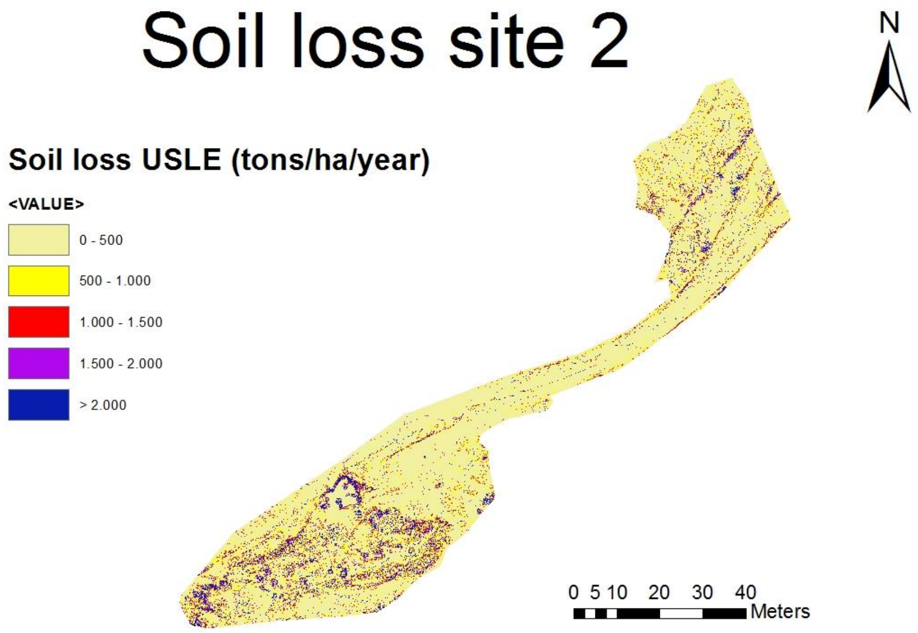

Figure 22: Soil loss site 2 gully

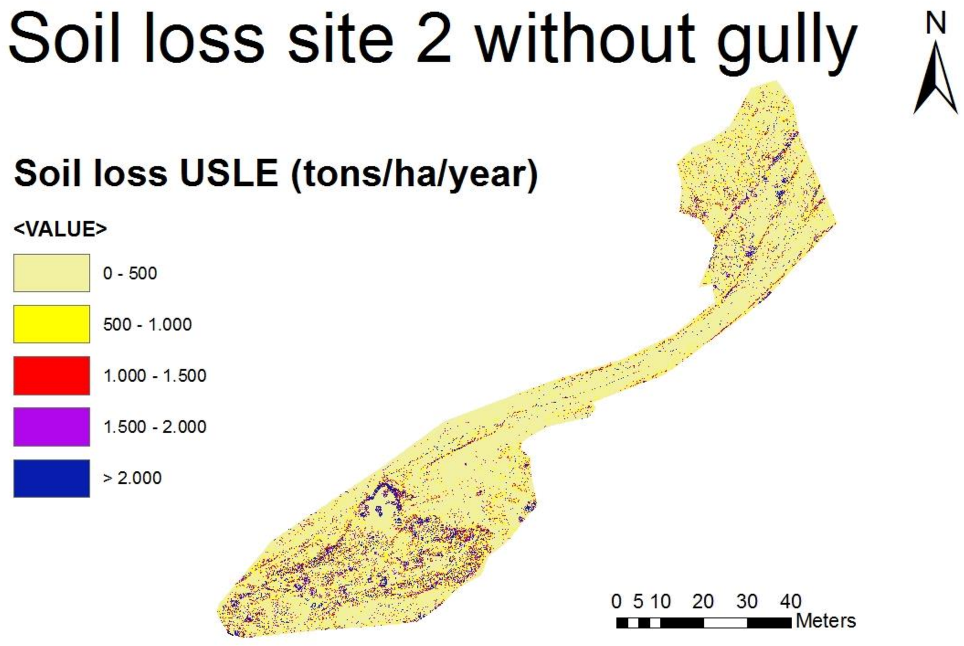

Figure 23: Soil loss site 2 without gully

Figure 24: Soil loss difference

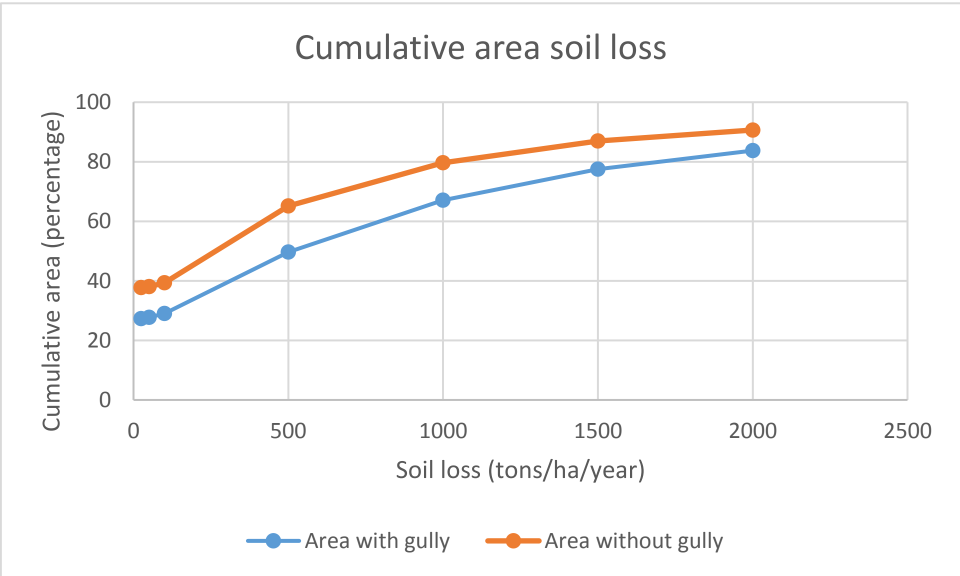

Figure 25: Cumulative area soil loss site 2

Comparison site 1 and site 2

The average soil loss of site 1 is much higher than the soil loss of site 2. The main reason probably is the average slope of the watersheds. Site 2 has some areas with a very small slope, while site 1 has a big slope in the areas with the gullies. This high soil loss area is partly compensated by the flat road but still plays a big role in the high amount of soil loss.

4.3 Connectivity index

Connectivity index maps

In this paragraph the output maps of the connectivity index are shown. The sites with and without the gully erosion are compared and areas with big changes in connectivity are highlighted. A scale ranging from minus 12 till 0.5 represents the level of connectivity. The connectivity is the highest at 0.5 and the lowest at -12(Figure 26). It is not possible to quantify the values because it is an index. However the maps with and without gullies could be compared based on the differences in colors. A visual evaluation of the maps is performed to point out the differences.

4.3.1 Site 1

First of all a quick analyse of the whole catchment area is conducted to see the main differences of the color maps. The connectivity map with the gully erosion is characterized mainly with a red color in the middle and some pink areas (Figure 26). Furthermore on the borders of the catchment area there are some orange parts . A high disconnectivity is visible in the bottom right (area with coordinates (no specific scale) in the range of [2000-2500;2500-3000]) with a big green area. The main reason of the disconnectivity is the big length of the flow lines towards the sink of the area which is located in the bottom left.

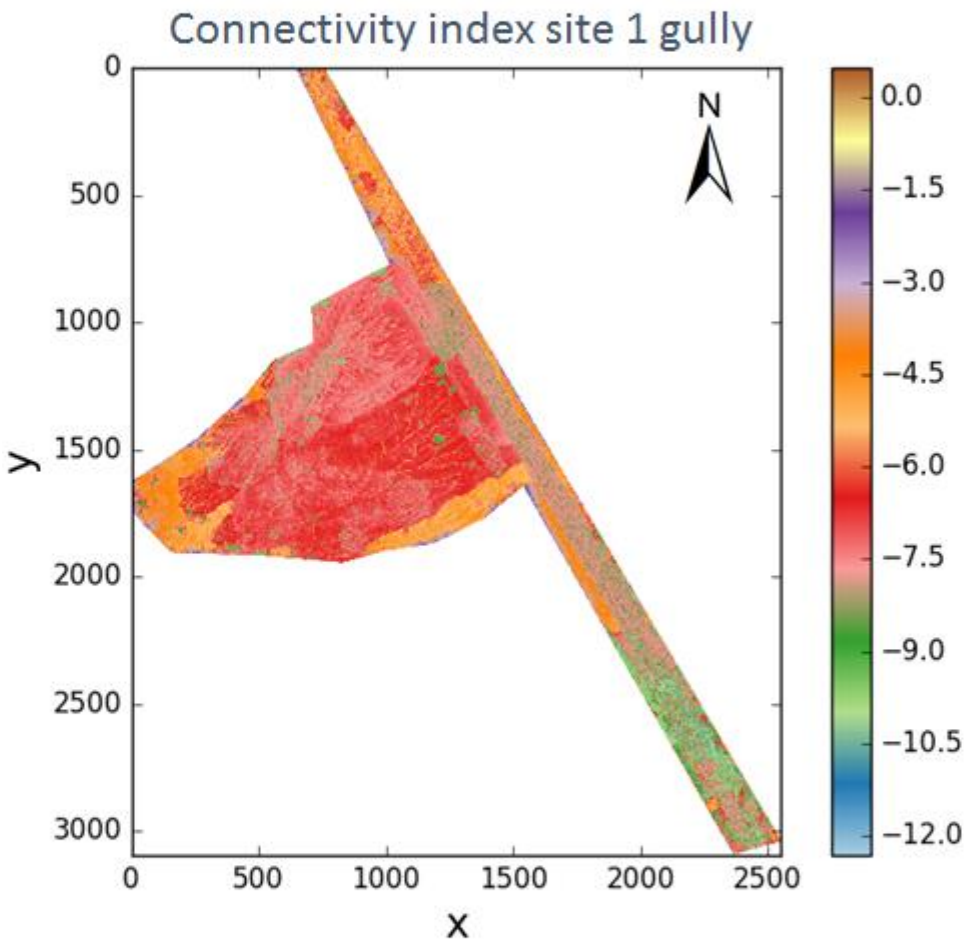

Figure 26: Connectivity index site 1 gully

The main differences in the global image of the connectivity index is the predominant pink color in the middle of the map (Figure 27). This point out a lower connectivity compared to the map with the gully erosion (connectivity index is around -7 for pink areas and -6 for red areas). Besides the increased pink area a part of the orange area in the bottom left part of the map (coordinates [100-300;1700-1900]) turned red/pink. This is the area with the biggest gully. Meaning that the connectivity without the gullies became worse.

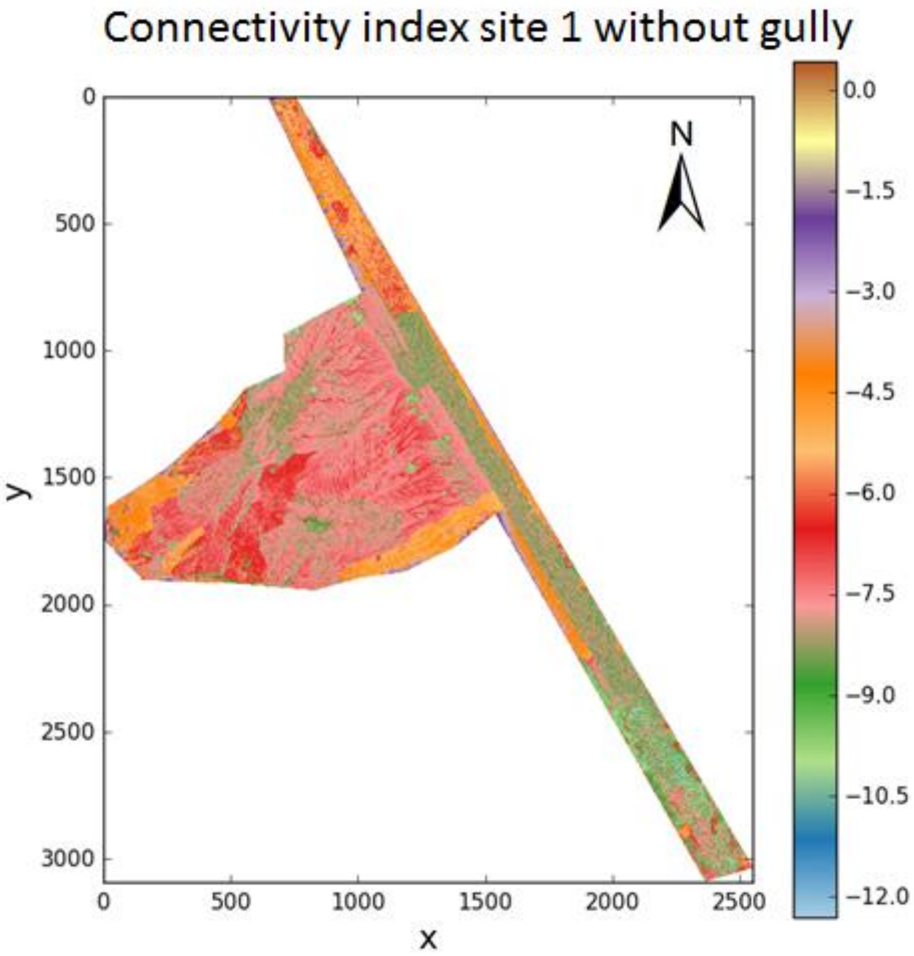

Figure 27: Connectivity index site 1 without gully

Looking at a more detailed level reveals the small streamlines displayed with a different color than the other part of the area (Figure 26) (Figure 27). This points out that the connectivity is higher when the sediment is located near/in the streamlines which is logical because the water flow is higher than in the other part of the area. A very interesting area is highlighted in the upper part of the catchment area. No adjustments are made in this area itself relating the gullies. However a clear difference in color of the streamlines is visible. The orange color of the streamlines with the gullies changed in a red color when the gullies are eliminated. Meaning the connectivity gets lower. This implies that the elimination of the gullies in the down part of the area affects the connectivity of the upward part of the catchment area and not only the area where the gullies occur.

4.3.2 Site 2

Looking at the second area comparable differences are visible in the connectivity index maps. A red/pink color characterize the area with gully erosion while the area without gully erosion is characterized by pink/green colors (Figure 29) (Figure 29). Also meaning the connectivity with gully erosion is higher than the connectivity without gully erosion. The upper right part without gully erosion mainly shows a green area with some pink parts while the map with gully erosion is mainly pink in that area. Meaning that the removed gullies in the area [0,500;0,2500] affect the connectivity all the way till the upper part of the watershed (Figure 30) (Figure 31). The gullies increase the connectivity in the area where they are removed and in the upstream parts of the watershed.

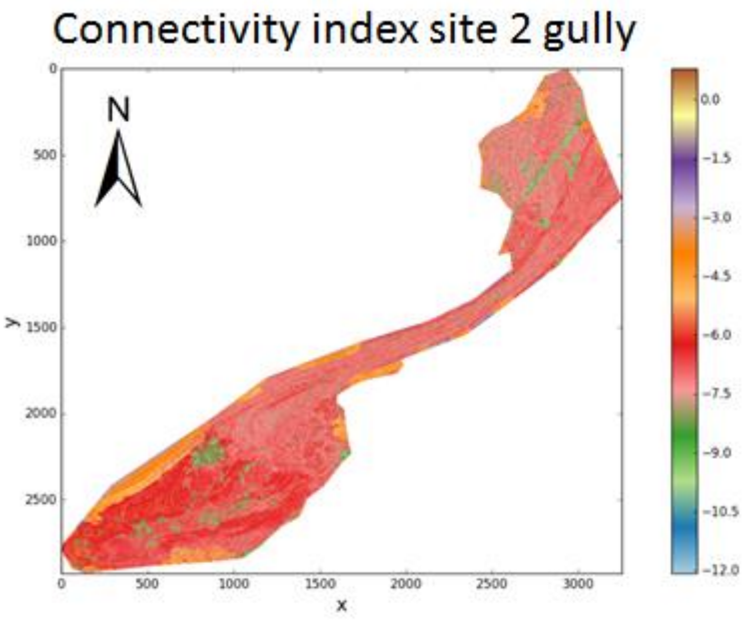

Figure 29: Connectivity index site 2 gully

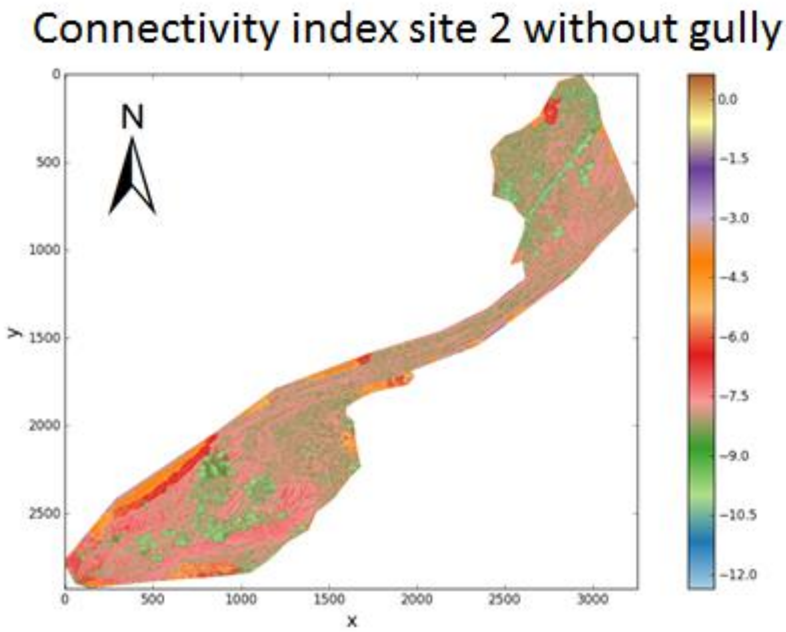

Figure 28: Connectivity index site 2 without gully

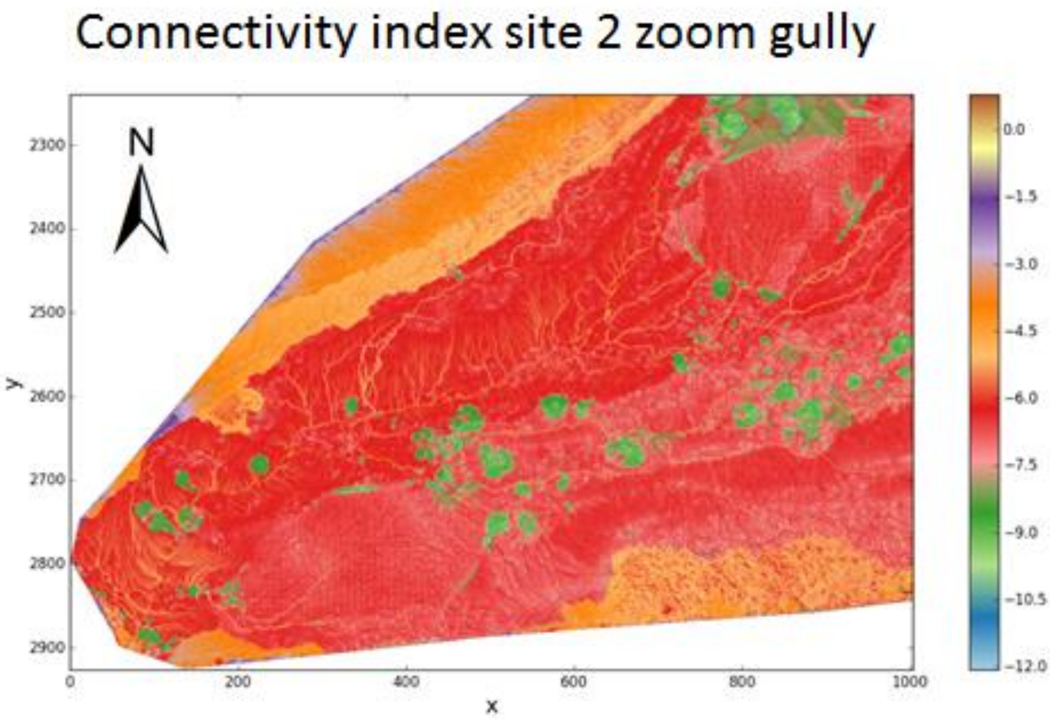

Figure 30: Connectivity index site 2 zoom gully

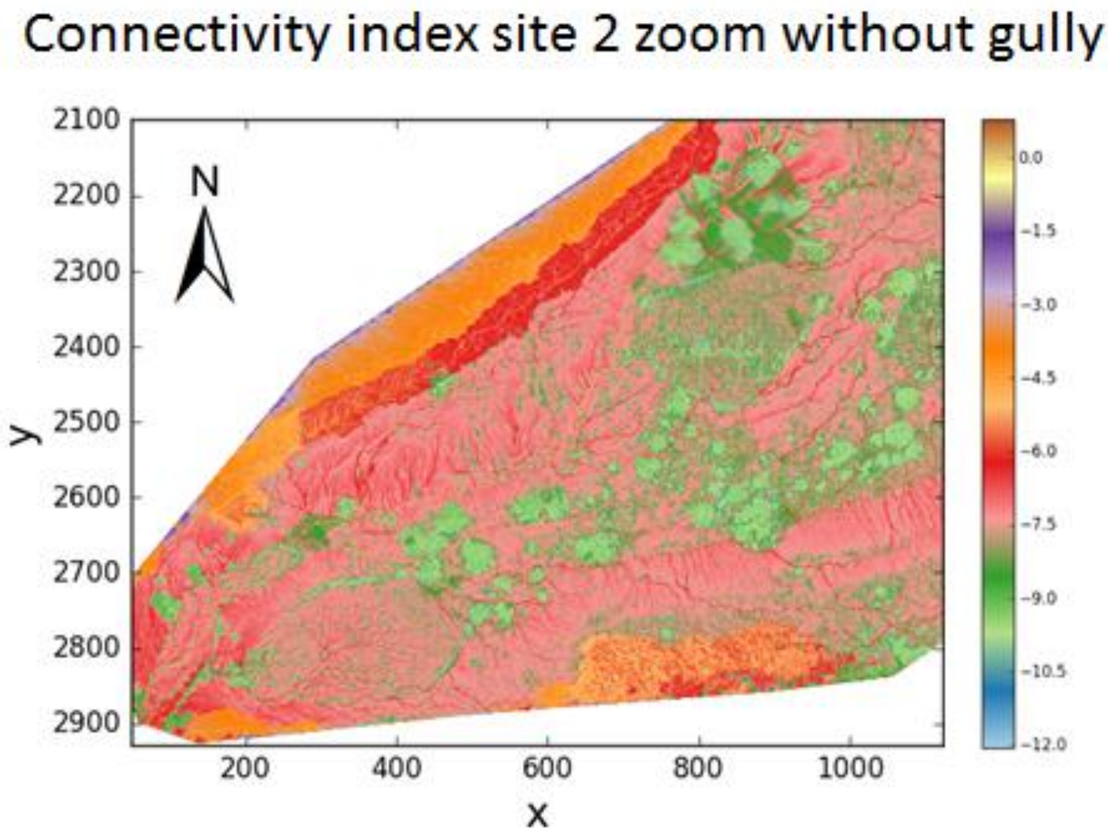

Figure 31: Connectivity index site 2 zoom without gully

4.4 Sediment delivery ratio

4.4.1 Site 1

The average elevation of the watershed is 286,6 m and the elevation of the outlet is 282,3 m. So the relief of the watershed would be the difference between each other. The other parameter is more difficult to determine because the largest gully has to be chosen in order to appoint a straight line parallel to this gully. The length of the red line constructed in Figure 32 is the maximum length of the watershed according to Maner.

Figure 32: Constructing maximum length of watershed 1

Equation 13 shows a SDR% of 100% because the inverse log of 2 is 100.

$$Log(SDR\%) = 2{,}943 - 0{,}824.Log\left(\frac{60}{4{,}3}\right) = 2{,}00$$

(Equation 13)

4.4.2 Site 2

The average elevation of the watershed is 271,1 m and the elevation of the outlet is 266,0 m. The red line is constructed parallel to the gullies and extrapolate over the whole watershed and has a length of 165 m (Figure 33). Equation 14 shows a SDR% of 50% because the inverse log of 1,7 is 50.

$$Log(SDR\%) = 2{,}943 - 0{,}824.Log\left(\frac{165}{5{,}1}\right) = 1{,}7 \text{ (Equation 14)}$$

Figure 33: Constructing maximum length of watershed 2

A significant difference in SDR is visible between the two watersheds. This mainly is the result of the method used to compute the length of the watershed, which in this case takes the largest area into account for the second watershed. This however is not the case for the first watershed.

5. Discussion

In this research a lot of assumptions are made and there are a lot of uncertainties. In the first part of the discussion these assumptions and uncertainties are evaluated and discussed. In the second part results are compared to similar studies and researches.

5.1 Assumptions and limitations

In the beginning of the research three gully erosion sites were already measured and all data needed for the study was available. A fourth site was going to be measured by UAV as well to have sufficient data. Unfortunately the trip to the study area was postponed many times and in the end I was not able to join the trip anymore during the research period. For that reason the fourth area could not be included in this research. The third site did not turn out to be suitable in the research because there was too much vegetation present in the gully erosion site. For that reason the surface topography measurements were not accurate enough to include the third site in the research.

The gully spline method is an accurate method to obtain a fitted surface to fill the gullies. However there are many uncertainties in addressing the boundary points of a gully because of all different shapes and types of gullies. In this research the limits of the gully are set by two reference points and are the points which have a top. If the cross section has no top a point with a transition zone in the derivative is chosen. The most important errors are related to difficulties in correctly identifying gullies (Frankl & Poesen, 2013). The use of an UAV is already an improvement and makes it easier but still there are no clear agreements of the boundaries of a gully.

The equation used to compute the R factor is designed for the southern part of Brazil. There are some climate differences between the North and the South part of Brazil affecting the rainfall intensities and energy levels.

The Maner method does not take changes in the topography of the area into account, but only considers the boundaries and the elevation of the watershed and might not be the best method to compute the SDR. The sedimentation study (de Araújo, Fernandes, Júnior, Oliveira, & Sousa, 2003) also showed a poor performance when slopes differ considerably, for instance for the Várzea da Volta basin. The method suits terrains with uniform slopes more and in this case the gullies create an non-uniformity in the slopes. The use of the Forest Service Model to compute the SDR would be better after all. The Forest Service Model is developed to compare the sediment delivery ratios before and after a natural disaster. A forest fire will damage the vegetation cover and might change the surface roughness and the slope shape. Using this method to compare the SDR for watersheds with and without gullies would be more suitable.

Concerning the connectivity index the vegetation cover gives high uncertainties due to high fluctuations over the year. The use of Cavalli's method instead of the method of Borselli is very useful if the vegetation cover is reduced (Cavalli, Trevisani, Comiti, & Marchi, 2013) (Borselli, Cassi, & Torri, 2008). However the connectivity index will decrease in case of a larger vegetation cover in the rain season. In this report the vegetation cover is assumed to be reduced. The surface roughness is used as a replacement, but also has some uncertainties. The surface roughness is computed by considering the standard deviation of the elevation. The high resolution (4x4 cm^2 cells) might cause a high surface roughness due to small disturbances in the topography.

5.2 Comparison to other researches and studies

In the Spanish Pyrenees the connectivity index is also computed on a high spatial resolution size (1x1 m^2 cell size) (López-Vicente, Nadal-Romero, & Cammeraat, 2016). This is a significant difference in relation to the cell size used in this research (4x4 cm^2), but already fits better than the cell size used by Borselli and Cavalli of a couple of meters (Borselli, Cassi, & Torri, 2008) (Cavalli, Trevisani, Comiti, & Marchi, 2013). Outcomes of the research are that the connectivity index is high at roads, trails, steams and gullies. Remarkable is the high connectivity on the road, because that does not fit the results of the connectivity index performed on site 1. Reasons therefore might be the slope of the road of site 1 which is almost flat. Another reason might be that the Spanish Pyrenees have areas with a lot of vegetation (forest lands) and compared to these areas the connectivity of the roads would be better, because there is no vegetation on roads. In this study there is no vegetation at all in the watersheds.

Concerning the soil loss, computed with the USLE hundreds of comparable researches have been performed. The big difference with this research is that the cell size used to compute the soil loss, was a lot bigger. Could reach up to 30x30 m^2 for instance. The soil loss computed in this research is pretty high compared to other studies from India, Uganda and China (Patil, Sharma, Tignath, & Sharma, 2016) (Karamage, Zhang, Liu, Maganda, & Isabwe, 2016) (Zhang & McBean, 2016). The soil loss in that study areas differs from 0 till 50 tons/ha/year. There needs to be mentioned that there are other climate conditions and the erosivity of the rainfall in Brazil is 10 times as high as in the compared study areas. Also the difference in soil loss got to do with the lack of vegetation on the sites which make the watersheds extremely vulnerable for erosion. The presence of vegetation on the sites could decrease the soil loss 5 times already compared to the C factor of 0.18 which is used the most in the case study in India. This type of vegetation is indicated as open land. All together the erosivity factor caused by the climate of Brazil and the lack of vegetation cover result in a high amount of soil loss on the sites. So the obtained soil losses are plausible.

6. Conclusion

The research questions stated in the beginning of the report will be answered in this section. A resume of the outcomes is given in this paragraph for each section. In the end an overall conclusion will be drawn to answer the main research question: How does gully erosion changes sediment connectivity patterns in a small-scale catchment area in the Brazilian semiarid region?

6.1 Soil loss computation

"How does gully erosion affect the soil loss of a watershed?''

The occurrence of the gullies results in higher amounts of soil loss. The soil loss due to the gullies increased according to the USLE. Especially the gully erosion area showed big changes in the soil loss.

For site 1 the average soil loss of the whole area is 761 tons/ha/year with the gullies and 744 tons/ha/year without the gullies. The average soil loss of the gully erosion site is 1076 and without gullies is 708 tons/ha/year. That is a decline of 34,2 % for the specific gully erosion area.

For site 2 the average soil loss of the whole area is 454 tons/ha/year with the gullies and 448 tons/ha/year without the gullies. The average soil loss of the gully erosion site is 1356 and without gullies is 910 tons/ha/year. That is a decline of 32,9 %.

In this computation the amount of soil loss was mainly affected by the gully erosion area itself and almost got no influences on upstream parts of the watershed. The gully erosion result in a higher amount of soil loss.

6.2 Connectivity index

"How did the occurrence of gullies affect the connectivity patterns of the watershed?''

The occurrence of gullies indicated with the black lines in Figure 6 and Figure 7 changed the topography of the watersheds. The connectivity index is computed with and without the presence of the gullies and pointed out that the gullies increase the connectivity. Not only the gully erosion areas itself got a higher connectivity with the gullies but also the upstream flowlines got a higher connectivity. In contrast to the soil loss the elimination of the gullies did affect the whole watershed. So the gullies improve the connection between the upstream area and the sink.

6.3 Sediment delivery ratio

"What is the difference in the sediment delivery rate comparing an area without the presence of gully erosion and a further developed area of gully erosion?''

The sediment delivery ratio computed by making use of the Maner method did not result in a different SDR. The SDR for site 1 was 100% and the SDR for site 2 was 50% no matter if the watershed had gullies or not. The use of the Forest Service Model on the other hand showed that the occurrence of gullies could change the SDR, because the gullies affect the topography of the watershed. Meaning the parameters ´surface roughness´, ´slope gradient´ and ´slope shape´ will change in a way that the SDR gets higher. Indicating that a higher ratio of sediment will run off from the watershed into the sink.

6.4 Relation between connectivity index and Sediment delivery ratio

"Is there a relationship between the connectivity and the sediment delivery ratio?''

The occurrence of gullies in the watersheds does not change the SDR according to Maners method. The shape of the area and a possible change in topography caused by gullies is not taken into account. In contrast to the sediment delivery ratio the connectivity index does take changes in the topography into account. The gullies induce a greater connectivity resulting in a higher sediment transport, while the sediment delivery ratio stays the same. So there is no direct correlation between these two parameters.

However the forest service model takes changes in the topography in the watershed into account. The presence of gullies will increase the percentage of the area drawn in the stiff diagram resulting in a higher sediment delivery ratio according to Figure 15.

A correlation between the connectivity index and the sediment delivery ratio strongly depends on the method used to calculate the sediment delivery ratio. In the end it would be more useful to use the forest model service to compute the SDR instead of the Maner method used in this research.

6.5 Overall conclusion

''How does gully erosion change sediment connectivity patterns in a small-scale catchment area in the Brazilian semiarid region?''

Overall, the occurrence of gullies will increase the soil loss mainly because the slopes are higher of the gully erosion area compared to a flat surface. Furthermore the gullies increase the connectivity in the downstream as the upstream part of the watershed. Therefore sediment is discharged more easily from the watershed with the presence of gullies than without the gullies. In contrast to the connectivity index, there are no changes in the SDR due to the occurrence of the gullies. This partly caused by the method used to compute the SDR. A correlation between the connectivity index and the SDR computed by the Forest Service Model is visible, but not elaborated. An indication of the effects gullies have in a small watershed is given and could be applied in other areas as well to evaluate the influences of the gullies on the area, rivers and lakes.

7. Recommendations

In this research the effects gullies have on the connectivity, soil loss and the SDR are pointed out. The relationship between the occurrence of gullies in a watershed and the growing connectivity of sediment transport is highlighted. The degradation of land is a growing problem, but in this study just a small piece of land is picked to evaluate. A way needs to be found to model the ephemeral gullies in other potential gully erosion risk areas. Afterwards the same analysis could point out the possible soil losses and changes in connectivity. In that way the areas could be subdivided in areas of high risk and low risk based on the impact the gullies would have on the watershed.

Furthermore a second evaluation of the SDR would be recommended as the method (Maner method) used at first does not include the topography of the watershed itself. Using another method, like the Forest Service Model presented in this report will give other insights in the correlation between the SDR and the connectivity index. The parameters needed to compute the SDR according to the Forest Service Model could be affected by the gullies in a way that the SDR will grow when gullies occur.

Another notification has to be made relating the method used to compute the soil loss. The USLE does not take landslides caused by the gully occurrence into account. A big gully might induce landslides when the slope of the bathymetry of the gully gets too high. This can result in instant soil losses which are not taken into account in this report. A more accurate analysis could be performed if this phenomena is included.

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Appendices

Appendix A: Computation K factor

The K factor is computed by making use of the formulas presented by Williams (Williams, 1995).

```
%input soil fractions percentage
m_s= 33    %(sand fraction content (0.05-2.00 mm diameter)[%];
m_silt=31 %(silt fraction content (0.002-0.05 mm diameter)[%];
m_c= 26    %(clay fraction content (<0.002 mm diameter)[%];
orgM=4     %(organic matter content [%];
orgC=orgM*0.58    %(organic carbon content [%];

%computation K-value
f_csand=(0.2+0.3*exp(-0.256*m_s*(1-(m_silt/100))))

f_cl_si=(m_silt/(m_c+m_silt))^0.3

f_orgc=(1-((0.25*orgC)/(orgC+exp(3.72-2.95*orgC))))

f_hisand=          (1-((0.7*(1-(m_s/100))))/((1-(m_s/100))+exp(-5.51+22.9*((1-
(m_s/100))))))

K_USLE=f_csand*f_cl_si*f_orgc*f_hisand
```

Validation K-value

To validate the obtained K-values the table presented by Schwab (1981) is used to be sure the computed K values do not differ too much (Schwab, Frevert, Edminster, & Barnes, 1981). The organic matter is 4% and the fractions of sand, silt and clay are respectively 33%, 31% and 26%. Silty clay has a K value of 0.19 and sand has a K value of 0.1 for 4% of organic matter. Based on Table 4 the K value would be around 0.16 by taking the fraction of sand and a fraction of silty clay. This value does not differ that much from 0.13 and 0.14 computed with the formulas of Williams. Especially because the uncertainty of the rainfall erosivity is much higher as this value can differ over each year.

Textural class	Organic matter content (%)		
	0.5	2.0	4.0
Fine sand	0.16	0.14	0.1
Very fine sand	0.42	0.36	0.28
Loamy sand	0.12	0.10	0.08
Loamy Very fine sand	0.44	0.38	0.30
Sandy loam	0.27	0.24	0.19
Very fine sandy loam	0.47	0.41	0.33
Silt loam	0.48	0.42	0.33
Clay loam	0.28	0.25	0.21
Silt clay loam	0.37	0.32	0.26
Silty Clay	0.25	0.23	0.19

Table 4: K-values for different soil types (Schwab, Frevert, Edminster, & Barnes, 1981)

Appendix B: Computation slope (S) and slope length (L)

Validation SL value

The SL values obtained in the map in ArcGIS range from nearly zero to 70. A new range need to be set to eliminate the values which are too high. Table 5 shows an indication of the SL values based on the slope and the slope length. The gully erosion sites are small areas not reaching a slope length up to 1000 feet. Approximately the slope length can reach up to 70 meters (230 feet) and differs for each site. There is no limitation for the slope, so the maximum SL value could be set to 18.92.

	Slope length in feet																
Slope	<3	6	9	12	15	25	50	75	100	150	200	250	300	400	600	800	1000
%																	
0.2	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.06	0.06	0.06	0.06	0.06	0.06	0.06
0.5	0.07	0.07	0.07	0.07	0.07	0.07	0.08	0.08	0.09	0.09	0.10	0.10	0.10	0.11	0.12	0.12	0.13
1.0	0.09	0.09	0.09	0.09	0.09	0.10	0.13	0.14	0.15	0.17	0.18	0.19	0.20	0.22	0.24	0.26	0.27
2.0	0.13	0.13	0.13	0.13	0.13	0.16	0.21	0.25	0.28	0.33	0.37	0.40	0.43	0.48	0.56	0.63	0.69
3.0	0.17	0.17	0.17	0.17	0.17	0.21	0.30	0.36	0.41	0.50	0.57	0.64	0.69	0.80	0.96	1.10	1.23
4.0	0.20	0.20	0.20	0.20	0.20	0.26	0.38	0.47	0.55	0.68	0.79	0.89	0.98	1.14	1.42	1.65	1.86
5.0	0.23	0.23	0.23	0.23	0.23	0.31	0.46	0.58	0.68	0.86	1.02	1.16	1.28	1.51	1.91	2.25	2.55
6.0	0.26	0.26	0.26	0.26	0.26	0.36	0.54	0.69	0.82	1.05	1.25	1.43	1.60	1.90	2.43	2.89	3.30
8.0	0.32	0.32	0.32	0.32	0.32	0.45	0.70	0.91	1.10	1.43	1.72	1.99	2.24	2.70	3.52	4.24	4.91
10.0	0.35	0.37	0.38	0.39	0.40	0.57	0.91	1.20	1.46	1.92	2.34	2.72	3.09	3.75	4.95	6.03	7.02
12.0	0.36	0.41	0.45	0.47	0.49	0.71	1.15	1.54	1.88	2.51	3.07	3.60	4.09	5.01	6.67	8.17	9.57
14.0	0.38	0.45	0.51	0.55	0.58	0.85	1.40	1.87	2.31	3.09	3.81	4.48	5.11	6.30	8.45	10.40	12.23
16.0	0.39	0.49	0.56	0.62	0.67	0.98	1.64	2.21	2.73	3.68	4.56	5.37	6.15	7.60	10.26	12.69	14.96
20.0	0.41	0.56	0.67	0.76	0.84	1.24	2.10	2.86	3.57	4.85	6.04	7.16	8.23	10.24	13.94	17.35	20.57
25.0	0.45	0.64	0.80	0.93	1.04	1.56	2.67	3.67	4.59	6.30	7.88	9.38	10.81	13.53	18.57	23.24	27.66
30.0	0.48	0.72	0.91	1.08	1.24	1.86	3.22	4.44	5.58	7.70	9.67	11.55	13.35	16.77	23.14	29.07	34.71
40.0	0.53	0.85	1.13	1.37	1.59	2.41	4.24	5.89	7.44	10.35	13.07	15.67	18.17	22.95	31.89	40.29	48.29
50.0	0.58	0.97	1.31	1.62	1.91	2.91	5.16	7.20	9.13	12.75	16.16	19.42	22.57	28.60	39.95	50.63	60.84
60.0	0.63	1.07	1.47	1.84	2.19	3.36	5.97	8.37	10.63	14.89	18.92	22.78	26.51	33.67	47.18	59.93	72.15

Table 5: Maximum SL values

Appendix C: Reconstruction surface without gullies

The four reference points (Y) with the corresponding elevation are used to fit a cubic spline through in Excel (Figure 34). Figure 35 displays the gully cross section with the fitted cubic spline, creating a smooth overtopping layer. Replacing current data points in the range limited by the second and third reference point will fill the gully and will create a smooth surface. A reconstruction of the surface roughly 60 years ago is obtained (Figure 36).

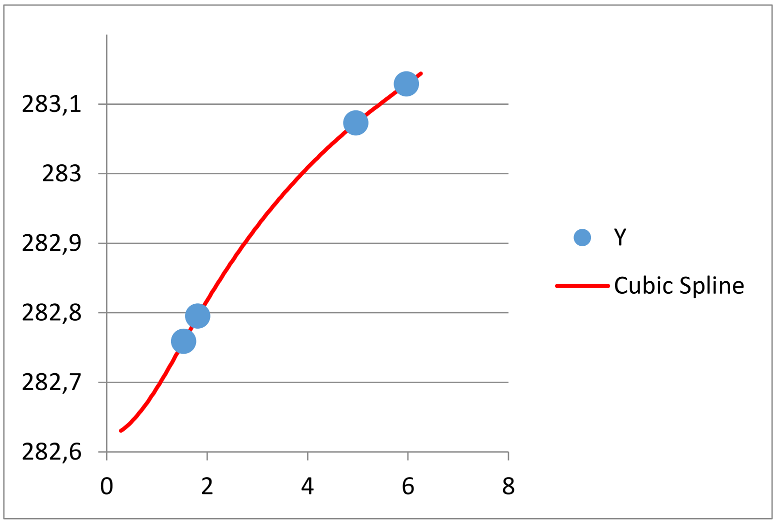

Figure 34: Cubic spline

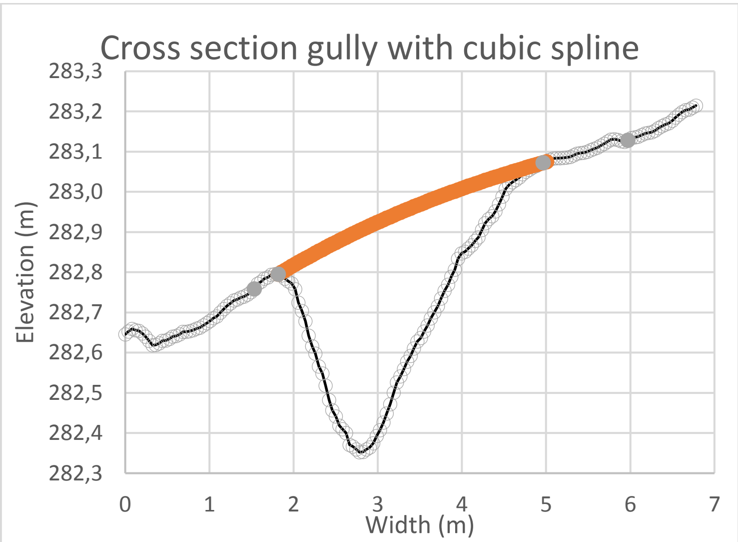

Figure 35: Cross section gully with cubic spline

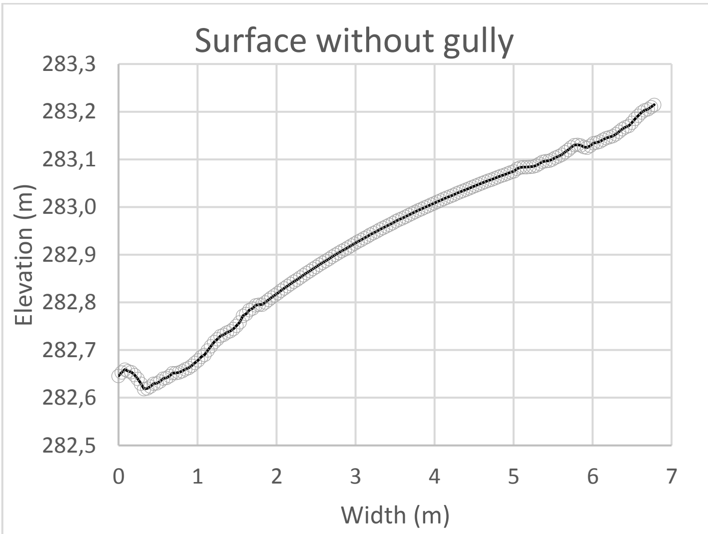

Figure 36: Surface without gully

A couple of cross sections of the gullies are extracted from ArcGIS with the corresponding coordinates. For each cross section the same approach as described above is used to create a surface without a gully. A scientific way need to be found to address the reference points which are used to fit a spline through. The limits of the gully are set by two reference points and are the points which have a top. If the cross section has no top a point with a transition zone in the derivative is chosen. The reference points are used to create multiple polygons. Afterwards the same steps presented in Appendix D are taken to make the surface rough and fit in the current DEM.

Appendix D: Remove vegetation cover ArcGIS

The vegetation cover should be eliminated from the DEM because it will disturbs the flow direction of the water and the areas have slopes which are way too high. The following steps are taken to obtain the surface without a vegetation cover in ArcGIS:

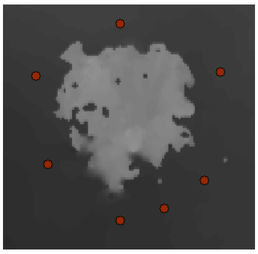

Figure 37: Point features

Point features are draw surrounding the vegetation cover area. The xy coordinates are added (Data management-Features-Add xy coordinates) and the Z value of the DEM too (Spatial Analyst-Extraction-Extract multi values to points) (Figure 37).

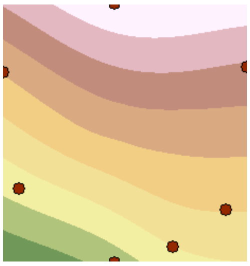

Figure 38: Cubic spline

The points are used as an input to fit a regularized spline through (3D analyst-Raster interpolation-Spline) (Figure 38).

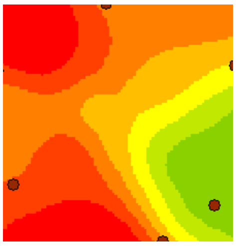

Figure 39: Cubic spline rough

The surface of the spline is very smooth and will cause an unrealistic value for the roughness index. The goal is to create a roughness comparable to the roughness of the area, so the weighting factor used to compute the connectivity index will be realistic. To create small disturbances in the elevation of each cell, a normal distribution is used to adjust the elevation of the cells a little bit.

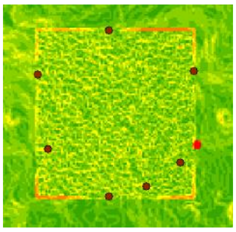

Figure 40: Replacement eliminated area rough

In order to adjust the spline raster a normal raster is created with the mean of 0 and a standard deviation based on the average standard deviation of the elevation computed with the roughness index tool of Cavalli (2013) (0,014303 m for a comparable area for site 1). For each cell grid a positive or negative value around 0 is obtained from the normal raster. A summation of the spline raster with the normal raster will result in a raster with irregularities over the surface (Figure 39). This become clear in the difference in the slopes of the spline raster and the raster with irregularities(Figure 40). However the transition zones of this raster with the original DEM is not smooth and result in high slopes.

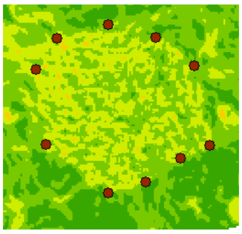

Figure 41: Replacement eliminated area

To avoid big differences in elevation a polygon is created of the points to extract the specific area of the vegetation. In this way the transition in elevation gets smoother (Aggregate points tool) (Figure 41).

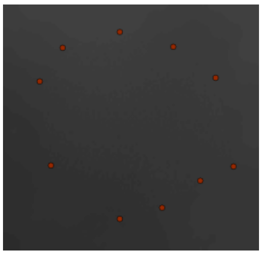

Figure 42: New DEM

The data obtained in the new raster need to replace the data in the DEM (Data management-Raster dataset-Mosaic to new raster). Afterwards a new raster is obtained with the surface without a vegetation cover (Figure 42).

This procedure is repeated for the biggest vegetation areas and disturbances in the DEM to come as close as possible to the natural surface. The new DEM will be used as an input for the computation of the SDR and the connectivity index.

Appendix E: flow chart connectivity index