Structural network connectivity in a semi-arid catchment, Morocco

Degraded hillslopes in the Anguelz catchment, Morocco (photo: perma-atlas.com)

Jessica Lensing

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A master's thesis by

Jessica Lensing (4267125)
Department of Earth Sciences
Faculty of Geosciences
Utrecht University

Supervised by

Angeles Garcia Mayor
Department of Sustainable Development
Faculty of Geosciences
Utrecht University

&

Steven de Jong
Department of Physical Geography
Faculty of Geosciences
Utrecht University

Utrecht University

Abstract

Over 45% of the world surface exists of drylands, that together support over 2 billion people. Despite the importance of drylands, they are often subject to severe land degradation. This is only expected to increase in the coming decades due to climate change, which on the long term affects ecosystem sustainability and economic stability. Restoration practices in these areas are aimed to reduce the effect of local erosion processes. However, current success rates of restoration practices are low, as there is a lack of knowledge on how small-scale erosion processes result in broad-scale geomorphological patterns. Therefore, the objective of this study is to incorporate these relations through a connectivity-network approach, to understand the long-term behavior of sediments within a catchment.

Connectivity - the physical coupling of landforms through geomorphological processes – is used to assess the spatial patterns of water and sediment distribution in the Ounila catchment, Morocco. In the Ounila catchment land degradation leads to a decrease in land productivity and an increase in flood risk. Therefore, the non-profit organization Perma-Atlas started restoration practices. However, knowing where in the catchment their restoration would have a larger effect is crucial in order to maximize the results of their interventions. Therefore, the aim of this research is twofold: first, to gain insight in the functioning of the Ounila catchment and second, to locate areas where geomorphic change will affect the entire catchment (hotspots). The identified hotspots are the recommended locations for Perma-Atlas for the relocation of water- and erosion conservation measures.

In this thesis the concept of connectivity is combined with graph theory, where the catchment is seen as a network of nodes and edges. The benefit of this is that nodes can be hierarchized based on intrinsic properties and corresponding indices of the network. The Network Structural Connectivity (NSC) index is used to analyze the connectivity patterns in the Ounila catchment. Local hotspots are located with the NSC index and insights in the functioning of the catchment are addressed through flow analyses at the outlet of the catchment. Different scenarios are explored to assess the functionality of the proposed method: the effect of spatial extent on the method is investigated and the effect of restoration practices specifically in highly connected areas is quantified. The results from this research show that a connectivity-network approach is a good start to gain the first insights in the functioning of a catchment and to locate hotspots. However, the applied method would benefit from the inclusion of the distances of the sediment pathways. The addition of topological distance would not increase the complexity of the method excessively and is a promising next research step.

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4. Methodology

1. Introduction

Drylands are areas that are characterized by a higher rate of evaporation than precipitation and form an important terrestrial environment. In total, drylands cover ± 45% of the Earth's surface and support over 2 billion people (Prăvăli et al., 2016). For these areas land degradation is an increasingly urgent problem, accelerated by climate change (Council, 2009/IPCC, 2012). Land degradation is the overarching term to describe the effect of soil erosion, vegetation degradation and nutrient loss; processes that negatively affect land's functioning. In drylands, severe land degradation leads to a decrease in ecosystem sustainability, economic instability, and eventually to irreversible damage with desertification as result (Dregne, 2002). On catchment scale land degradation results in two main problems: a decrease in land productivity and an increase in flood risk. The first is due to nutrient loss and water stress and the latter is due to a decreased water holding capacity of the soils (Zuazo & Pleguezuelo, 2008). Overall, land degradation decreases the functionality of catchments and due to climate change, this is expected to increase in the coming decades.

To maintain drylands functionality, it is crucial to restore degraded land, however restoration success rates remain low (James et al., 2013). The success of restoration practices depends, among other things, on where in the catchment they are carried out. Preferably, locations for restoration are chosen in areas where the effects are noticed throughout the entire catchment. Sediment cascades, the pattern of repeated detachment, transport and deposition, play an important role in the redistribution of water and sediment and thus for the success of restoration. However, understanding how these small-scale processes result in broad-scale geomorphic patterns and processes remains difficult (Bracken et al., 2015). The concept of connectivity – the coupling of landform through geomorphic process – bridges this knowledge gap as it provides a tool to assess spatiotemporal patterns in landscapes (Bracken et al., 2015). The extent of connectivity in a catchment determines the spatial and temporal patterns of water and sediments redistribution (Najafi, et al., 2020). In a highly connected catchment, sediments are able to move through the system to the outlet with ease, whilst in dis-connected catchments sediments encounter many obstacles before reaching the outlet. Also, connectivity provides information on the systems response to change, where in highly connected systems change is easily propagated downstream. Assessment of connectivity adds to the understanding of how small-scale processes relate to broad-scale geomorphic patterns.

A number of studies have demonstrated the advantage of using a connectivity framework in order to assess spatial and temporal patterns of water and sediment distribution. Initially, by assessing the sediment delivery of a catchment, where the amount of sediment at the outlet is compared to the (modelled) eroded sediment within the catchment (e.g. Medeiros et al., 2010). However, this method masks the internal dynamics: sediment cascades but also smaller scaled dynamics, that play a crucial role (Baartman et al., 2013). The latest contribution to the connectivity framework bypasses this lack of internal dynamics through the addition of graph theory. Sediment cascades in a catchment are described through a network structure where nodes represent spatial units and edges represent sediment pathways (Cossart & Fressard, 2017). Essential is the definition of spatial units, sediment pathways and spatial scale, as this influences the connectivity. However, the benefit of graph theory is that the nodes can be hierarchized based on their intrinsic properties and corresponding indices (Cossart et al., 2016). Therefore, graph theory helps to identify local hotspots: nodes in the network with high influence in the sediment cascade as they control the fluxes passing between many other nodes. For catchment management, locating these areas is of high importance because here restoration practices are expected to be most effective to increase catchment functioning, e.g. to increase land productivity and to increase flood safety.

In Morocco roughly 98% of the land consist of drylands, and land degradation is a pressing issue (Prăvăli et al., 2016). The Ounila catchment, located 90km south east of Marrakesh, already endures many environmental issues as a results of climate change. In 2014 heavy rainfall led to floods and landslides, compromising the safety of many locals. The area experiences long periods of drought, whilst the main source of income is from agriculture. And in the last decades there has been a shift from nomadic to sedentary livestock farming leading to overgrazed hillslopes with severe erosion as results. For this reason, the non-profit organization Perma-Atlas started restoration practices. However, knowing where in the catchment their restoration would have a larger effect is crucial in order to maximize the results of their interventions. This thesis intents to contribute to that information by identifying hotspots of connectivity in the Ounila catchment.

This research explores the potential of using a connectivity-network approach, with the focus on sediment cascades in a semi-arid catchment in Morocco. The aim of this research is to get insight in the functioning of the catchment and to locate hotspots of connectivity. Sediment cascades are presented in a network structure and connectivity is addressed through indices derived from graph theory, in line with the work of Cossart & Fressard (2017). The research is structured around three main questions:

1. What are the spatial patterns of connectivity in the Ounila catchment?
2. What is the role of spatial extent on the connectivity index?
3. What is the effect of using a connectivity index for the relocation of restoration practices?

This thesis consists of seven chapters that together present an overview of all the research steps necessary for answering the above-mentioned questions. First, a theoretical framework is provided, in which the existing theories around connectivity and graph theory are discussed (chapter 2). Then, the research area is discussed in detail, with a focus on geomorphological characteristics (chapter 3). Next, the methodology is explained, where a virtual data set is used to illustrate the method (chapter 4). After this, the results of the method on the real data set are examined (chapter 5). Then, the applied method and final results are discussed (chapter 6). And finally, the conclusions of this research are given (chapter 7).

The research area is the Ounila catchment in the High Atlas Mountains, Morocco. In this catchment, Perma-Atlas has started restoration practices after devastating floods in 2014. The goal of this organization is to revitalize the Atlas Mountains by (re)introducing restoration practices to inhabitants of the Ounila Valley. Their restoration practices are based on the permaculture techniques that are in line with old Berber traditions. Through teaching the inhabitants these techniques, they aim for a sustainable recovery of the Atlas Mountains ecosystem (Perma-Atlas, 2020). This research is part of a long-term project from Utrecht University, where the Ounila Valley is extensively investigated in collaboration with Perma-Atlas. The contribution of this research to the overall project is an overview map of the Ounila Valley with connectivity values (hotspots), an in-depth analysis of the effect of scale on the used methods and finally in a quantitative answer on the contribution of using connectivity for the relocation of restoration practices.

2. Theoretical framework

In this chapter the key concepts of this research are explained in detail and are put in perspective with current research. First, the different theories and established ideas around the concept of connectivity and its parameters are explored (section 2.1/2.2). Then, the existing connectivity indices are briefly described (section 2.3). And finally, the concept of graph theory and its applications within Earth Sciences is considered (section 2.4).

2.1 Concept of connectivity

The concept of connectivity exists in various disciplines and comprises several components that together describe the dynamics of a system. In broad terms, the objective of connectivity is to understand system complexity and systems response to change. Ecology was the first discipline to use connectivity, here *landscape connectivity* was introduced to assess the ability of organisms to move across landscape patches and thereby explain distribution of species (Heckmann et al., 2015/Cossart et al., 2018). More recently the concept is applied within Earth Sciences, especially in hydrology and geomorphology. For an open system, with focus on the relationship between process and landform, the components of connectivity are characterized by input, output, storage and the flux of matter and energy (Wohl et al., 2014). Nevertheless, a multitude of definitions for the term connectivity exists in academic literature. For example, Fryis et al. (2007) define *connectivity* as the transfer of energy and matter between two landscape compartments or within a system as a whole. Whilst Bracken & Croke (2007) distinguish three types of connectivity's: *landscape connectivity, hydrological connectivity* and *sediment connectivity*. Where landscape connectivity relates to the physical coupling of landforms through geomorphic processes, hydrological connectivity refers to the passage of water from one part of the system to another and sediment connectivity relates to the physical transfer of sediments through a catchment (Bracken & Croke, 2007). Moreover, Medeiros et al. (2010) define *catchment connectivity* as the degree to which sediment production on the hillslopes is connected to the river network through overland flow. Heckmann & Schwanghart (2013) define *(sediment) connectivity* as the degree of coupling; the combined effect of longitudinal (hillslope to channel) and lateral (one river to another river) linkages between system components. Overall, three aspects are important in all definitions: landscape units, transport vectors and scale. Connectivity as defined by Bracken et al., (2015) also indicates this; connectivity arises through the transfer of material between two zones and occurs via transport vectors (e.g. water, wind, glaciers, gravity, animals) that move these materials over a range of spatial and temporal scales where each zone has two parts: the morphologic system and the cascading system. This overview shows that the definition of connectivity greatly depends on what system is studied and what processes are of interest.

Another important aspect of connectivity is the differentiation between structural and functional connectivity. Cossart et al. (2018) define *structural connectivity* as the influence of the spatial patterns in the landscape on both sediment transfer and sediment pathways. The assessment of structural connectivity reveals the skeleton of the system and this shows the basic functioning of a catchment. Functional connectivity, on the other hand, refers to the actual sediment transport in a catchment and gives information on what processes are responsible for this (Cossart & Fressard, 2017). Functional connectivity gives more detailed insight in the functioning of catchments but needs field measures and often a way of dynamic modelling.

In the last two decades connectivity further gained increasing importance in river and catchment management (Poeppl et al., 2017). Rivers and catchments have a broad functioning, for ecological and social purposes but also for economic means. Even so, 60% of all rivers on

Earth are altered by anthropogenic influence, whilst the consequences of this are uncertain. Catchments often remain a black box, and how small-scale processes cause large scale landscape changes is not (yet) completely understood. The concept of connectivity gives insight on these processes; it described linkages between sediment source and sediment sinks in catchments along temporal as well as spatial dimensions. Furthermore, connectivity gives an indication of the sensitivity and resilience of a system to change (Cossart & Fressard, 2017). Highly connected catchments, thus with high connectivity, transfer disturbance in the system quickly. Whilst in poorly connected catchments, with low connectivity, disturbance is not propagated which makes the system less sensitive to change (Fryis, 2013). Locating areas of high connectivity is a necessity in catchment management, as these are the areas where anthropogenic or natural change affects the system most. In order to anticipate to these (unwanted) affects, it is important to redirect catchment strategies specifically to these locations (Cossart & Fressard, 2017).

2.2 Connectivity parameters

The relevance of connectivity for the functioning of geomorphic systems (e.g. catchments) calls for connectivity assessment. Catchments are open systems that generally have the tendency for steady-state conditions, but various variables influence this steady state. Such that these variables are in control of the systems state, and consequently are crucial for the assessment of connectivity. The variables can be summarized in external forcing, intrinsic properties, geomorphic processes and human impact. And combined can lead to system response that is often non-linear and which depends greatly on temporal and spatial scale (Wohl et al., 2014). To assess connectivity, it is important to have a clear understanding of the different variables. Here, the four variables are discussed on catchment scale where water is responsible for the transport of sediment.

The first variable is external forcing, which relates to natural forces that are exerted on a catchment (Figure 2.1a). Consequently, external forcings are largely influenced by climate and by local weather conditions, e.g. precipitation, gravity and wind. Precipitation is one of the external forcings that partly determines the water discharge in a catchment and is responsible for erosion. Different parameters characterize the dynamics of precipitation; the amount of kinetic energy, the intensity, the magnitude/frequency of the event, the seasonality and the spatial distribution all play a role (Heckman et al., 2018). Kinetic energy contributes to splash erosion, whilst an increase in intensity or in magnitude/frequency will contribute to sheet erosion and finally to concentrated erosion where the erosion processes are controlled by the flow itself. Another important external forcing is temperature, where especially water loss through evapotranspiration and snow-melt driven water input are important features for connectivity. Also, land movements under the influence of gravity and/or water are an external forcing. Land movements (e.g. landslides, debris flows or mudflows) displace large amounts of sediments that alter the connectivity in a catchment significantly. Wind is another external forcing; especially in arid regions wind is responsible for erosion. However, because the focus is on water mediated sediment transport, wind and its effects are not considered significant in this thesis. The last external forcing is due to anthropogenic activities; especially in cultivated areas this has great influence. Erosion is enhanced due to tilling activities, but also dams, canals and dikes influence connectivity. Overall, external forcings greatly influence catchment connectivity.

The second variable is summarized as the intrinsic properties of a system (Figure 2.1b). Intrinsic properties are based on the fundamental units and are a representation of the entities that are used to describe connectivity along (Poeppl & Parsons, 2018). For each research the entities that connectivity is described along should be chosen accordingly. On catchment scale the most important properties are slope, topography, landform, land use and land cover. For a large part the intrinsic properties determine the ease at which sediment can move through the catchment. Intrinsic properties can form barriers, enhance sediment displacement and largely determine sediment availability. Especially, the first three (slope, topography and landform) can form barriers or enhance sediment displacement whilst the last two (land use and land cover) for the most part determine sediment availability. However, often it depends on the specific system that is studied which factors contribute the most.

The third variable relates to all the geomorphic processes that are responsible for the transport of sediment from source to sink (Figure 2.1c). The dominant process depends on the system that is studied; in high mountains gravity plays a more important role than in low mountain areas, and for water vice-versa (Heckmann & Vericat, 2018). When a system is water dominated, external forcings (e.g. precipitation) and intrinsic properties (e.g. slope and land use) determine the amount and intensity of sediment transport. A distinguish can be made between three types of transport: debris flow, normal runoff flood and flash floods. Debris flow transport unsorted sediments and often form barriers in the landscape. Normal runoff flood transport bed load and suspended load and flash floods transport extreme high sediment loads (Benda et al., 2004a). Rivers and streams respond dynamically to changes in external forcing and intrinsic properties therefore the variables are closely intertwined. When connectivity is assessed along a river network, three spatial scales can be taken into consideration, namely: longitudinal (headwater to outlet), lateral (river to floodplain) and vertical (river to groundwater) (Pringle et al., 2003).

The last variable is that of human impact. It is nothing new that humans alter geomorphic systems to fit the needs of society (Peoppl et al., 2017). However, in the last decades the scale of alterations changed significantly due to an increase in technological developments (Figure 2.1d). Human impact can be divided in two types: direct and indirect. Direct impact is the adjustment to the system that influences connectivity directly, e.g. the building of dams, bridges or reservoirs. Indirect impacts are all adjustments that effect connectivity indirect, e.g. land cover change or agriculture use of land. All changes, either direct or indirect, also affect the effects of external forcing, intrinsic properties and the geomorphic processes.

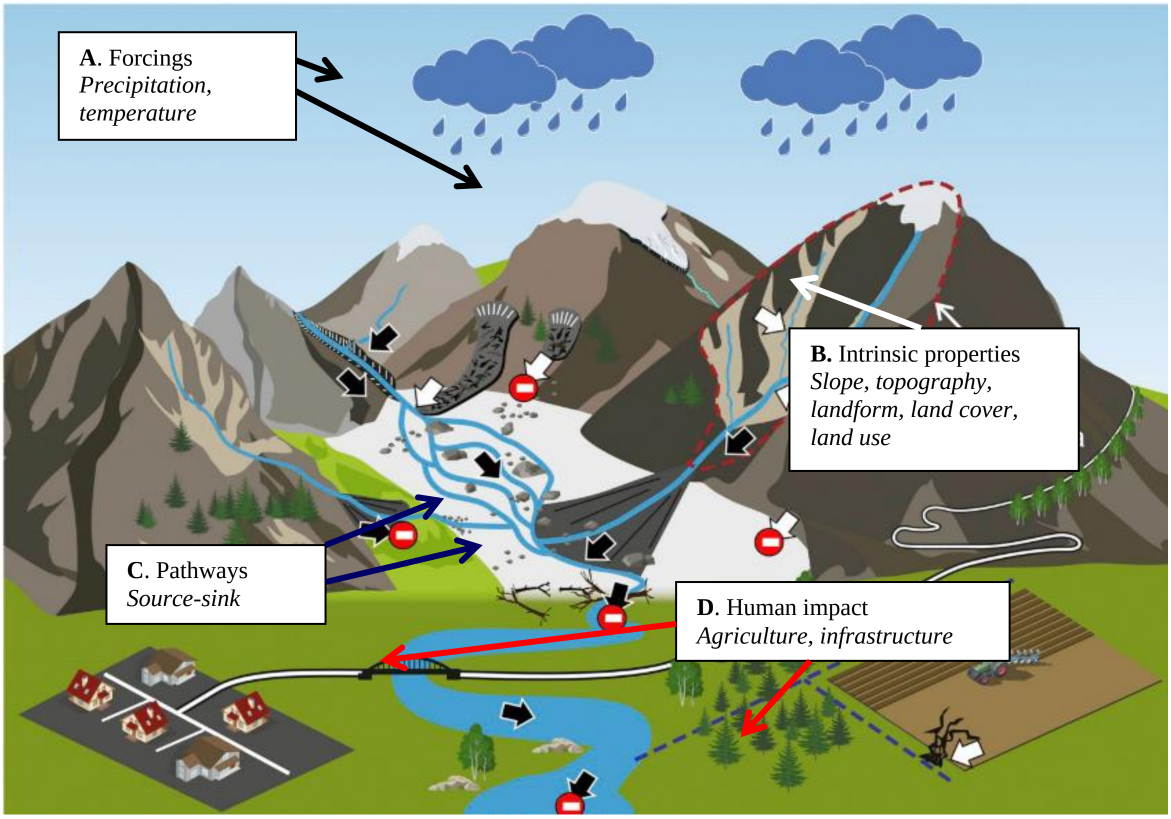


Figure 2.1 Simplified representations of the four variables that influence connectivity. A) Forcing: *precipitation, temperature.* B) Intrinsic properties: *slope, topography, landform.* C) Pathways: *geomorphological processes responsible for transport from source to sink.* D) Human impact: *agriculture, land use, bridges/dams, reservoirs* (Heckmann et al., 2018)

2.3 Overview connectivity indices

Since the variables that are responsible for connectivity are so extensive and intertwined multiple indices exist with different combinations of these variables. One of the most known indices to assess connectivity is the Sediment Delivery Ratio, application of this index started already in the mid 90's and is still used today. This index is based on the sediment delivery of a catchment, which is the ability of a catchment to transport sediment (Fryirs, 2013). The index is defined as the ratio of sediment delivered at the outlet (V_o) to the gross erosion within a catchment (V_h):

$$SDR = {}^{V_o}\!/_{V_h} \tag{1}$$

High SDR values correspond to highly connected catchments, where eroded sediments reach the outlet quickly. Consequently, low SDR values correspond to disconnected catchments, where sediments encounter many barriers or sinks before reaching the outlet (Cossart & Fressard, 2017). However, the Sediment Delivery Ratio has many critics. Firstly, the method is highly dependent on either field measurements or modelled erosion values. And second, the processes that play a role in sediment transport and deposition are mostly ignored and therefore the catchment itself remains a black box (Cossart & Fressard, 2017).

An increase in knowledge, computer power and availability of high-quality Digital Elevation Models at the end of the 20th century led to indices that have a more spatially distributed approach. One of these indices is based on stream power, which is the amount of energy available for sediment transport along a certain flow path. The Stream Power Index (SPI), as defined by Marchi & Fontana (2005), combines local slope and contributing area to evaluate the topographic control on erosion. By comparing the SPI to a threshold value, areas of high connectivity are assigned. This index relates connectivity to many intrinsic properties but is limited to sediment fluxes along the longitudinal channel network.

Another index is the Index of Connectivity (IC) as proposed by Borselli et al. (2008) and used by many other (e.g. Cavalli et al., 2013/ Foester et al., 2014). Connectivity is approached from elevation data in a GIS environment. For each raster cell in a catchment an upslope component and downslope component is calculated:

$$IC = {}^{D_{up}}\!/_{D_{dn}} \tag{2}$$

The upslope component combines slope, area and a weighting factor for the upslope contributing area and accounts for all the sediment upstream available for transport. The downslope component combines the length of the downslope sediment pathway, a weighting factor and the slope gradient and accounts for all the possible paths the sediment has downstream. High IC values correspond to high connectivity, where sediments move through the catchment easily. Even though the IC knows many purposes and revised versions, the main critic remains that the weighting factor is rather arbitrary, and that the IC is calculated per pixel with no spatial meaning. Another critic is that the quality and resolution of input data significantly influence final results (Borselli et al., 2008).

Similar to the Index of Connectivity is the Simplified Connectivity Index as proposed by Grauso et al. (2018). Here the research area is divided in spatial units, and for each unit the soil loss and the distance to the outlet are estimated. A mathematical combination of these values gives the connectivity values of the spatial units (Grauso et al., 2018). Hence, to address connectivity with this index knowledge on specific soil loss is necessary which is impractical for many purposes (Heckman et al., 2018).

Flowlength has also been proposed as a connectivity index, and it is used to assess the connectivity of runoff sources on a fine spatial scale (Mayor et al., 2008). The index is based on elevation data and land cover information, with the focus on vegetation patches in semi-arid areas. The Flowlength index is defined as the average length of all the potential runoff pathways, where vegetation patches are runoff sinks and bare soils are runoff sources. An algorithm calculates the Flowlength, with single flow direction and calculation ends when the flow has reached a sink or goes outside the area of interest (Mayor et al., 2008).

A rather different quantitative approach towards connectivity is proposed by Cossart & Fressard (2017) and is the Network Structural Connectivity index (NSC). This index makes use of graph theory to describe sediment cascades, where sediment cascades are depicted with a network structure. In this network structure landscape units are represented by nodes, whilst sediment pathways are represented by edges. From this, the potential flux (F) and accessibility (Shi) of each node (i) can be determined, and combined give the connectivity values (Cossart & Fressard, 2017):

$$NSC_i = {}^{F_i}/_{Shi_i} \tag{3}$$

In this thesis the Network Structural Connectivity index (NSC) will be used to assess connectivity. This method provides an understandable algebraic framework to hierarchize the nodes within a system. The hierarchized nodes give insight in the basic functioning of a catchment and geomorphic change can be mimicked through easy adjustable algebraic structures; this makes the index is a highly suitable method for this thesis (Cossart & Fressard, 2017).

2.4 Concept of graph theory

Up to now, the concept of graph theory is briefly touched upon section 2.3 as a method to define the NSC index. Here, the concept is elaborated. Graph theory provides the mathematical tools to present systems in a network structure, this network describes the structure of a system which on turn governs the systems properties. The concept itself is not new, as it has a long history with the roots in mathematics, and is often used in social, ecological or infrastructure studies (Heckmann et al., 2015). Now, the concept of graph theory is successfully linked to the representation of sediment cascades and linked to connectivity (e.g. Heckmann & Schwanghart, 2013/ Heckmann et al., 2015/ Cossart & Fressard, 2017).

Any system can be represented with a graph G(N, E) with nodes N and edges E, as long as there is a relation between N and E. A graph can be undirected, where edges relate to nodes on both ends or directed, where edges are one way only (Figure 2.2).

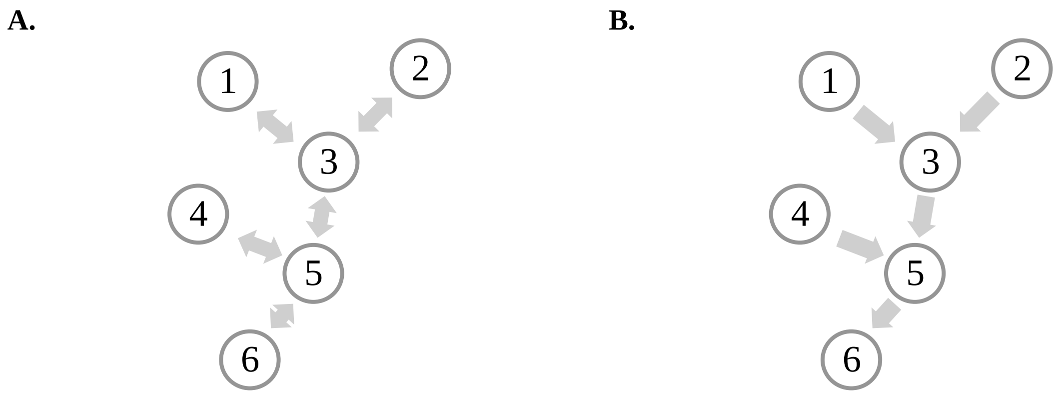


Figure 2.2 Undirected graph (A) and directed graph (B)

Graphs are represented with an adjacency matrix (A) that is a matrix of the size n^2, where n is the number of nodes in the graph; the rows are the source nodes whilst the columns are the destination nodes. When nodes are connected this is shown with a nonzero element in the representative row of the source node and column of the destination node (Figure 2.3).

A.

Source nodes \ Destination nodes	**1**	**2**	**3**	**4**	**5**	**6**
1	0	0	1	0	0	0
2	0	0	1	0	0	0
3	1	1	0	0	1	0
4	0	0	0	0	1	0
5	0	0	0	1	0	1
6	0	0	0	0	0	1

B.

Source nodes \ Destination nodes	**1**	**2**	**3**	**4**	**5**	**6**
1	0	0	1	0	0	0
2	0	0	1	0	0	0
3	0	0	0	0	1	0
4	0	0	0	0	1	0
5	0	0	0	0	0	1
6	0	0	0	0	0	0

Figure 2.3 Example of adjacency matrix undirected graph (A) and directed graph (B)

Graph theory provides many indices that represent the structural properties of a graph, with the aim to provide a hierarchy of the influence of nodes within a network. Nodes with high influence within the network correspond to nodes with high connectivity, as they control many fluxes throughout the network (Cossart & Fressard, 2017). One of the simpler indices is the beta index, which divides the number of edges (e) i.e. the number of non-zero elements in the matrix by the number of nodes (v) i.e. the number of columns/rows in the matrix

$$ß = {}^{e}/_{v} \tag{4}$$

The beta index primarily relates to the complexity of a network. More complex networks have a beta value greater than 1; where nodes have multiple edges. Simpler networks have a value smaller than 1; where there are more nodes than edges. And networks with one cycle have a value of exactly 1: where exactly all nodes have one edge. Another fairly simple index is the order index; here for each node the number of edges are summed:

$$k_i = \sum_{j}^{N} x_{ij} \tag{5}$$

High values correspond to a more important node as many edges enter the node. Source nodes only have an outgoing edge and thus have an order value of 1, destination nodes can have values higher than one and only terminal nodes have values lower than 1. A more complex index is the Betweenness index:

$$B_i = {}^{\sum n_{ijk}}\Big/_{n_{jk}} \tag{6}$$

Here, for a node *i*, the number of paths that go from *j* to *k* and pass through i are summed and divided by the total number of paths in the network from *j* to *k*. A high Betweenness index is correlated with high connectivity, as such a node *i* ensures sediment transport. Related to the betweenness index is the Shimbel index:

$$Shi_i = {}^{\sum d_{ij}}\Big/_{\sum d_{jk}} \tag{7}$$

This is also known as the measure of accessibility and is the sum of the length of all the shortest paths connecting all other nodes, divided by the sum of all possible paths. A high Shimbel index means that a node i creates long paths within the network, and therefore decreases connectivity. A low Shimbel index contributes to short paths, which makes the network more compact, and results in a higher connectivity.

In a spatial system the nodes are represented by spatial units (e.g. landforms, catchments or hydrological response units) and the edges are represented by the relation between the spatial units (e.g. sediment pathway from or to units). Important to note is that a network representing sediment cascades exist of directed graphs, because sediments are transported mainly due to gravity driven processes.

2.5 Conceptual framework

This chapter has demonstrated the relevance of connectivity, and how the concept can be combined with the tools derived from graph theory to get insight in the functioning of a catchment. Together this resulted in the research question: *"what are the spatial patterns of connectivity in the Ounila catchment, Morocco*". The main assumption in this research is that a catchment is seen as a network structure. Geomorphological characteristics form the foundation to reconstruct the catchment in a network, which exists of nodes and edges. From the network structure sediment flow is simulated and connectivity is assessed. First, the focus is on using the Network Structural Connectivity index, as defined by Cossart & Fressard (2017), to find out the general pattern of connectivity in the catchment. Second, the importance of scale is investigated and finally an effort is made to quantify the effect of using connectivity as an indicator to relocate restoration practices (Figure 2.4).

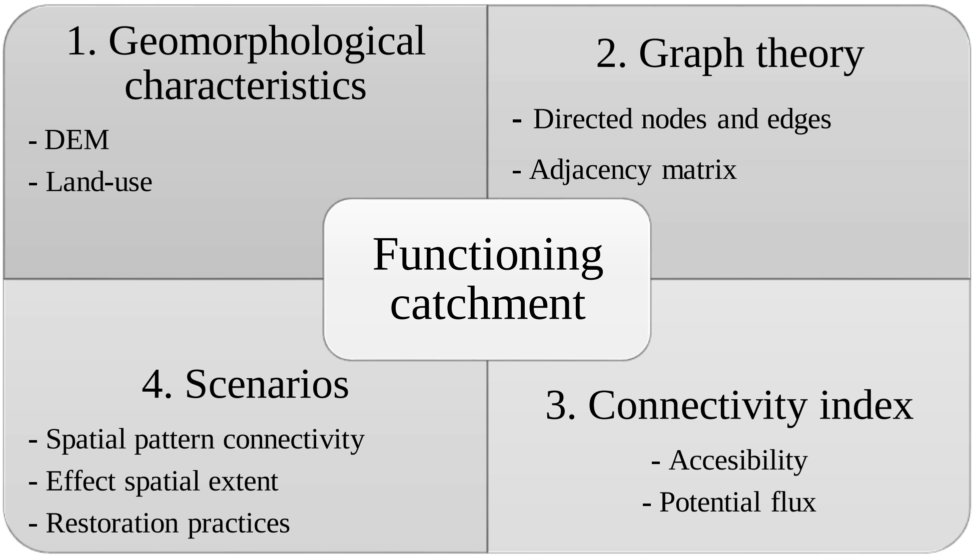


Figure 2.4 Overview of the concepts that form the framework of this research

3. Research area

North Africa is divided in three main geomorphic units: the Sahara, the Atlas Mountains and the Nile river delta system. The overall climate is characterized by a wet season in winter and dry conditions in summer. However, three climate regions can be identified: the Atlantic realm, the Mediterranean realm and the Sahara realm. The regions are separated by the Atlas Mountains, which stretch 2500 km through Algeria, Morocco and Tunisia and form a barrier between the Atlantic/Mediterranean coastlines and the Sahara Desert resulting in different the climatic regions. The High Atlas Mountain range is not continuous and just in Morocco three parts can be distinguished: the Anti-Atlas, the High Atlas and the Middle Atlas, which together occupy two third of the land. The topography is of tectonic origin, formed during three different phases. In the Paleozoic the Anti-Atlas formed as result of continental collision, at the beginning of the Mesozoic rifting took place and the current Atlas was a sedimentary basin. Finally, the High and Middle Atlas were formed as a result of the Alpine Orogeny (Pastor et al., 2012). The mean elevation in the High Atlas is 2000m, but mountain peaks can reach up to 4000m forming the highest topographic relief in North Africa.

The study area, the Ounila Catchment, is on the southern slope of the High Atlas Mountains in the upper Oued Drâa catchment (Figure 3.1). The river that drains the catchment is the Asif Ounila, which is a tributary of the Oued Drâa located towards the south. The upper parts of the Asif Ounila cut through Cretaceous and Tertiary sediments and here the predominant rock types are granites, limestones, marls, slates, shales and argillaceous rocks (Wyss et al., 2016). On the lower parts of the catchments, the foothills, the most abundant rock types are limestones, marls and argillaceous rocks. The higher parts exist of V-shaped valleys whilst the lower parts exist of canyon-like stepped foothill valleys. Natural vegetation in the area exists of perennials, conifers and evergreen oaks (Wyss et al., 2016). Yet, the natural vegetation density is low, mainly due to overgrazing.

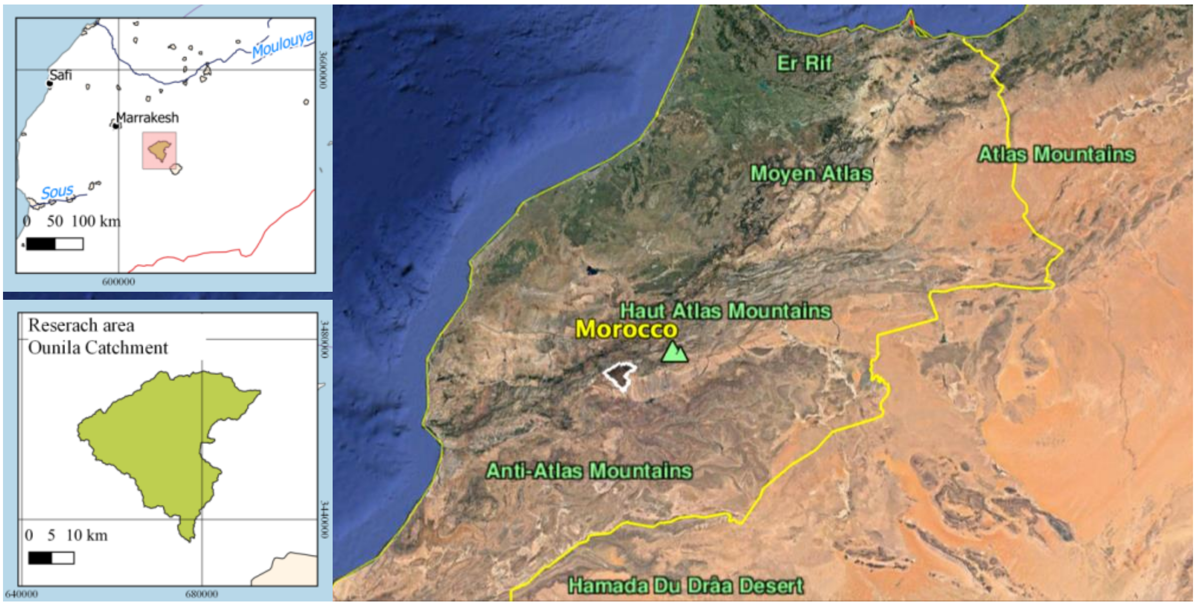


Figure 3.1 Location of research area, the Ounila Catchment in the High Atlas Mountain Morocco (source: Google Earth)

The outlet of the Ounila Catchment is close to Aït Ben Haddou (1270m) a ‘ksar’[1] that has been listed as UNESCO heritage since 1987 and has a great cultural importance with a population of 57,245. Upstream, in the hinterland, are the towns Tigzha (2035m) and Telouet (1820m) which roughly coincide with the end of the catchment. Marrakesh is located approximately 90km in northwestern direction and Ouarzazate roughly 40km in southwestern direction. In the study area there are no dams or reservoirs, but 25km south of Ouarzazate is the El Mansour Eddahbi hydraulic dam that holds up to 260 million cubic meters of water (Diekkrüger & Busche, 2012). The dam was built in 1972 and initially had a capacity of 560 million cubic meters, due to sedimentation this decreased drastically over the years.

In the research area the elevation ranges between 1240m and 3244m, and the area is approximately 730 km^2. In the current climate classification of Beck et al. (2018) the research area is classified as a temperate climate, with hot and dry summers. However, climate change induces a shift to more dry conditions and thus towards a more arid climate (Schilling et al., 2012). Therefore, the study area is said to have a semi-arid climate, where temperature and precipitation are highly dependent on elevation. The closest weather stations are in Ouarzazate and Toubkal, with elevations of 1120m and 1760m respectively (Figure 3.2). Therefore, this data is not entirely representative for the study area. In winter the area is subject to short periods of heavy rainfalls, whilst the yearly precipitation is only 250mm/yr. These numbers differ somewhat from the weather station in Ouarzazate and Toubkal mainly because of the elevation dependency of both precipitation and temperature. Furthermore, on locations higher than 2000m precipitation can fall as snow from October to May, but periods of snow are altered with periods of ablation, so a thick snow cover does not form (Schulz & de Jong, 2004). Nonetheless, snowfall is of great importance for the area, due to snowmelt the Asif Ounila is a permanent river.

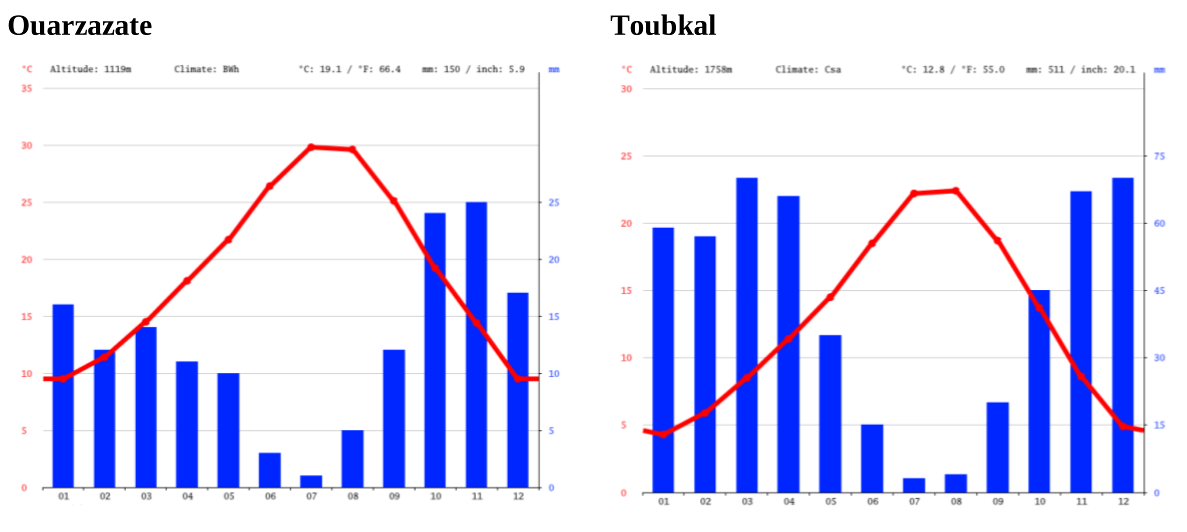


Figure 3.2 Overview of monthly precipitation and temperature over a 30-year period in Ouarzazate and Toubkal, located 40km southeast and 70km west from the research area, respectively (source: climate-data.org)

[1] Ksar is the North African term for a fortified village

Along the Asif Ounila there are multiple small compact villages and around the floodplain agriculture fields are abundant. The main cultivated crops are grain, vegetables and cattle fodder crop. The fields are for 90% irrigated with surface water (Schilling et al., 2012). The risks of cultivating on the floodplains are high; on the outer bank erosion is high whilst on the inner banks sedimentation occurs. Erosion poses a threat to the agriculture fields and houses on the riverbanks, whilst sedimentation increases the risks for floods. Therefore, the floodplains have a high susceptibility to floods, which increases the chance of crop failure and also proposes a threat to the villages. Further away from the floodplain locals keep livestock, but a shift from nomadic to sedentary livestock farming has caused exhaustion of the land (Figure 3.3). Even so, locals remain highly dependent on agriculture and farming, and most households do not have enough resources to survive repeated failures of harvest (Parish & Funnel, 1999). The focus of Perma Atlas is on repairing the ecosystem and to increase the community's knowledge on how to manage their lands in a sustainable way. For this, knowing where in the catchment restoration practices have maximum effect is crucial.

A.

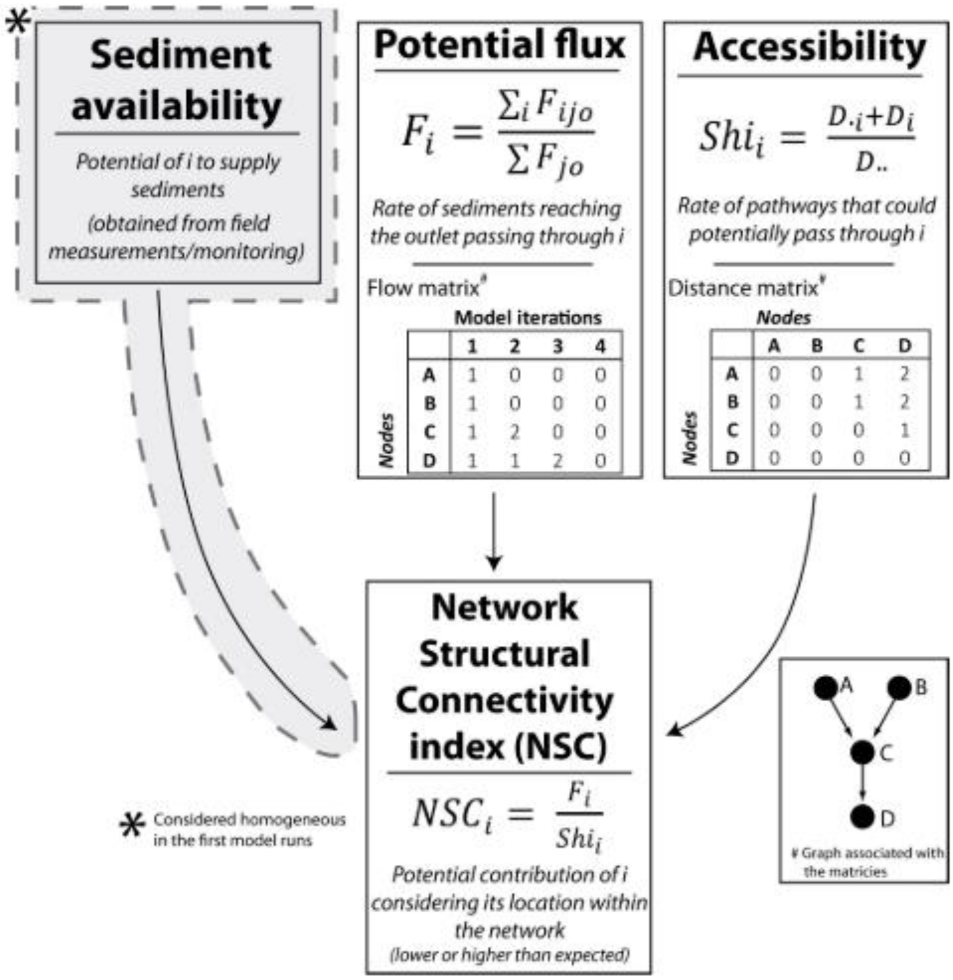
B.

Figure 3.3 Overview of the study area: a. degraded hillslopes b. agriculture fields near the town Anguelz, photos taken on a field campaign in spring 2015 (source: water4future)

4. Methodology

In this thesis a methodological approach is applied for the assessment of structural network connectivity. The aim is to locate areas of high connectivity, as these areas play an important role in the redistribution of water and sediments. In catchments where water is scarce and where soil erosion leads to the loss of fertile soils, locating these areas is of high importance. In order to redirect catchment restoration practices to areas of high connectivity, because here restorations are expected to have most impact.

For this study sediment cascades in the Ounila catchment are portrayed in a network structure, where sub-catchments are nodes and sediment pathways are edges. Such that, the network is represented by a graph G(N, E) and corresponding adjacency matrix. From here graph theory provides the tools to acquire structural properties of the graph which are used to assess connectivity. In this study the *potential flux* and *accessibility* are used, the first provides information on the movement of sediments through the network whilst the latter provides information on the influence of a node on the length of the sediment pathways (compactness of the network). The ratio between the potential flux (F_i) and the accessibility (Shi_i) gives the Network Structural Connectivity (NSC_i) index, as defined by Cossart & Fressard (2017). The NSC index is used to assess the structural network connectivity (Figure 4.1).



Flow matrix	1	2	3	4
A	1	0	0	0
B	1	0	0	0
C	1	2	0	0
D	1	1	2	0

Distance matrix	A	B	C	D
A	0	0	1	2
B	0	0	1	2
C	0	0	0	1
D	0	0	0	0

Figure 4.1 Network Structural Connectivity index (Cossart & Fressard, 2017)

First, the network structure was constructed. The sub-catchments and stream network were delineated with QSWAT+ and from this the adjacency matrix was derived (Table 4.1a). In RStudio the potential flux and accessibility were calculated, both were derived from the adjacency matrix (Table 4.1b). The potential flux is based on the sediment availability and imitates the movement of sediments through the system. The accessibility is based on the distances between the nodes and shows the spatial structure of the network. From this the NSC index was calculated, first with spatially uniform sediment availability and second with adjusted sediment availability (Table 4.1c). Finally, two different scenarios were explored, one to investigate the role of spatial extent on the NSC index and one to quantify the effect of using connectivity as decision maker tool for the location of restoration practices (Table 4.1d). In the following sections the various steps are explained in more detail.

Table 4.1 Summarized overview of the method, more information is given in the corresponding sections

A. Network structure (section 4.1)

QSWAT+ ➡	DEM ➡	Stream network (edges) ➡	Sub-catchments (nodes) ➡	Adjacency matrix

B. Parameters Network Structural Connectivity index (section 4.2)

Potential flux	Adjacency matrix ➡	Sediment availability ➡	Flow matrix ➡	F_i
Accessibility	Adjacency matrix ➡	Distance matrix ➡		Shi_i

C. NSC index scenarios (section 4.3)

	Adjacency matrix	Sediment availability	Distance matrix
Run 1	n^2	Spatially uniform	d^2
Run 2	n^2	Relation vegetation cover and soil loss	d^2
Scenario 1	Role of spatial extent on the NSC index		
Scenario 2	NSC index as indicator for choosing location or restoration practices		

4.1 Data preparation

Available data sets

Intrinsic properties of the system are important when assessing connectivity, for this research information on topography and land use are most relevant (Cossart & Fressard, 2017). Digital Elevation Models (DEMs) are a powerful tool to represent the topography of an area because it represents continuous elevation. For this research a DEM was used as input to create the watershed and to delineate the catchment into sub-catchments. The imagery was derived from the Shuttle Radar Topography Mission (SRTM), which was launched in 2000 by NASA. Initially the resolution was 3-arc second (90m). However, since 2015 this dataset was improved significantly which resulted in the NASADEM dataset with a resolution of 1-arc second (30m) which is the dataset used for this research (Figure 4.2).

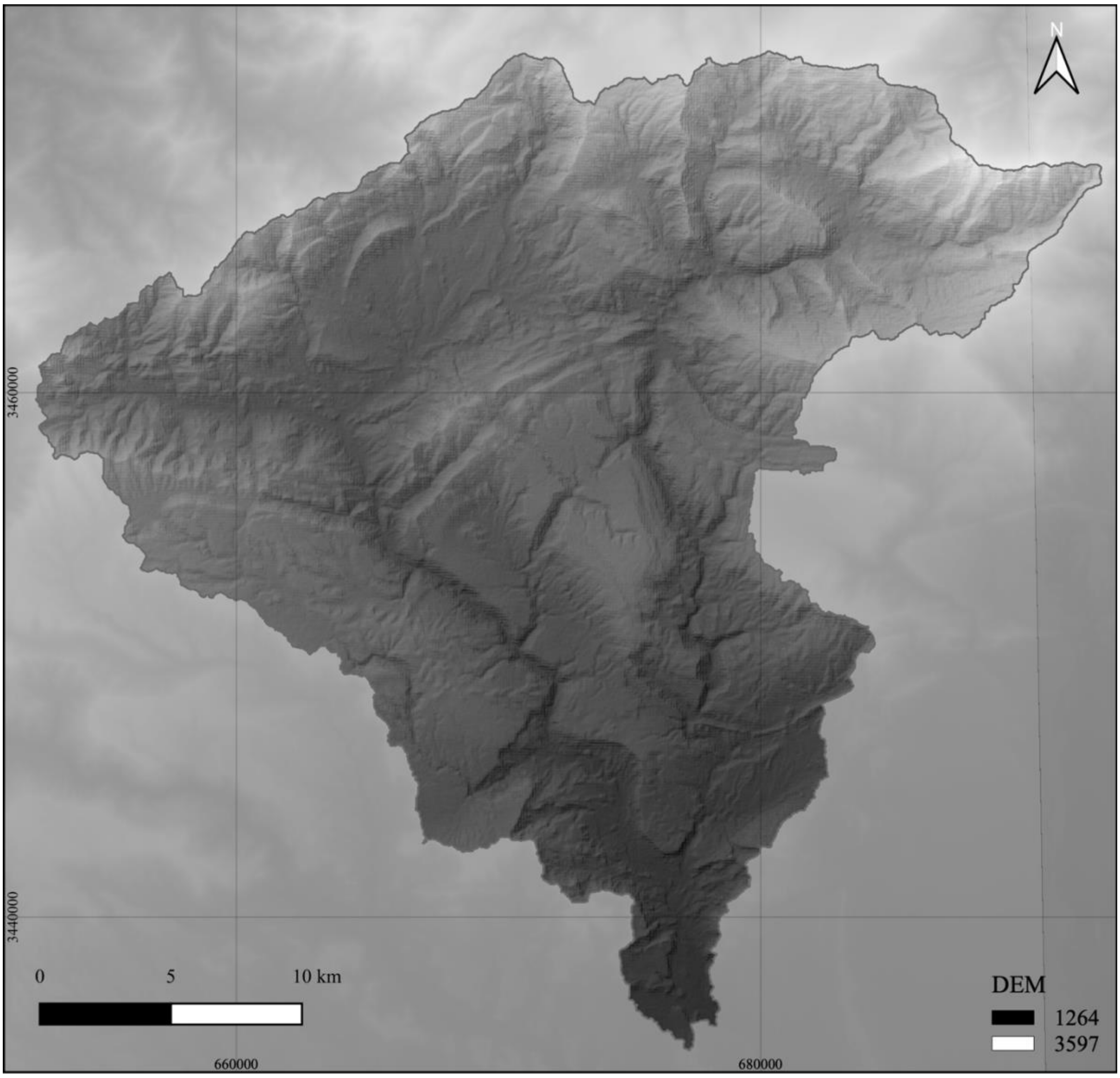


Figure 4.2 Digital Elevation Model of the Ounila Catchment, derived from the NASADEM dataset with a resolution of 30mx30m (source: https://dds.cr.usgs.gov/srtm/)

The availability of sediments is highly dependent on land use, since vegetation acts as a sediment sink whilst bare soils act as a sediment source. The European Space Agency (ESA) has freely available land cover data on resolutions ranging from 20m to 500m. For this research the highest possible resolution is used: 20mx20m (Figure 4.3). The area has 8 different classes, where bare areas are predominant. For this study both maps are projected in the local coordinate system of the research area: WGS 27BE/ UTM zone 29N and the maps are clipped to match the size of the study area.

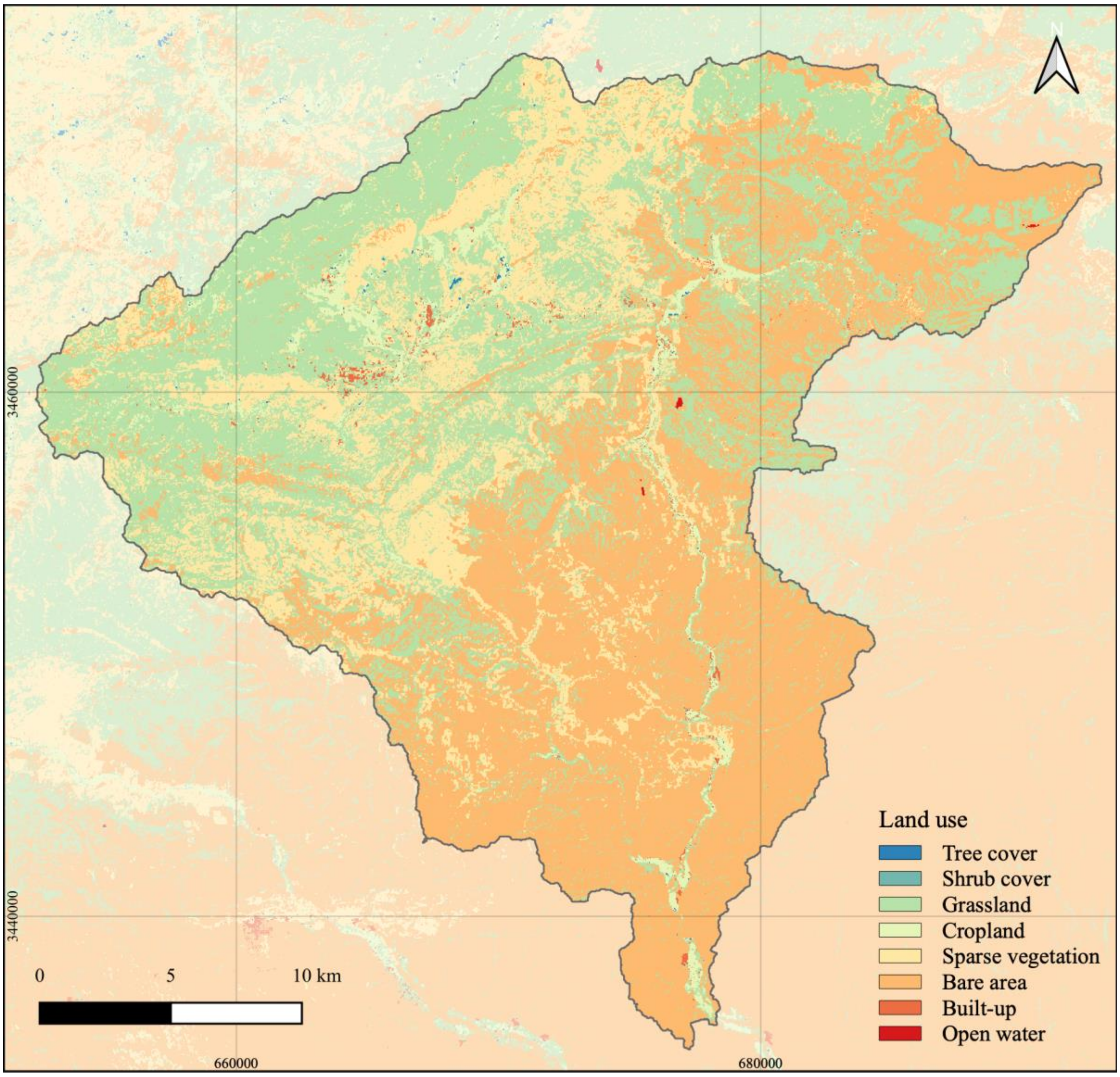


Figure 4.3 Land use resolution 20mx20m (source: https://www.esa-landcover-cci.org/?q=node/164)

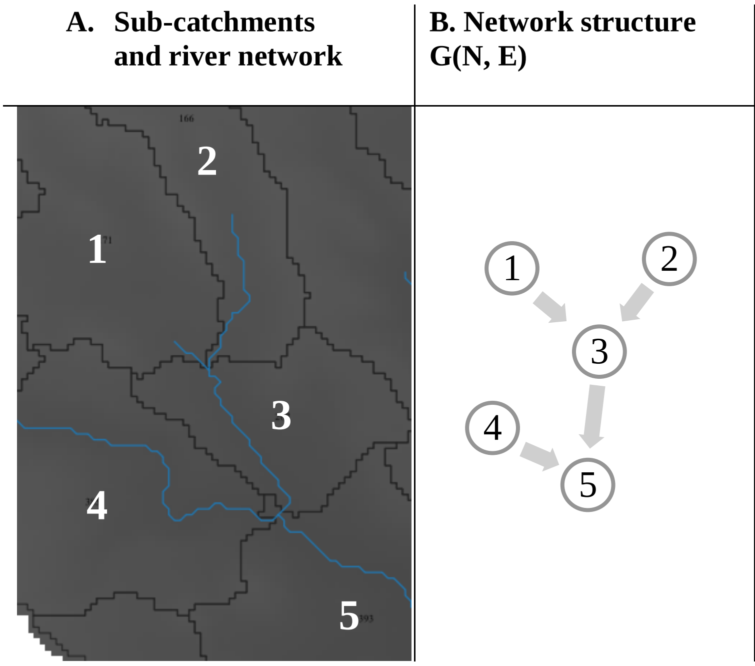
Delineation catchment

The spatial units that represent the nodes in the network structure are chosen to be sub-catchments. The sub-catchments are delineated with QSWAT+, which is the QGIS plugin for the SWAT+: Soil & Water Assessment Tool. The SWAT+ tool is a small watershed to river-basin scale model and is often used to model surface and groundwater flow and to predict the effects of environmental change (SWAT+, 2020). However, for this research the SWAT+ tool is used to delineate the watershed which is the first step when working with the SWAT+ model.

Input data was a Digital Elevation Model, with a resolution of 30mx30m. From the DEM, the watershed, the channels and the streams were differentiated, here converging flow is assumed. The creation of channels and streams was based on a threshold value which indicates the minimum area that needs to drain into a pixel to be classified as a channel or stream. Two different threshold values are necessary; the first threshold value is for the creation of channels and the second is for the creation of streams. Trial and error combined with visual comparison determined the threshold values, which for channels was 9ha and for streams 90ha. After the creation of the channel/stream network the outlet was defined. In this research area the outlet is next to Aït Ben Haddou located at: 31º02’55”N 07º07’58”W. From this the watershed was created and QSWAT+ divided the area in numbered sub-catchments. All adjacent sub-catchments smaller than 50ha were merged, in order to create more realistic units.

Network structure

For the application of graph theory, sediment cascades are represented with a network structure. In this research, sub-catchments represent nodes, and the river network represents sediment pathways and thus the edges (Figure 4.4a/b). To create the network structure information on sub-catchments that are connected through the river network was necessary. The output from QSWAT+ contains this information in the form of an edge list, where for every sub-catchment the downstream neighbor is given. Such that the edge list provides information on how the sub-catchments are connected. The edge list was transported in RStudio and from this the network structure was created. The last step was to create an adjacency matrix from the network structure, where rows are the source nodes and columns are the receiving nodes. For every connected sub-catchment, a 1 is given to the corresponding row/column (Figure 4.4c).



Source nodes \ Destination nodes	1	2	3	4	5
1	0	0	1	0	0
2	0	0	1	0	0
3	0	0	0	0	1
4	0	0	0	0	1
5	0	0	0	0	0

Figure 4.4 Example of the transformation of sub-catchments that are connected through the river network (A) to a network structure (B) and eventually to an adjacency matrix (C)

4.2 Parameters NSC index

Potential flow (F_i)

The potential flow is closely related to the betweenness index, discussed in chapter 2.4. The focus is to identify how the spatial structure of the network influences sediment transfer. This provides information on how each node impacts the movement of sediments through the system to the outlet. The adjacency matrix provides information on which nodes are connected and therefore can be used to simulate the evacuation of sediments through the system, from this the flow matrix is constructed:

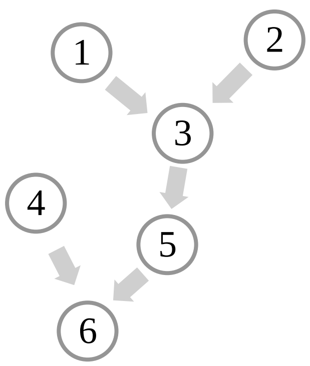
$$S_t = S_{t-1} * A \tag{9}$$

Here, S_t is a matrix (1x*n*) that represents the amount of sediments at each node at time step *t*. S_{t-1} represents the location of sediments at the previous iteration, and A is the adjacency matrix. Each time step corresponds to one iteration where the sediments are moved one edge in the direction of the outlet. The first time step (S_0) has the values of the initial sediment input (sediment availability per node). The iteration is repeated until all the sediments are evacuated, and the S_t matrix merely exists of zeros. Combining all the S_t matrixes give the synthetic matrix S which is the flow matrix. The flow matrix gives information on the number of paths from *j* to *o*, that lie on a specific node *i* (sum per row indicated by F_{ijo}) and on all the possible paths from *j* to *o* (sum of the paths indicated by F_{jo}). The potential flow is then:

$$F_i = {\sum_i F_{ijo}} \Big/ {\sum F_{jo}} \tag{10}$$

Where for each node *i* the potential flow is the ratio between the number of paths that lie on that node *i* and the total number of paths. This tells the potential proportion of flux discharge passing through this node *i* (Cossart & Fressard, 2017). For a virtual sediment cascade the network structure is drawn and the adjacency matrix is shown (Figure 4.5a/b). From the adjacency matrix the flow matrix is constructed, where S_0 represent a spatially uniform sediment input of 1. After four iterations the flow matrix becomes zero, which means that all the sediments are evacuated, and the flow matrix is constructed (Figure 4.5c). F_{ijo} is obtained from the sum of the rows of the flow matrix and F_{jo} is the sum of all F_{ijo} values (Figure 4.5d).

A. Network structure



B. Adjacency matrix

Destination nodes (columns) / Source nodes (rows)

Source nodes	1	2	3	4	5	6
1	0	0	1	0	0	0
2	0	0	1	0	0	0
3	0	0	0	0	1	0
4	0	0	0	0	0	1
5	0	0	0	0	0	1
6	0	0	0	0	0	0

C. Flow matrix

Source nodes	Model iteration S_0	S_1	S_2	S_3	S_4	S_5
1	1	0	0	0	0	0
2	1	0	0	0	0	0
3	1	2	0	0	0	0
4	1	0	0	0	0	0
5	1	1	2	0	0	0
6	1	2	1	2	0	0

D. Potential flow

Source nodes	Model iteration **0**	**1**	**2**	**3**	**4**	F_{ijo}	F_i
1	1	0	0	0	0	1	0,06
2	1	0	0	0	0	1	0,06
3	1	2	0	0	0	3	0,19
4	1	0	0	0	0	1	0,06
5	1	1	2	0	0	4	0,25
6	1	2	1	2	0	6	0,38
F_{jo}						16	

Figure 4.5 Virtual sediment cascade (A) as example of the calculations of the potential flow (F_i). First the adjacency matrix (B), then the flow matrix (C) and finally the variables for the calculations are derived (D)

The flow matrix also gives information on the sediment flux at each node, as each iteration represents as a simplified form of time (Cossart & Fressard, 2017). Therefore, each row in the flow matrix gives information on the amount of sediment that passes through that specific node. This information can be visualized in a sedimentograph. Moreover, the potential flow of the network is dependent on the sediment availability, as for the potential flow matrix an initial sediment input is necessary (S_0). This initial sediment input is translated to sediment availability per node. For simplification the first run of the NSC-index is done with a uniform spatial homogenous sediment input of one (similar to the example). So, every node begins with a sediment unit of one, and after each iteration these sediments move one step through the network towards the outlet. This run gives insight in the basic functioning of the catchment. The second run has adjusted sediment availability, where vegetation cover is taken into account for the initial sediment input (S_0). Many researchers focus on the complex representation of the relation between vegetation cover and soil loss (Figure 4.6).

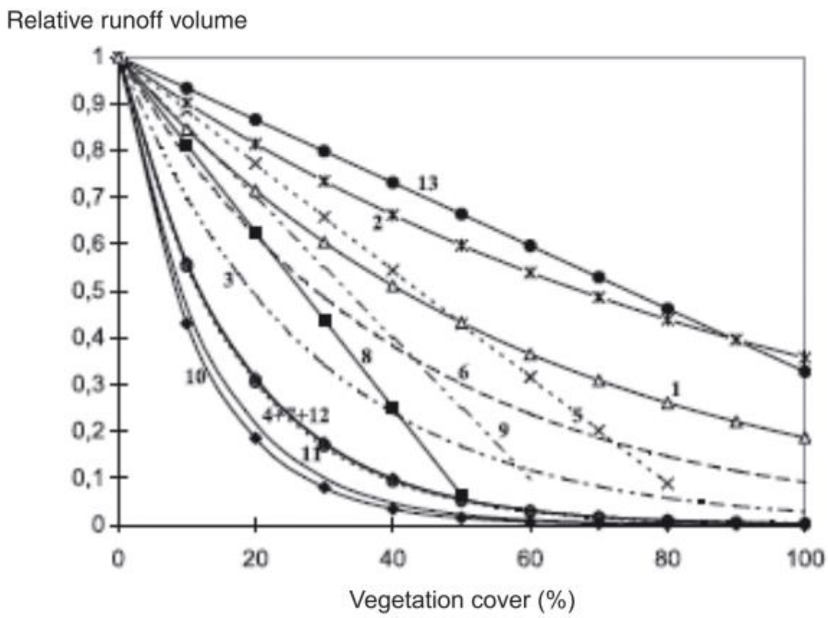


Figure 4.6 Different relationships for vegetation cover and relative runoff volume (Zuazo & Pleguezuelo, 2008)

The most acknowledged relation is a negative exponential curve (Figure 4.6, line 10):

$$SL = e^{-bC} \tag{11}$$

Here, SL is the relative soil loss compared to the soil loss on a bare surface, b is a constant ranging between 0.0235 and 0.0816 and C is the percentage of vegetation cover. The value of b depends on vegetation cover and their effectiveness in reducing splash, interril and rill erosion rates (Gyssels, et al., 2005). This relation is used to increase the representation of the area, with the value of 0.0816 for the constant b (Francis & Thornes, 1990). Percentage of vegetation cover is taken from the land use map. For simplicity everything but bare soil was considered vegetation, in QGIS the percentages vegetation cover was calculated per sub-catchment. This information was then used to calculate the relative soil loss, which eventually was used as S_0.

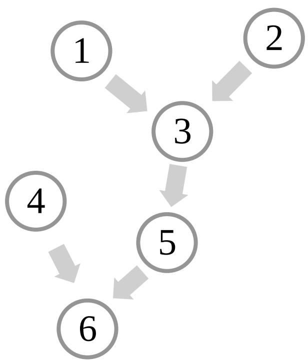
Accessibility (Shi_i)

The Shimbel index, discussed in chapter 2.4, gives information on whether a node increases or decreases the total length of all possible paths, and thereby gives information on the accessibility of the nodes inside a network. However, since the Shimbel index is for undirected graphs only, the original calculations need some adjustments, this is done through the creation of a distance matrix (Cossart & Fressard, 2017). A distance matrix has the same structure as the adjacency matrix (n^2), but besides information on the total length of all possible paths ($D_{\cdot\cdot}$), also gives information on the distances between node *i* and all the nodes downstream (D_i) and on the total distances between node *i* and its sources ($D_{\cdot i}$). Following Cossart & Fressard (2017) the Shimbel index becomes:

$$Shi_i = {D_{\cdot i} + D_i}/{D_{\cdot\cdot}} \tag{12}$$

The Shimbel index is the ratio of the length of paths that lie on node *i* to the total length of the paths within the network. The distance matrix is derived from the adjacency matrix, and for simplicity the distances between nodes are assumed to be in unity and not Euclidean distance (Figure 4.7a/b/c). In the distance matrix the sum of the row indicates the distance from the node to the outlet: D_i, whilst the sum of the column indicates the distance from the node to its sources: $D_{\cdot i}$ (Figure 4.7d). When the Shimbel index is low, the node contributes to creating short paths within the network. This makes the network more compact and thus increases connectivity. Likewise, a node with a high Shimbel index creates long paths in the network and therefore decreases connectivity.

A. Network structure



B. Adjacency matrix

Source nodes \ Destination nodes	**1**	**2**	**3**	**4**	**5**	**6**
1	0	0	1	0	0	0
2	0	0	1	0	0	0
3	0	0	0	0	1	0
4	0	0	0	0	1	0
5	0	0	0	0	0	1
6	0	0	0	0	0	0

C. Distance matrix

Source nodes / Destination nodes

	1	2	3	4	5	6
1	0	0	1	0	2	3
2	0	0	1	0	2	3
3	0	0	0	0	1	2
4	0	0	0	0	1	2
5	0	0	0	0	0	1
6	0	0	0	0	0	0

D. Shi calculations

Source nodes / Destination nodes

	1	2	3	4	5	6	D_i	Shi_i
1	0	0	1	0	2	3	6	0,32
2	0	0	1	0	2	3	6	0,32
3	0	0	0	0	1	2	3	0,36
4	0	0	0	0	1	2	3	0,16
5	0	0	0	0	0	1	1	0,37
6	0	0	0	0	0	0	0	0,58
$D_{\cdot i}$	0	0	2	0	6	11	19	

Figure 4.7 Virtual sediment cascade (A) as an example of the calculations of the accessibility (Shi). First the adjacency matrix (B), then the distance matrix (C) and finally the variables for the calculations are derived (D)

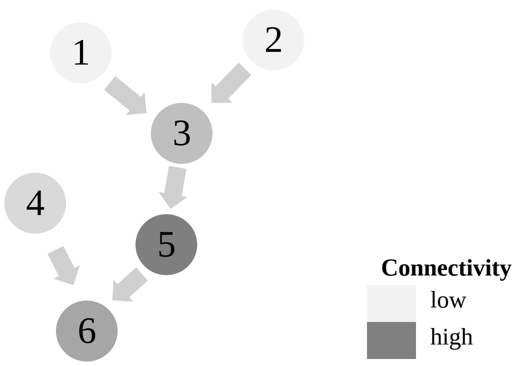
Example NSC

To get a better insight in the effect of the parameters on the connectivity, the connectivity of the example data set was calculated, with connectivity defined as the Network Structural Connectivity index (Cossart & Fressard, 2017):

$$NSC_i = {F_i}/{Shi_i} \tag{13}$$

The NSC index expresses connectivity as the ratio of the potential flow and the accessibility (Figure 4.8). For the example data set, node 1 and 2 have the lowest connectivity values, this is because they are furthest away from the outlet (high accessibility) and don’t have many sediment paths passing through them (low potential flow). However, node 5 and 6 have high connectivity values, both are close to the outlet (low accessibility) and have many sediments paths passing through them (high potential flow). Especially node 5 can be considered a geomorphic hotspot; the potential influence of this node on the network is high, where disruption may alter the interaction of the sediment paths and other nodes.

A. Network structure



B. NSC

Nodes

	F_i	Shi_i	NSC
1	0,07	0,32	0,22
2	0,07	0,32	0,22
3	0,2	0,36	0,56
4	0,07	0,16	0,44
5	0,27	0,37	0,73
6	0,38	0,58	0,65

Figure 4.8 Same example data set as before with the network structure (A) and the potential flow, accessibility and NSC index per node (B)

4.3 NSC index scenarios

For the Ounila catchment the NSC-index was first calculated with a spatial uniform sediment availability of one. This produced a base map that gave the first insights in the functioning of the catchment and possible locations of hotspots (hereafter referred to as run 1). However, since the potential flow (F_i) is related to the flow matrix and thus to sediment availability spatial uniform sediment is not representative enough. To increase accuracy a second run was explored where sediment availability was adjusted (hereafter referred to as run 2). Here, the relation between vegetation cover and soil erosion was taken into account, with the relation as defined by Francis & Thornes (1990). In both runs accessibility remained unchanged, accessibility only considers the location of nodes relative to each other and thus solely depends on the spatial structure of the network.

To explore the role of spatial extent on the NSC-index a scenario was run (hereafter referred to as scenario 1). Here, the same method was applied as for run 2, but for a smaller spatial scale. Instead of the entire Ounila catchment a smaller catchment was chosen; the Anguelz catchment located in the north east part of the Ounila catchment. Here, the town Anguelz is located, where in 2014 devastated floods occurred and as a result Perma-Atlas started restoration practices in this area. This makes the Anguelz catchment interesting for further investigation. The spatial patterns were than compared to find out if the spatial extent is of significant influence for the NSC index and the location of geomorphic hotspots.

Finally, the possibility of using the NSC-index as an indicator for choosing the location of restoration practices is examined with a new scenario (hereafter referred to as scenario 2). For this scenario again the Ounila catchment was used, but now a hypothetical five percent of the sub-catchments were selected to be restored. For restoration the vegetation cover was adjusted to imitate that of a healthy dryland vegetation cover (50%). First, the sub-catchments to restore were selected from sub-catchments with low vegetation cover and second the sub-catchments to restore were selected from sub-catchments with vegetation cover and high NSC index. In order to quantify the differences, the sediment flux at the outlet was compared.

5. Results

5.1 Network structure

The delineation of the Ounila catchment resulted in 389 sub-catchments (Figure 5.1). In this figure, the river network is also visualized: the channels functions as the sediment pathways between the sub-catchments. A distinction can be made between sub-catchments that have no incoming rivers, mostly found at the edges of the catchment, and those that have multiple incoming rivers.

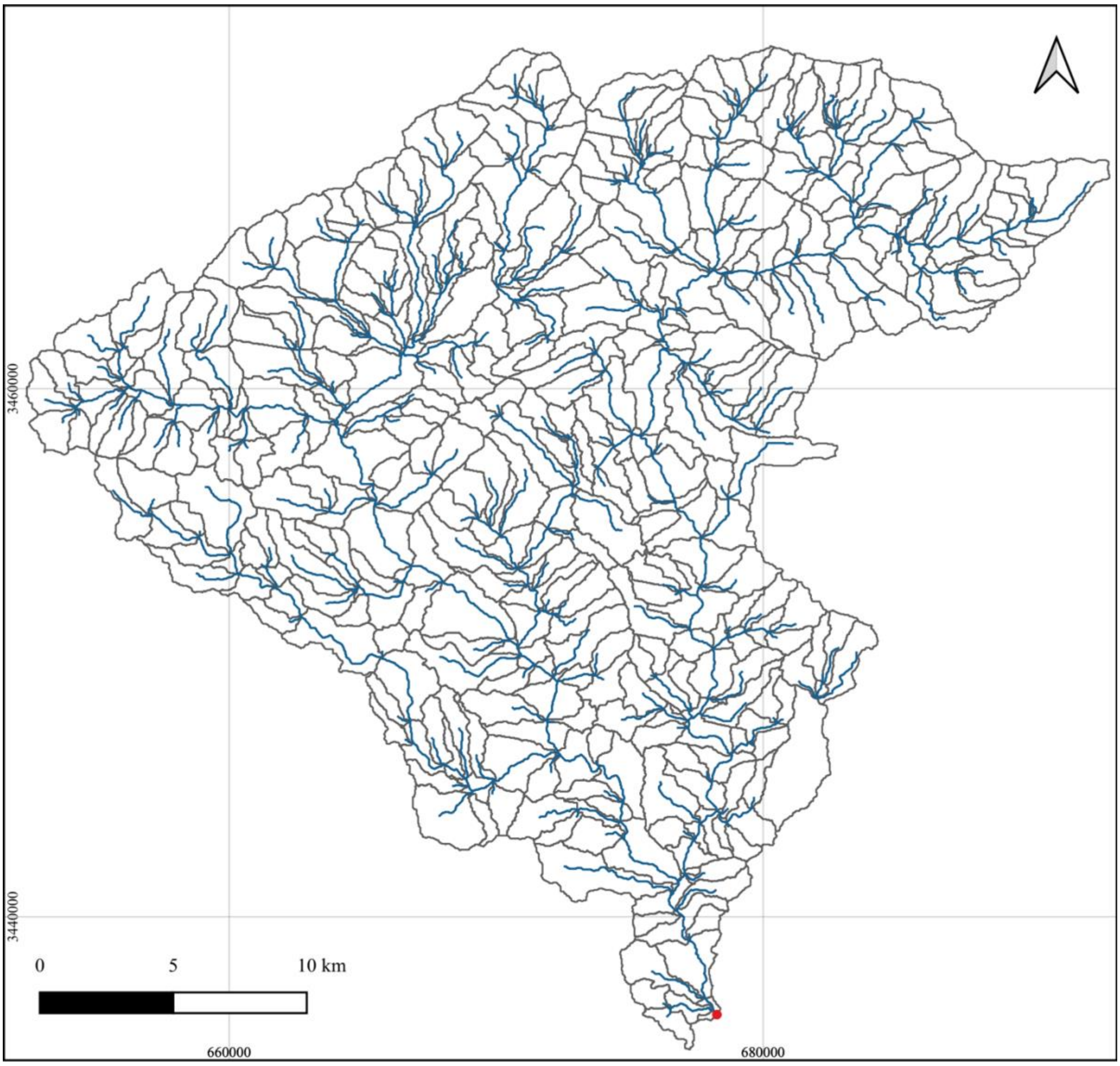


Figure 5.1 Delineation of the Ounila catchment: 389 sub-catchments, where sediment pathways are represented with the stream network. The red dot indicates the location of the outlet of the catchment

The sub-catchments range in size from 40 ha to 600 ha, with an average of 185 ha (Figure 5.2). There is only one sub-catchment with a larger area (838 ha), which is an outlier in the distribution. The sub-catchments and river network were transformed to a network structure, where sub-catchments form the nodes and the river network make up the connecting edges

(Figure 5.3). The highlighted nodes (sub-catchments 373, 399, 420 and 470) have many (>5) incoming rivers, and thus a high order index (section 2.2), therefore these are expected to have high importance within the connectivity framework.

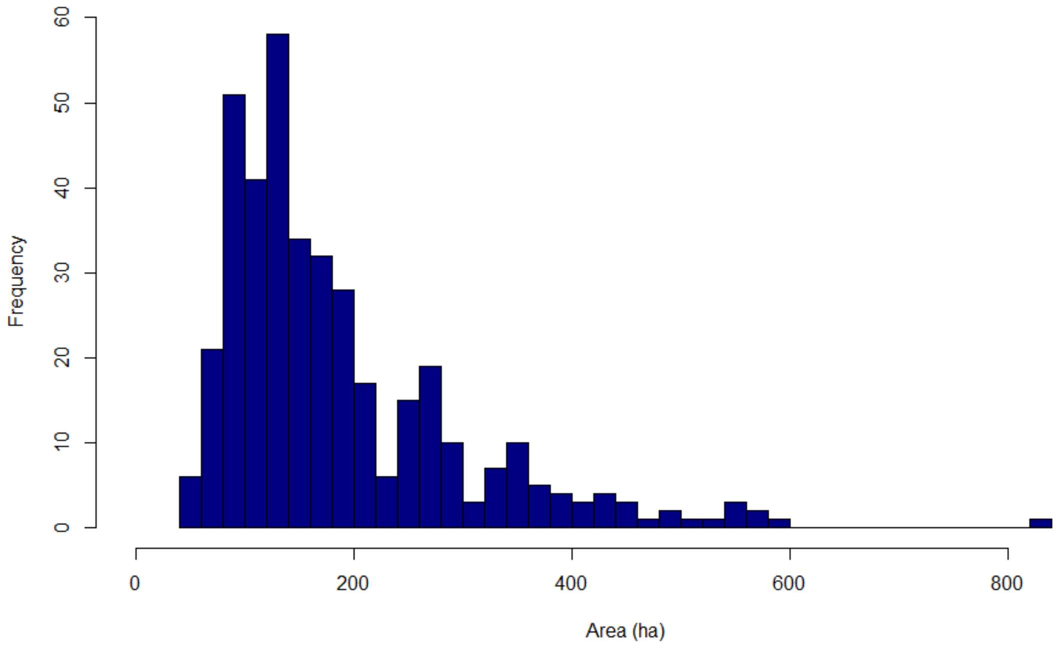


Figure 5.2 Size distribution of the sub-catchments (ha)

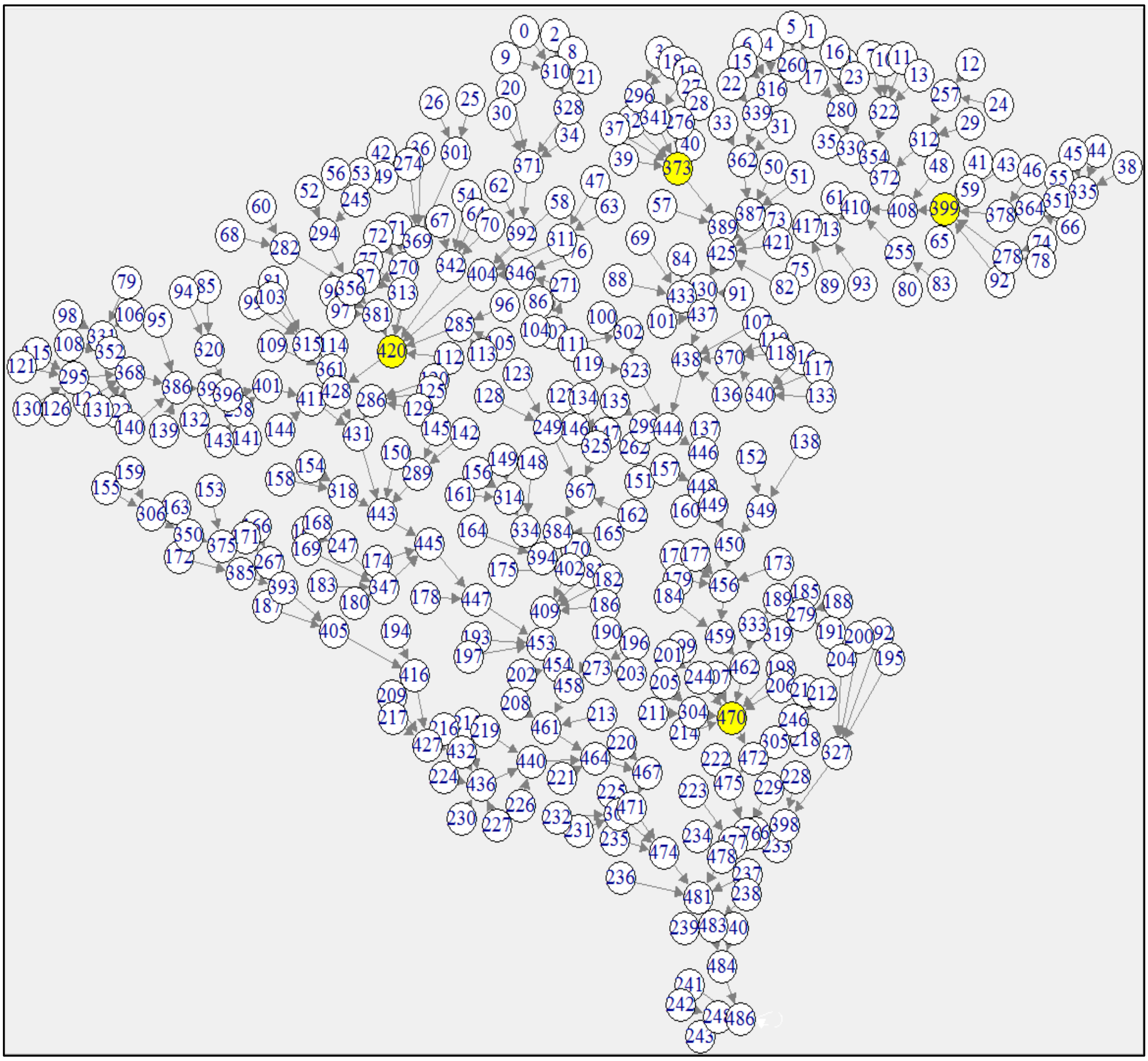


Figure 5.3 Network representation of the catchment, where nodes represent sub-catchments and edges represent sediment pathways. Highlighted are the nodes that have more than 5 incoming edges

5.2 Parameters NSC

Potential flow (F_i)

The potential flow is derived from the flow matrix, which is dependent on the sediment availability in each node. First, a spatial uniform sediment availability of 1 was assumed for each node and from this the flow matrix was derived. From the flow matrix the potential flux was calculated, and the values are visualized per sub-catchment (Figure 5.4). The potential flow values range between 0 and 0.08 and follow the river network. The values increase for the sub-catchments that are closer to the outlet and where the upstream contributing area is large. This is a logical response since the system has just one outlet and there are no sinks or barriers present Therefore, many sediments pass through the sub-catchments close to the outlet, which results in high potential flow.

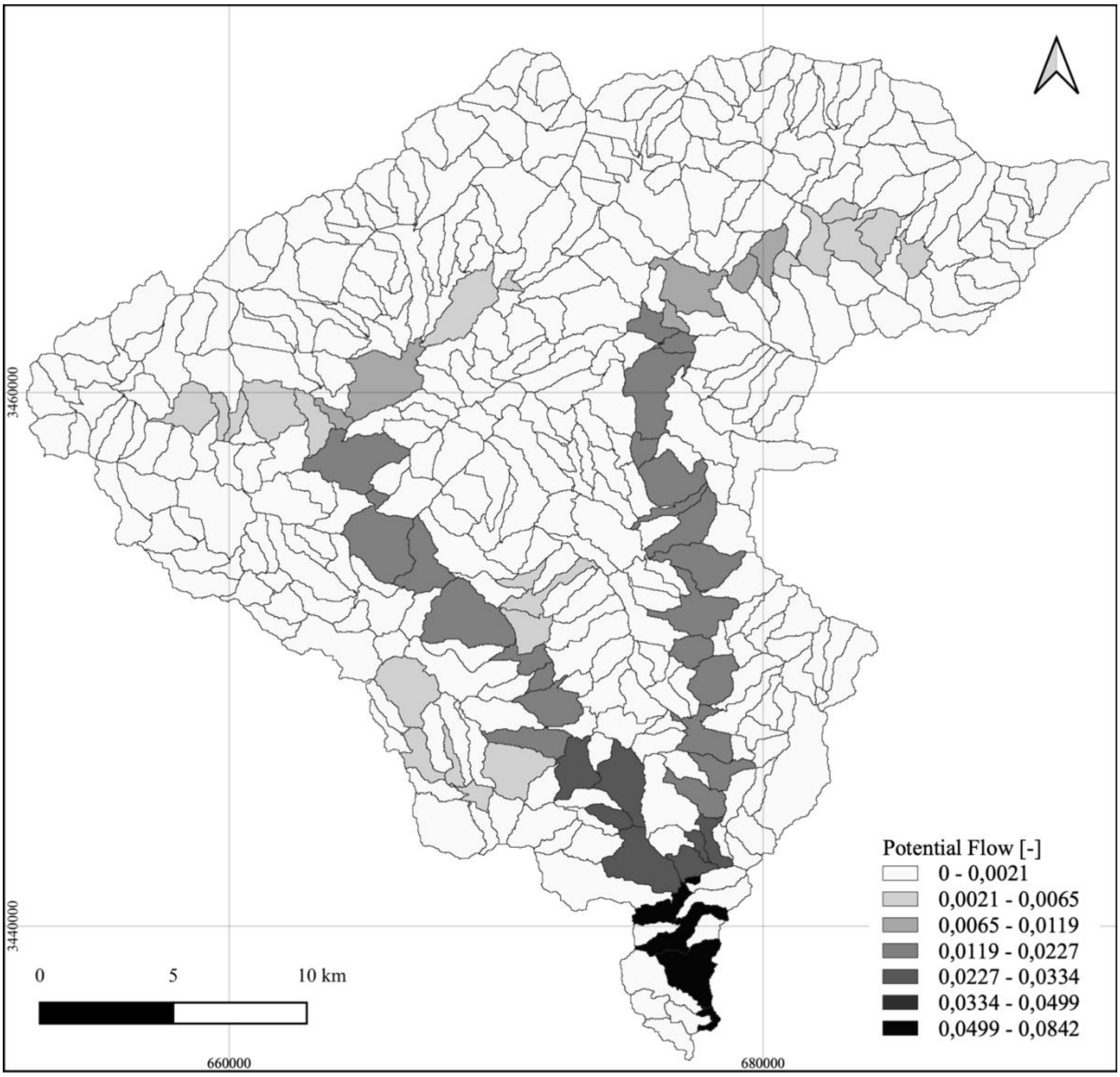


Figure 5.4 Potential flow Ounila catchment: spatial uniform sediment input (legend: natural breaks)

Sediment availability is highly dependent on vegetation cover, which is not taken into account in the previous calculations. Therefore, the potential flow was calculated a second time but with adjusted sediment availability based on the relation between vegetation cover and soil loss. High vegetation cover is found in the north west part of the area whilst low vegetation cover is at the south east part (Appendix 1). The sediment availability was calculated and presented on a scale of 0 to 1, where 0 means that there is no sediment available for transport, and 1 means that the available sediment is equal to that of a bare soil surface. Sediment availability is lowest in the north west part of the catchment, which clearly shows the effect of vegetation cover (Appendix 2). Concisely, the parts where sediment availability is high correspond to the parts were there is little to no vegetation. The sediment availability was then used as S_0 to calculate the potential flow again (Figure 5.5). The values range from 0 to 0.0842, and the effect of the high vegetation in the north west part is clearly visible. Overall, the pattern remains similar to the first run where the spatial patterns follow the river network and where values are found near the outlet for sub-catchment with a large upstream contributing area.

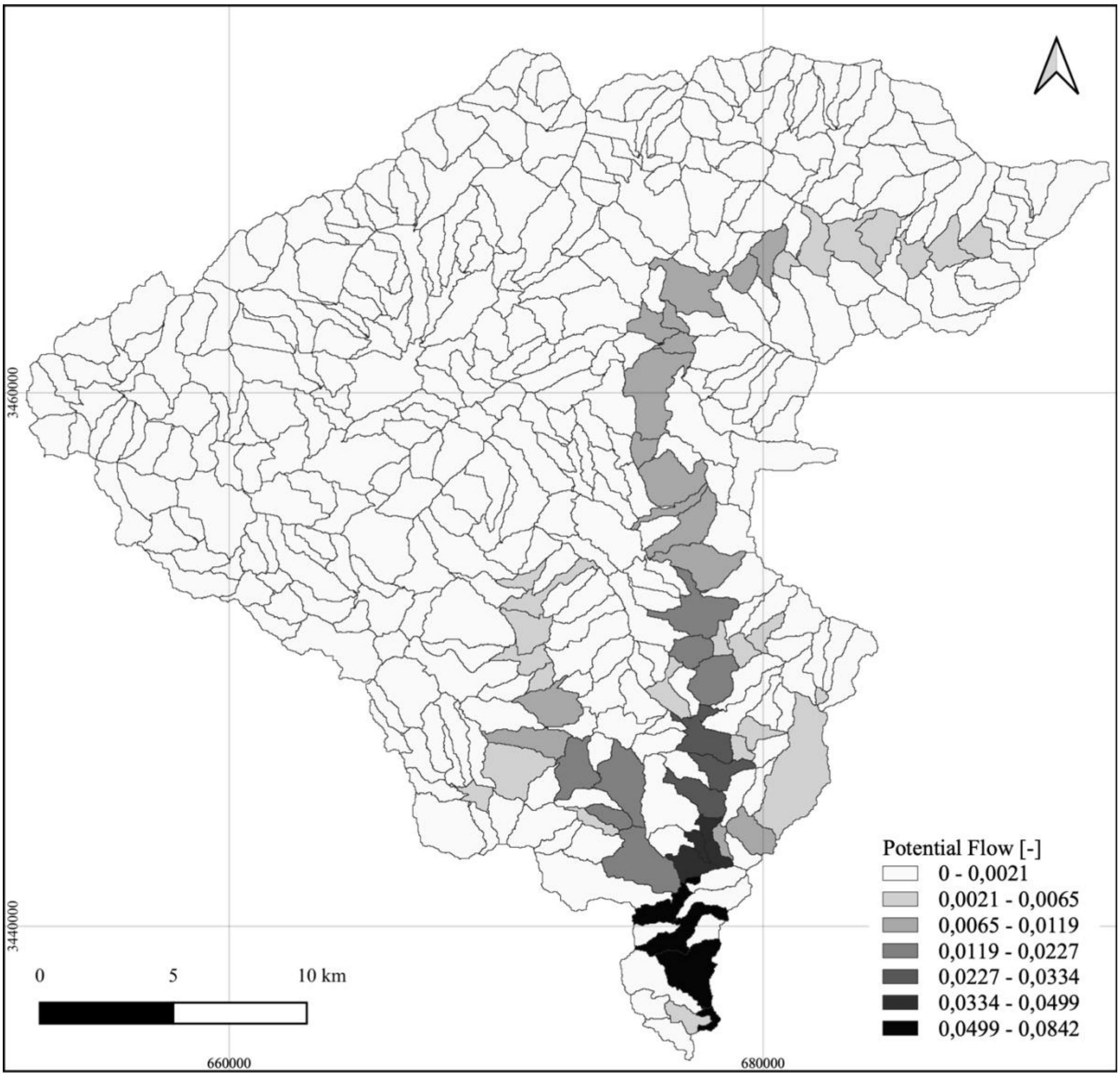


Figure 5.5 Potential flow Ounila catchment: sediment availability is adjusted based on the relationship between vegetation cover and soil loss (legend: natural breaks)

Accessibility (Shi)

Accessibility is the ratio of the distances of a node and its upstream/downstream paths and the total distances (Figure 5.6). Low values indicate high connectivity, because these sub-catchments create short sediment pathways in the network. Here, the values range from 0 to 0.092. A gradient is seen in the source sub-catchments: close to the outlet they have low values, and their value increases when moving north. This pattern is reversed for the river network. The highest values are closest to the outlet and the values decrease moving further north.

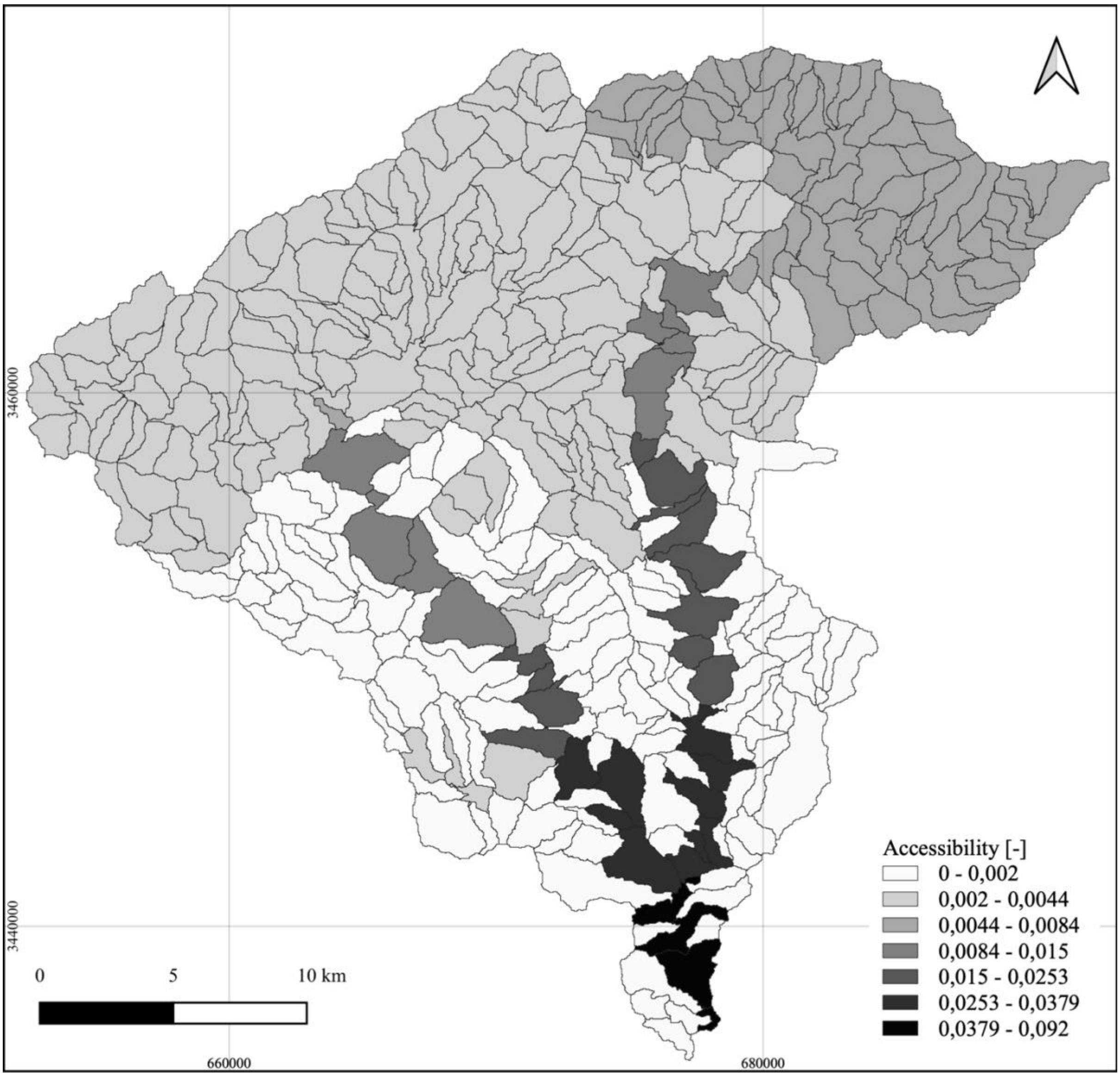


Figure 5.6 Accessibility Ounila catchment; distance per edge is assumed the value of 1 (legend: natural breaks)

5.3 NSC scenarios

Combining the potential flow and the accessibility gives the Network Structural Connectivity index. First two runs are explored, to examine the spatial patterns of connectivity in the Ounila catchment. The first run is based on potential flow with spatial uniform sediment input (Figure 5.4) and unadjusted accessibility (Figure 5.6). The second run is based on potential flow with adjusted sediment input (Figure 5.5) and unadjusted accessibility (Figure 5.6). Next, two scenarios are run that aim to give more insight in the used method. The first scenario is based on the same variables as run 2 but for a smaller catchment, to test the effect of spatial extent on the connectivity index. And for the second scenario the effects of restorations were imitated and analyzed.

Spatial uniform sediment availability

For the first run potential flow with a spatial uniform sediment availability was combined with accessibility (Figure 5.4/5.6). This resulted in a base map of connectivity values for the research area (Figure 5.7). The values range from 0 to 10,3 and a pattern similar to the river network can be seen. More specifically, the connectivity values show a longitudinal (headwater to outlet) pattern as well as a lateral (river to floodplain) pattern. Longitudinal, there is an increase in connectivity values from the headwaters to the outlet, with highest values closest to the outlet. Lateral, the connectivity values decrease with increasing distance from the river network. Moreover, the west part of the river network shows higher connectivity values than the east part. Lowest connectivity values are found in catchments that are far away from the outlet, e.g. the catchment at the borders and in between the river network. These catchments are all so called ‘source nodes’; sub-catchments that do not have an incoming river, and thus solely act as a source of sediment.

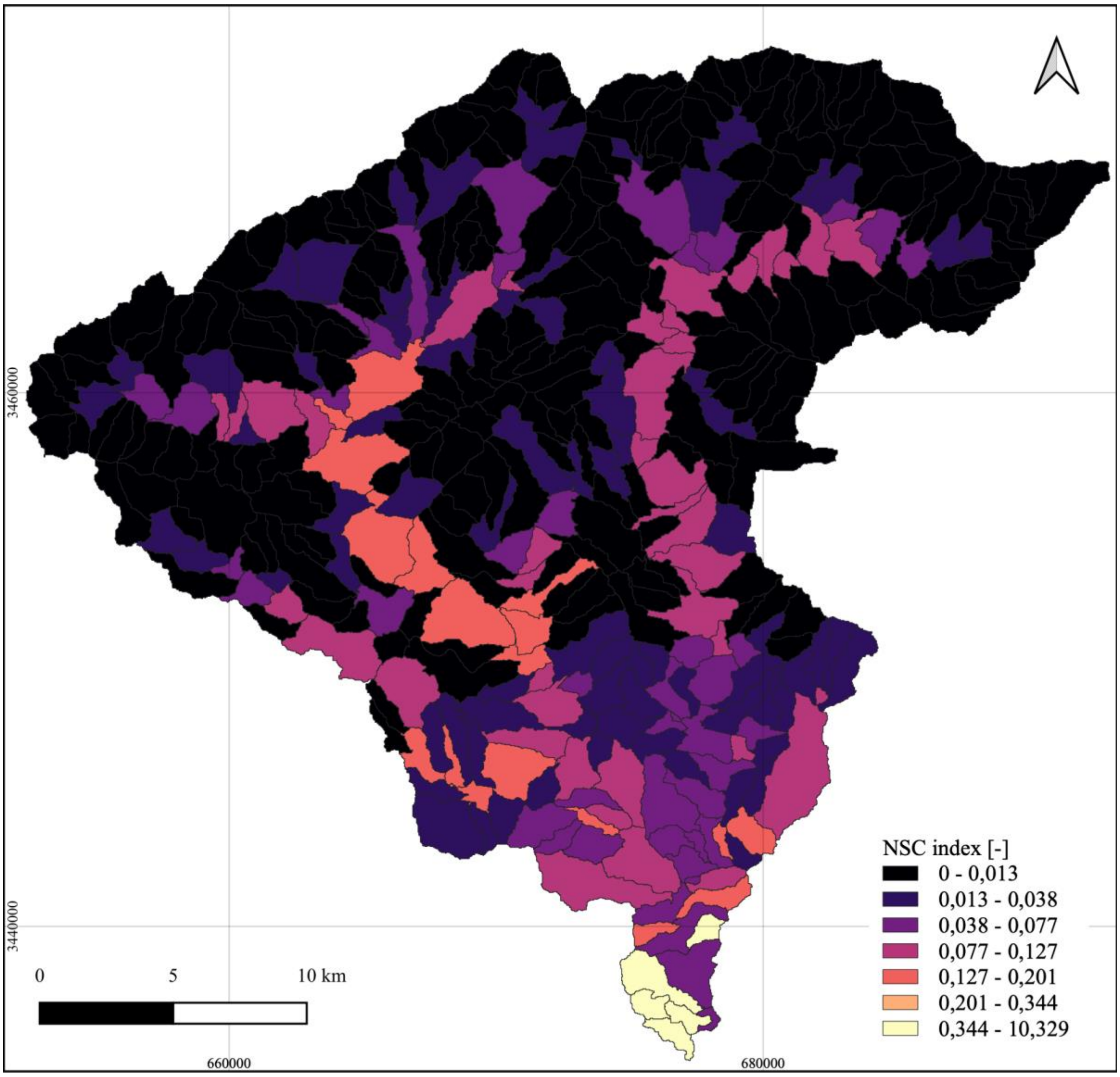


Figure 5.7 Network Structural Connectivity Index – spatially uniform sediment input (legend: natural breaks)

Adjusted sediment availability

For the second run the potential flow is adjusted whilst the accessibility remained the same (Figure 5.5/5.6). This resulted in a more realistic map of the connectivity values for the research area (Figure 5.8). The values range from 0 to 10.3, and more sub-catchments with high values are seen compared to the base map. The east part of the river network is still visible, and shows decreasing values moving further north. The longitudinal and lateral patterns are less visible. The main pattern is that sub-catchments located further away from the outlet decrease in connectivity value. Furthermore, the highest connectivity values are found closest to the outlet.

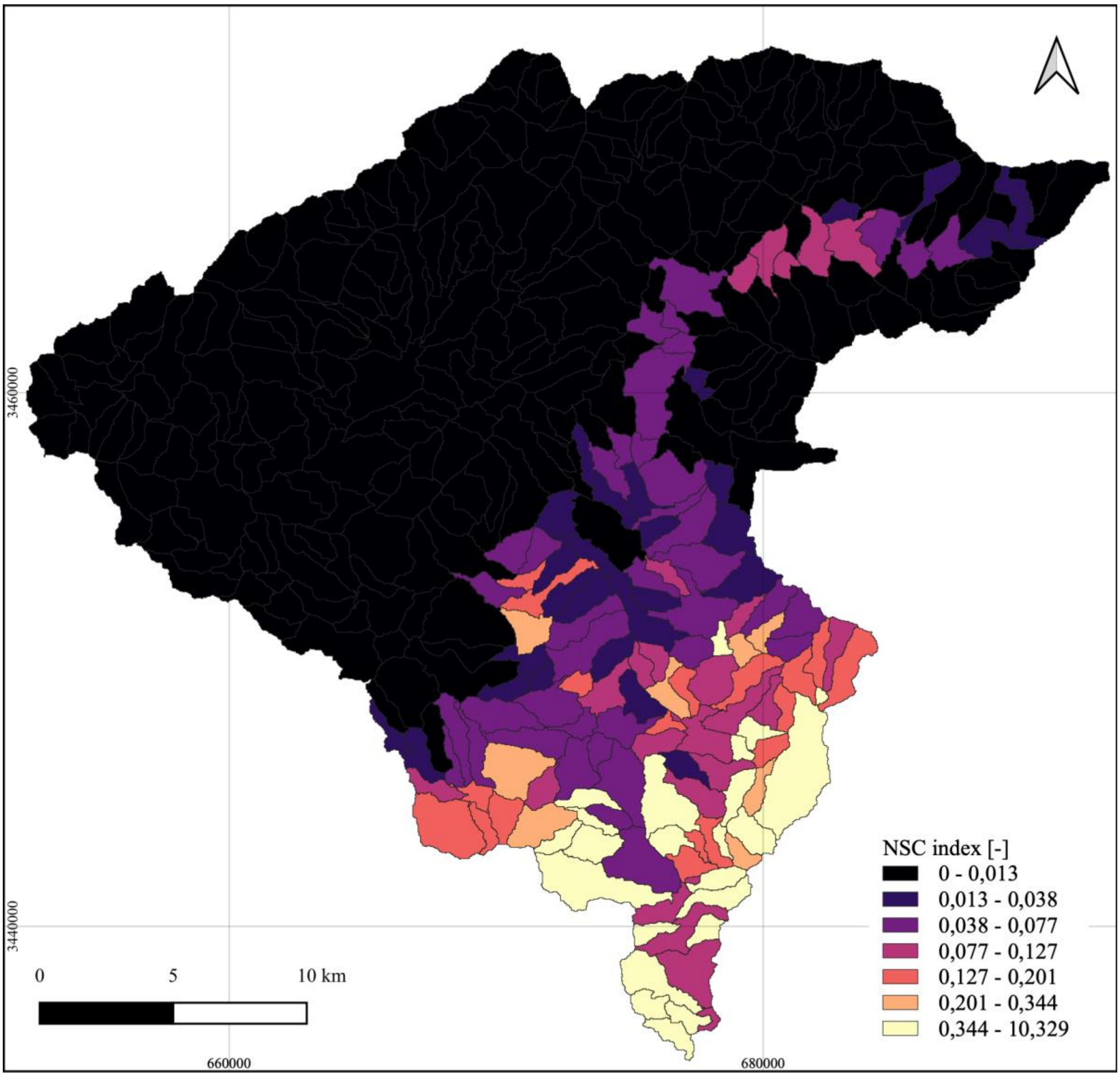


Figure 5.8 Network Structural Connectivity Index – adjusted sediment availability (legend: natural breaks)

Role of spatial extent

In order to find out what the role of spatial extent is on the NSC-index, the analysis is run for a smaller catchment. The Anguelz catchment is located in the north east part of the Ounila catchment, delineation of the catchment resulted in 95 numbered sub-catchments. (Figure 5.9). Because the Anguelz watershed was delineated again the sub-catchments differ very slightly in shape and size. Again, the network structure was created, where the river network provided information on the connected sub-catchments. Information on the sediment availability was derived from the relation between vegetation cover and soil loss, similar to run 2.

From this the potential flow and accessibility were calculated (Figure 5.10). The potential flow values range from 0 to 0.1 (Figure 5.10a). The sub-catchments that are close to the east part of the river network increase in value. The sub-catchments on around the edges and the west side of the catchment have very low potential flow values. The accessibility values range from 0 to 0.2 (Figure 5.10b). And a similar pattern is seen as the accessibility values for the Ounila catchment. The source sub-catchments show a decreasing pattern moving further away from the outlet, whilst sub-catchment close to the river network shows a reversed pattern, where accessibility increases towards the outlet.

From the combination of the potential flow and the accessibility the NSC index was calculated (Figure 5.11). The values range from 0 to 0.6. Sub-catchments close to the east part of the river network show the highest values. Source sub-catchments that are far away from the outlet have very low values, whilst source node close to the outlet increase in value.

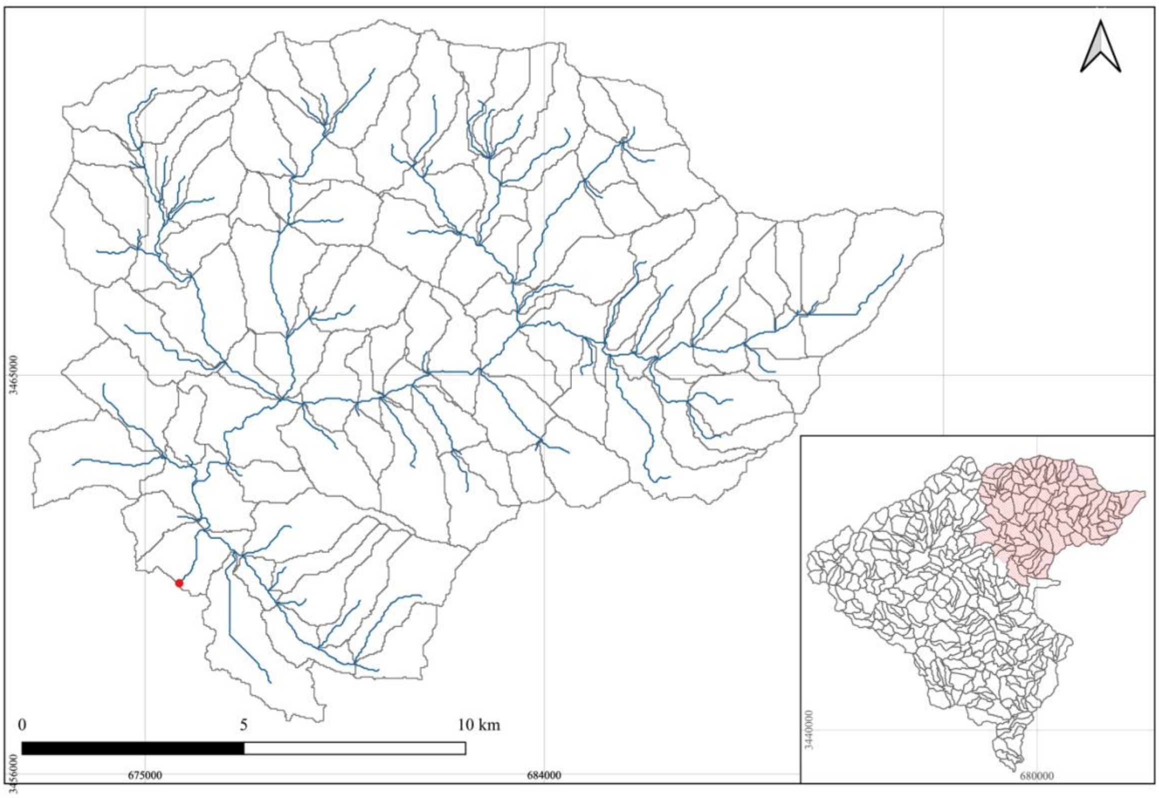


Figure 5.9 Anguelz catchment: delineation sub-catchments and river network

A. B.

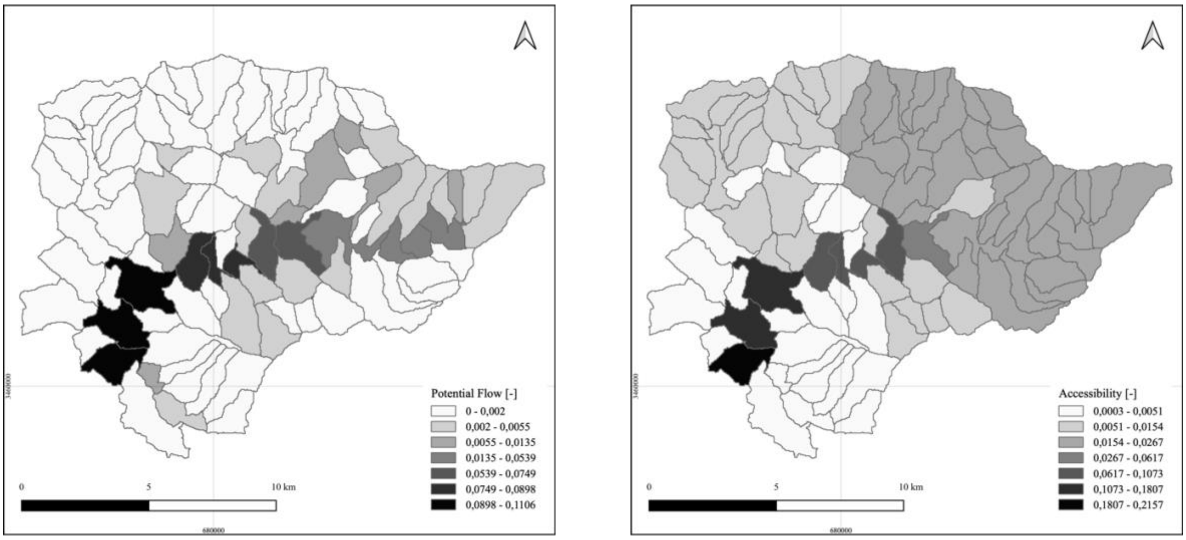


Figure 5.10 Potential flow (A) and the accessibility (B) for the Anguelz catchment

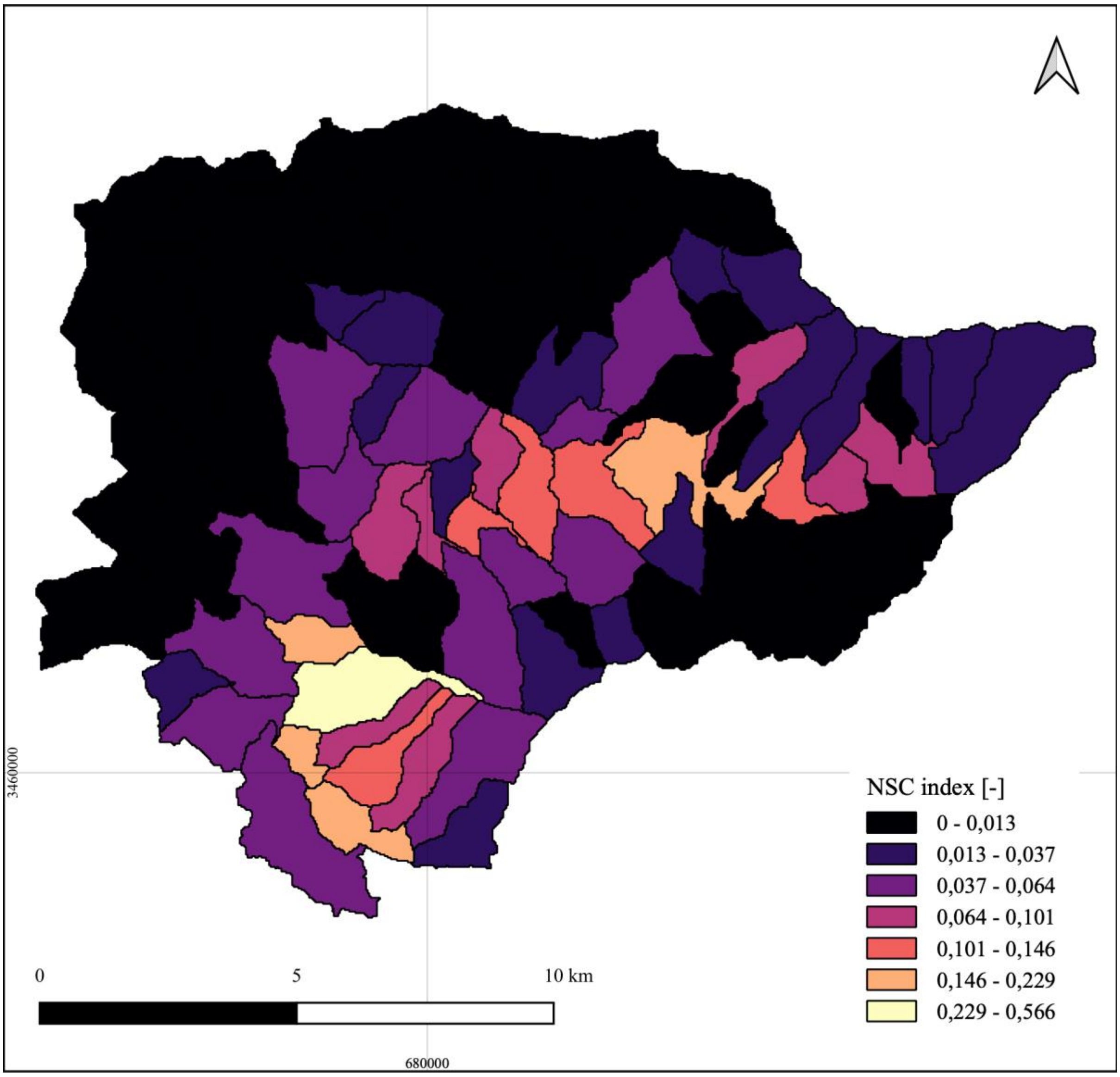


Figure 5.11 Network Structural Connectivity index for the Anguelz catchment (legend: natural breaks)

Restoration practices

In order to find out if the NSC-index is beneficial in choosing the location of restoration practices two simulations are explored. For this simulations five percent of the catchments were imitated to be restored, where restoration was imitated by increasing the vegetation cover to 50%. First, the sub-catchment to be restored were randomly selected, but only from sub-catchment with low vegetation cover (Figure 5.12). From the new vegetation cover values the potential flow was calculated and the sedimentograph was constructed (Figure 5.13). The sedimentograph is also compared with the sedimentograph from run 2. The shape of the sedimentograph looks similar, but the main difference is the intensity of the peaks. Especially the third peak has a much lower sediment volume. Also, the second peak is noticeable because of its distinct different shape. Overall, the sediment flux is decreasing compared to run 2.

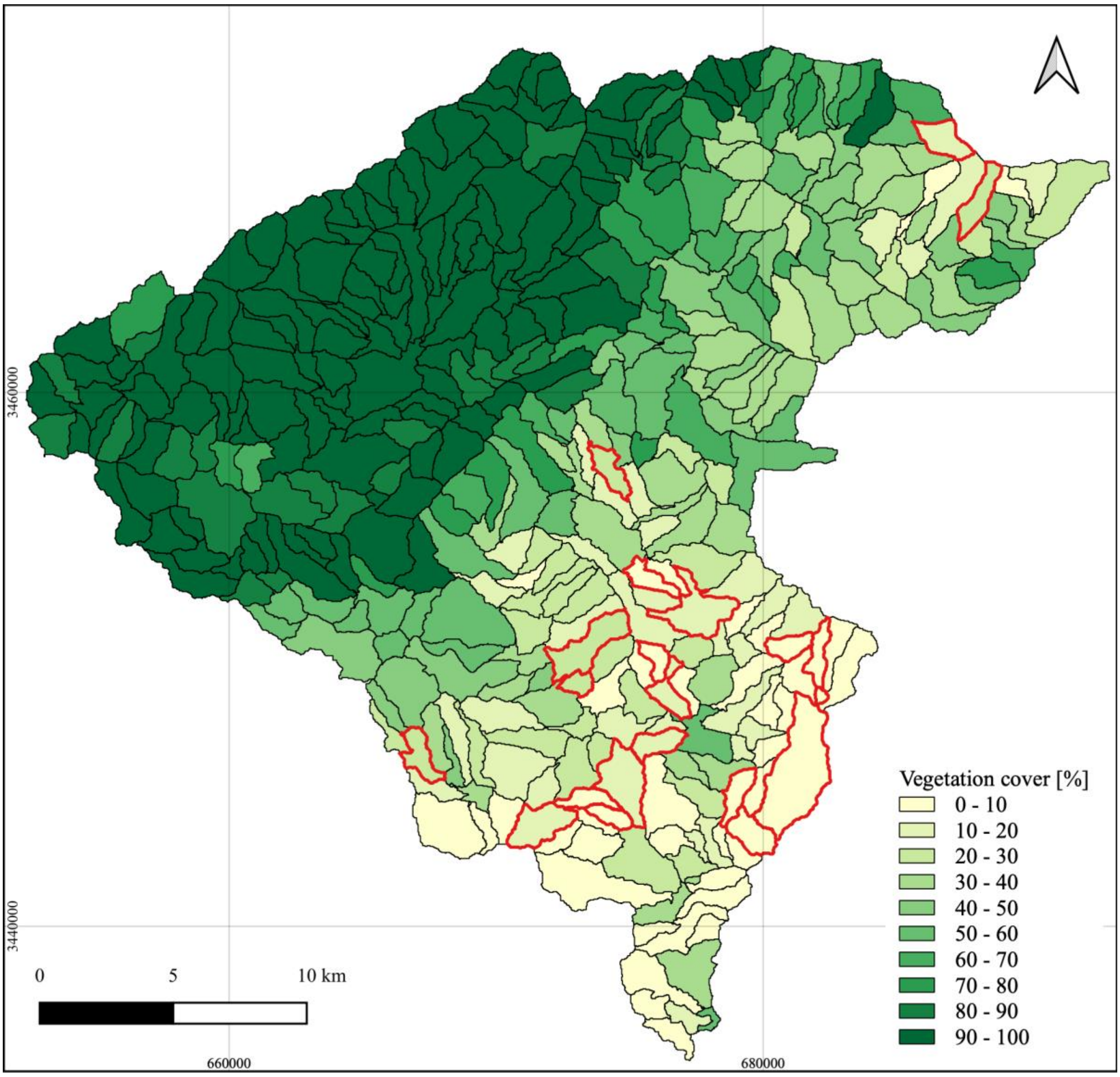


Figure 5.12 In red are the sub-catchment to be restored, based on low vegetation cover (<30%)

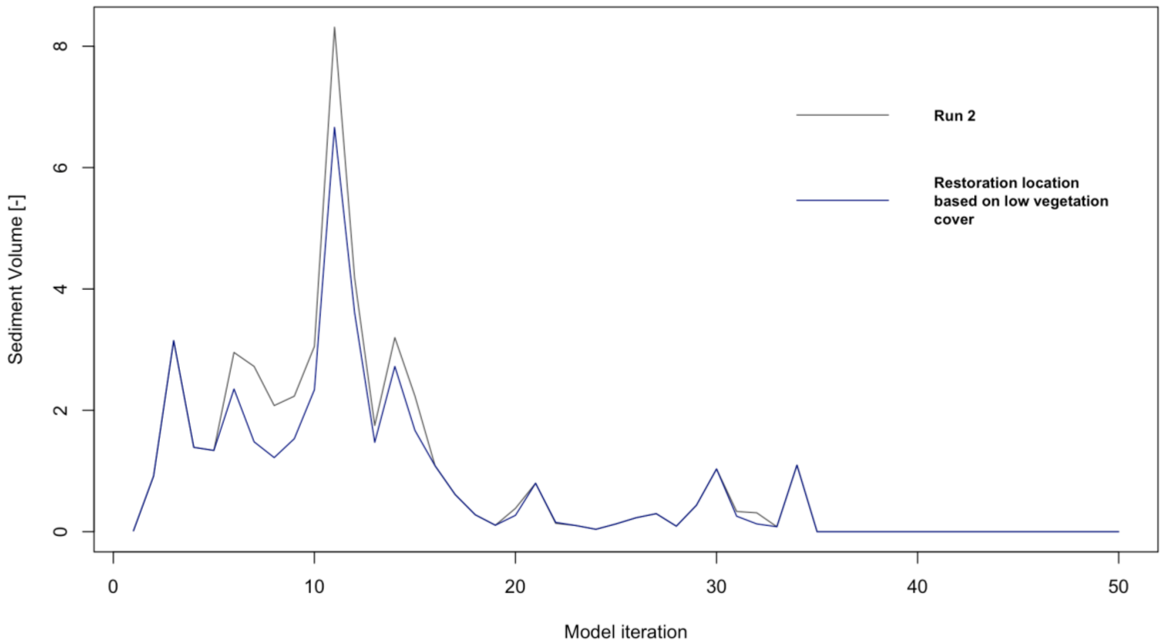


Figure 5.13 Sediment flux over time at the outlet for the system without restorations (grey) and for the system where restoration locations are based on low vegetation cover (blue)

Second, the sub-catchment to be restored were randomly selected but only from sub-catchment with low vegetation cover and high connectivity index (Figure 5.15). Again, with the new vegetation cover the potential flow was calculated and the sedimentograph was constructed (Figure 5.16). The shape of the sedimentograph looks very similar. For the first 16 iterations all sediment volume peaks are lower for scenario 2.2 than for run 2. But from iteration 16 to the end the sediment volume stays more or less the same for each step. Overall, a decrease in sediment flux is seen.

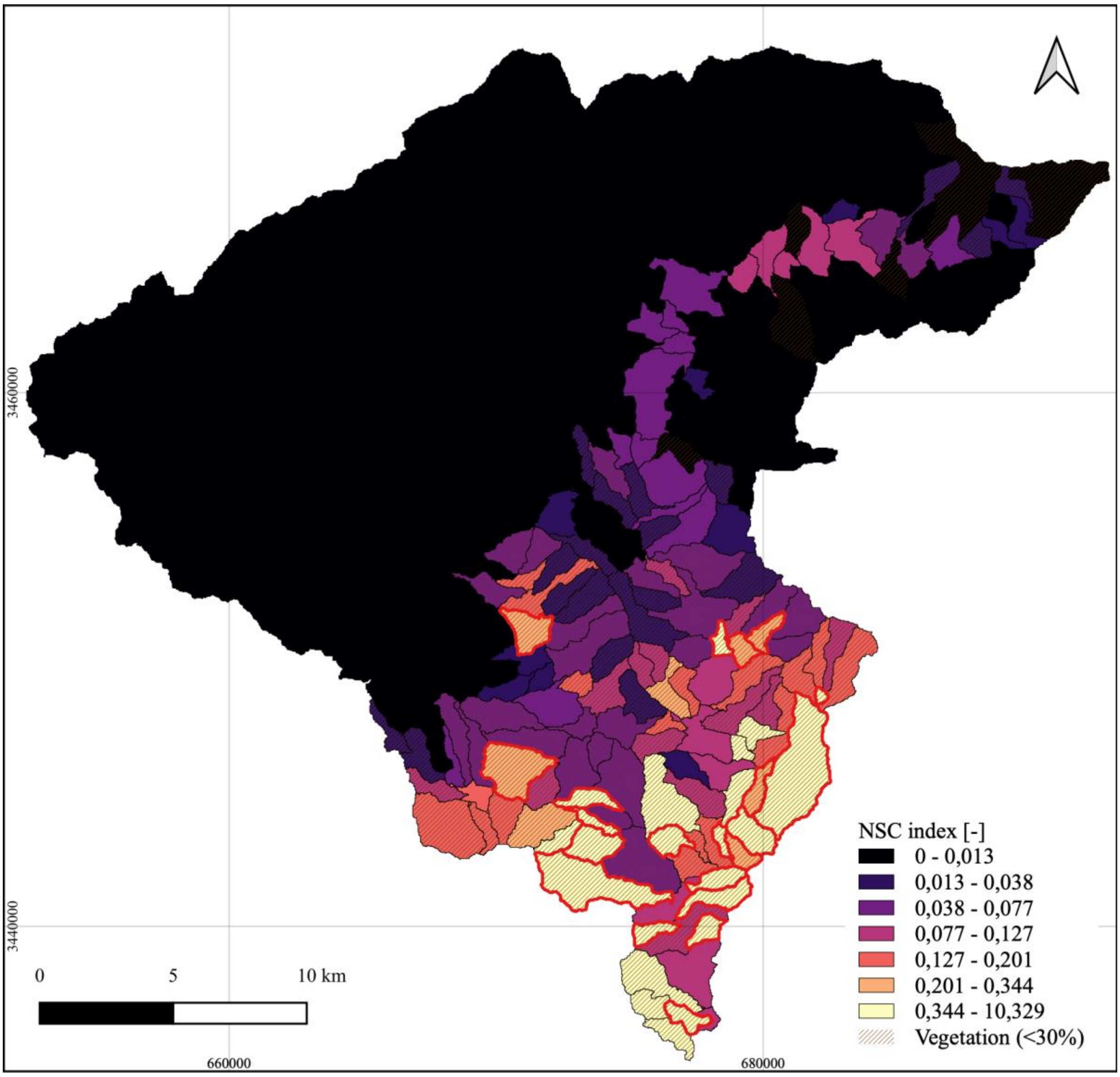


Figure 5.14 In red are the sub-catchment to be restored, based on low vegetation cover (<30%) and high NSC index (>0.2)

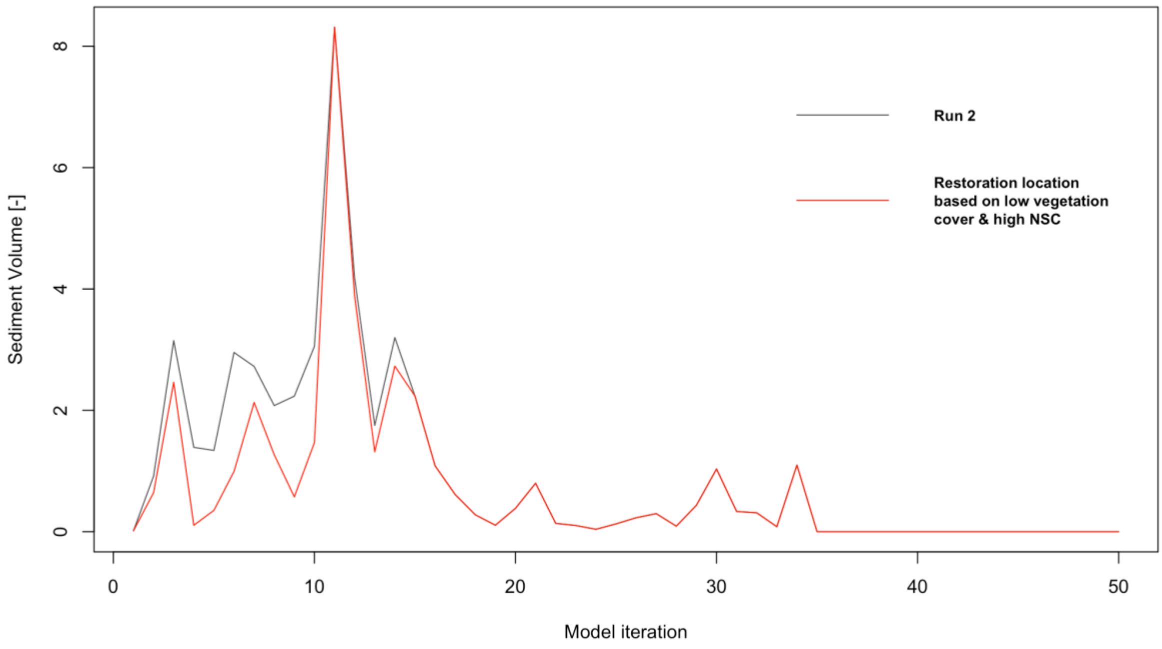


Figure 5.15 Sediment flux over time at the outlet for the system without restorations (grey) and for the system where restoration locations are based on low vegetation cover and high connectivity values (red)

6. Discussion

In this research a connectivity-network approach was used to get insight in the spatiotemporal patterns of water and sediment distribution within the Ounila catchment. The aim was to get insight in the functioning of the catchment and to indicate areas where geomorphic change would affect the entire system (hotspots). The results showed that a connectivity framework, where spatial units are nodes and sediment pathways are edges, combined with indices derived from graph theory is a good place to start to gather these insights. Added value of graph theory is that geomorphic expertise can be integrated algebraically, as graphs describe the system in a geometric and algebraic way (Cossart & Fressard, 2017). Furthermore, the Network Structural Connectivity index (NSC) provided the necessary information, whilst not overcomplicating the method. In this section first the applied method is addressed, then the results are discussed per research question, and finally some suggestions for future research are given.

NSC index

One of the main limitations of this method is that it is difficult to quantify the accuracy. Preferably, one would compare the location of the hotspots with a map of measured erosion in the research area. Unfortunately, data like that is currently not available. Nonetheless, an attempt is made to give some meaningful comments about the accuracy. Starting with the input data: a DEM and land use map are used with a resolution of 30mx30m and 20mx20m, respectively. To make sure the differentiated river network was realistic Google Earth was used for visual comparison, and through trial and error the correct threshold for delineation were found. The indices to assess connectivity with, potential flow and accessibility, are derived from graph theory. And to increase accuracy, some attributes related to the nodes and edges were integrated through algebraic structures: to mimic changes in the system (both natural and/or human induced changes).

Here, to increase the representativity of the research area, sediment availability was adjusted. Changing the sediment availability, by changing the S_0 matrix, had its effect on the flow matrix, the potential flow and eventually also on the connectivity. The sediment availability was adjusted based on the relation between vegetation cover and soil loss, however two assumptions were made. The first assumption was that all other classes than bare soil act as vegetation. But since soil loss was expressed in fractions of estimated soil loss compared to that of a bare soil surface, this is an acceptable method. Nonetheless, accuracy can be increased by either increasing the spatial resolution of the land use map or by increasing the spatial resolution of the landscape units, both will result in a more accurate representation of the soil surface. The second assumption is that the calculations for soil loss assumed a constant value for *b*. However, it is known that the value of *b* changes based on vegetation type, dominant process and experimental conditions (Zuazo & Pleguezuelo, 2008). But it is hard, if not impossible, to determine different values of *b* without field measurements (Gyssels et al., 2005); which justifies the decision to use a constant value. Nonetheless, sediment availability also depends on other factors such as vegetation type, slope, soil type or tillage practices. Moreover, sediment availability is a dynamic process that changes over time and is largely influence by local conditions (Bracken et al., 2014). If increasing the representatively of the catchment is the main goal, these kinds of factors should also be taken into account. However, such additions are at the cost of the simplicity of the method, which for this research was considered essential.

More significant, for this research, might be increasing the accuracy through the adjustment of the accessibility parameter. Accessibility is derived from the distance matrix, where for each node in the system the distance to its source and its outlet is depicted. In this study a distance value of one is used for each edge that connects two nodes. However, this does not take into account any form of process or geomorphic characteristics that exist for the path of one sub-catchment to another. Distance can be expressed in many forms; of which the most easily to implement would be topological distance. However, many other forms of distance might be relevant, as long as they give information on frictions that hinder the sediment pathways: e.g. flow velocity, slope, time, Manning coefficient or a roughness factor (Cossart & Fressard, 2017). Unfortunately, adding any types of these distances to the analysis was outside the scope of this study.

Furthermore, graph theory provides more indices, that might be less complicated, to get insight in functioning of a system. For example, the order index; nodes with a high order index are ought to be more important for the network since they form central points (Ducruet & Rodrigue, 2011). To find out the applicability of the order index, for the assessment of connectivity, a comparison is made between nodes with a high order index and the parameters from the NSC index (Figure 6.1). For node 399 and 470 the NSC index is high, but for node 373 and 420 the NSC index is low despite that all four nodes have a high order index. This can be explained through the potential flow of the nodes, for node 373 and 420 the potential flow is extremely low resulting in low NSC. The order index overlooks these kinds of intrinsic properties, which makes the order index on itself not a good proxy for connectivity but does give first insights in the system.

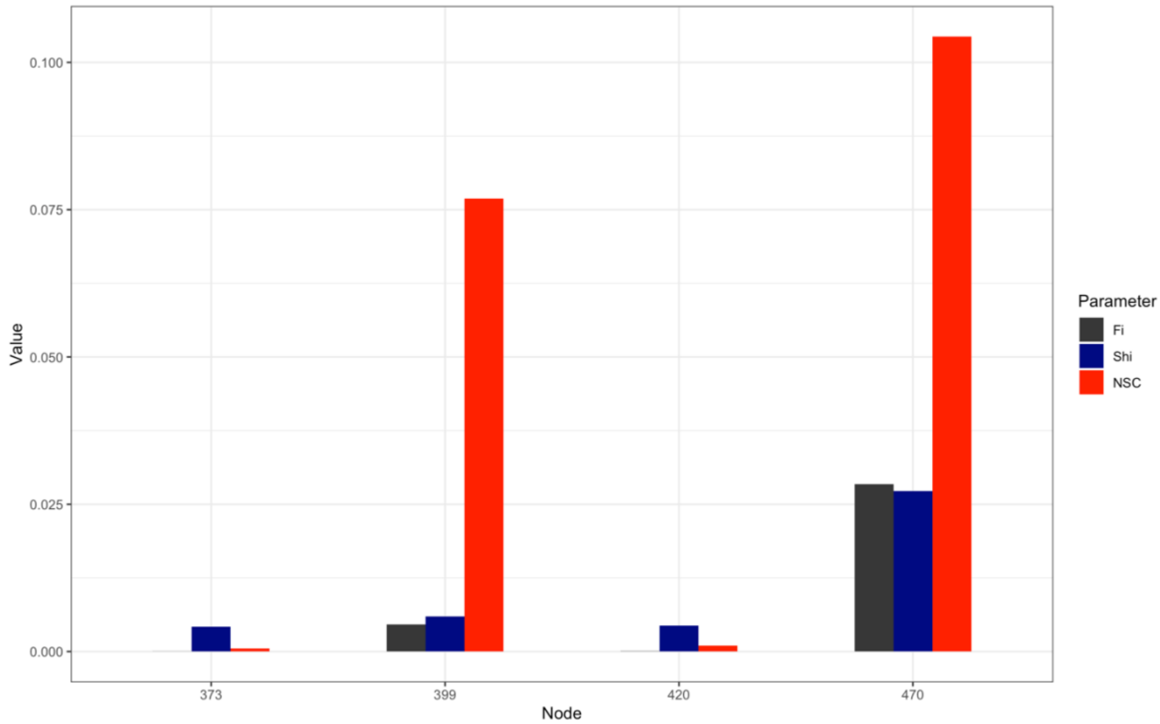


Figure 6.1 NSC index and parameter values of nodes with a high order index (>5 incoming edges), to illustrate that connectivity is not a direct result of the order index

Spatial patterns

To get an overview of the spatial patterns of connectivity in the Ounila catchment first a simplified map was created. To increase accuracy sediment availability was adjusted based on the relation between vegetation cover and soil loss. The effects of this were clearly seen in the connectivity values. On locations with high vegetation cover connectivity values decreased significantly. This is in line with current literature, where vegetation is shown to decrease connectivity (e.g. Sandercock & Hooke, 2011/Foerster et al., 2014/Poeppl et al., 2017). Furthermore, the spatial patterns of connectivity in the Ounila catchment show that connectivity decreases with increasing distance to the outlet and highest connectivity values are found at source nodes close to the outlet. Hotspots of connectivity are found at nodes with low potential flow index and a low accessibility index. It is interesting to note that the sub-catchments with high potential flow do not necessarily have high connectivity, although this might be expected. This shows that connectivity is not proportional to the total volume of sediment that passes through. The high connectivity values can be explained with the accessibility parameter, because this takes into account the spatial structure of the network. For two nodes the parameters and NSC values are shown (Figure 6.2). The nodes have a similar potential flow but a different accessibility. It can be seen that this results in two greatly different connectivity values, which highlights the importance of spatial structure on the connectivity.

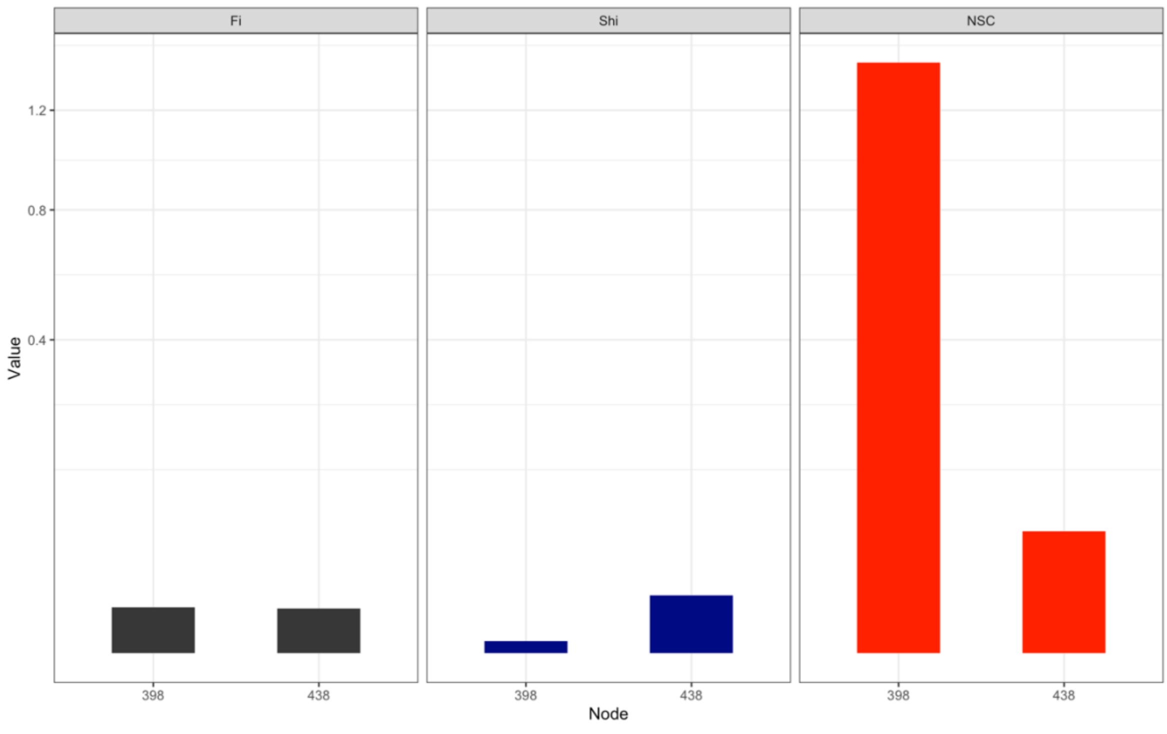


Figure 6.2 Two sub-catchments with similar potential flow to illustrate that connectivity is strongly influenced by accessibility

Role of spatial extent

The spatial patterns of connectivity revealed that connectivity is not proportional to the amount of sediment that passes through a node but is also largely influenced by accessibility. Accessibility is closely related to the distance from a node to the outlet. This raised the question how connectivity values will change, and thus hotspots, if the distance to the outlet is changed. Connectivity values were calculated for the Anguelz catchment and are compared to the connectivity values for the Ounila catchment. The connectivity values of the Ounila catchment are clipped to the extent of the Anguelz catchment, and the legends are equalized (Figure 6.3). Patterns are partially similar: in both cases sub-catchments close to the river network have high connectivity values and source sub-catchments further away from the outlet have lower values. However, connectivity values calculated with smaller spatial extent (Figure 6.3A) shows much more detail. Also, the connectivity values increase significantly, and therefore hotspots are more distinguishable. This shows that spatial extent is an important factor to consider when assessing connectivity, especially if the information is to be used for the relocation of restoration practices.

A. Anguelz catchment **B. Ounila catchment clipped**

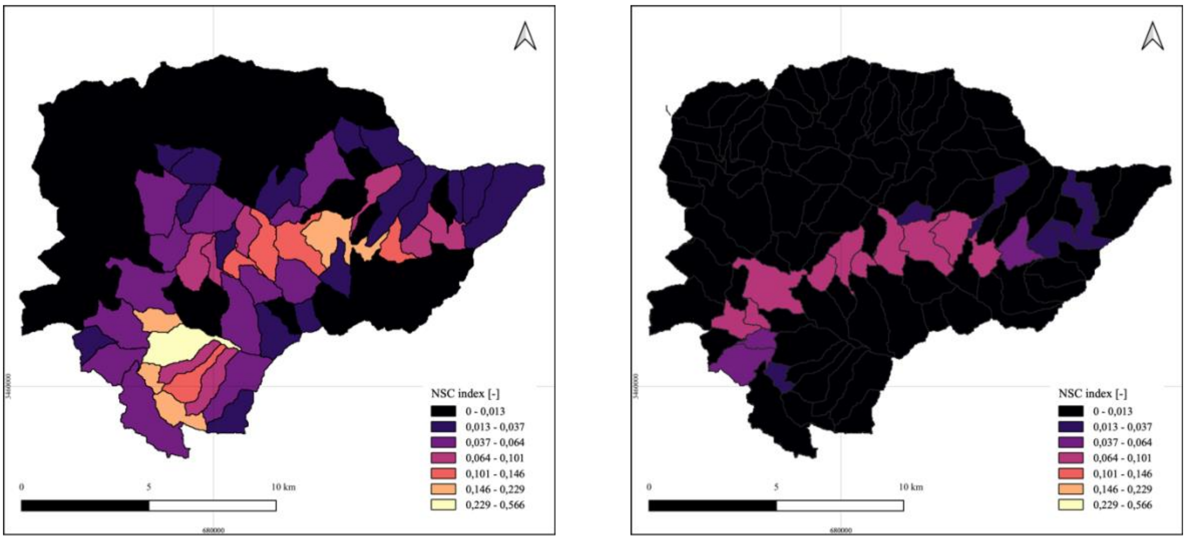


Figure 6.3 Comparison of the NSC index for the Anguelz catchment (A) and the values derived from the Ounila catchment but clipped to the Anguelz extent (B)

Restoration practices

The last part of this research focused on the possible benefit that a connectivity-network approach could have in relocating restoration practices. To quantify the effects two options were compared, in both cases five percent of the catchments were imitated to be restored. First, the (to be restored) catchments were selected based on low vegetation cover and second the catchments were selected based on low vegetation cover and high connectivity values. For the selected catchments restoration practices were imitated by increasing the vegetation cover to that of healthy drylands, which is about 50% (FAO, 2019). The results are compared based on the differences in sediment flux between restoration relocation based on low vegetation cover/ high connectivity and low vegetation cover (Figure 6.4). Here, the difference is shown per model iteration, where negative (blue) shows a decrease in sediment flux and positive (red) shows an increase in sediment flux between the two simulations. These results were obtained by subtracting the sediment flux values from the restoration practices based on low vegetation cover from the restoration practices based on low vegetation cover/ high NSC. Thus, in this case a decrease means that there is less sediment passing through the outlet, which is a desired effect. Overall, it is found that the restoration on location with low vegetation/high NSC decrease the sediment flux at the outlet with 8%. Also, most of the peaks in sediment flux are lower in the scenario where restoration location is based on low vegetation cover/ high NSC. Both are desirable effects from the viewpoint of catchment management. These results show that when restoration practices are relocated to catchments with low vegetation cover and high connectivity, maximum benefit of the restoration practices is achieved.

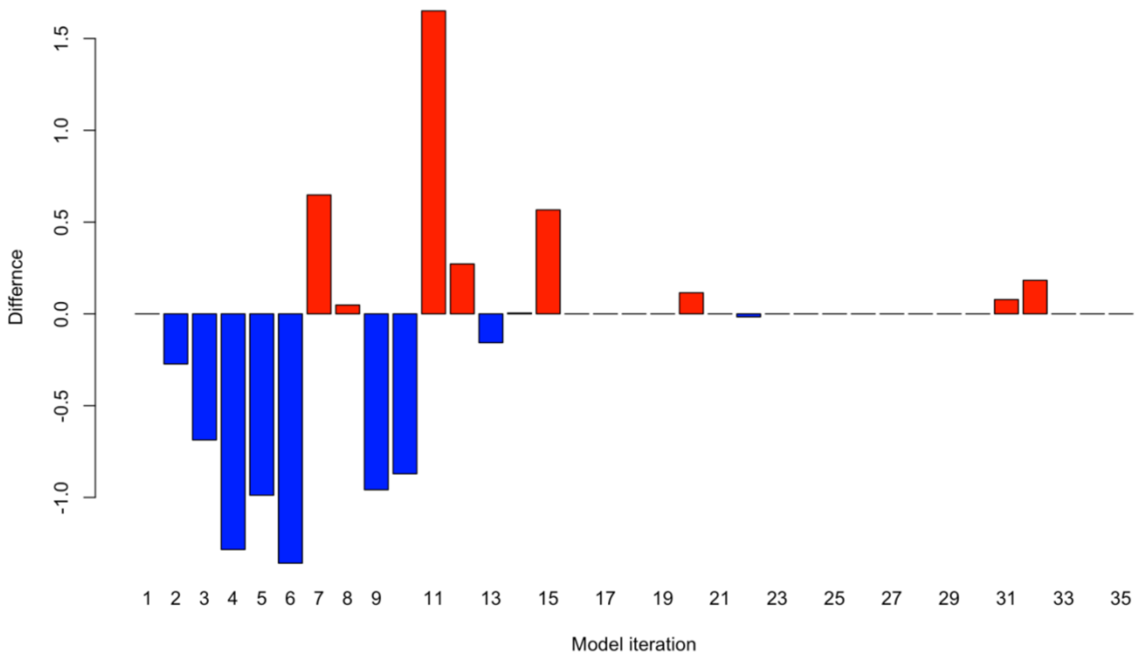


Figure 6.4 Differences of sediment flux per model iteration between restoration locations based on low vegetation cover/ high connectivity and restoration locations based on low vegetation cover. Negative values (blue) show a decrease in sediment flux and positive values (red) show an increase in sediment flux.

Suggestions future research

One of the things this research showed is that the addition of sediment availability, to the connectivity-network approach, significantly increased the representativeness of the area. Nonetheless, sediment availability is dependent on many other factors than vegetation cover. However, a balance should be sought between the adjustments and the complexity of the method. Field measurements, for example in collaboration with Perma Atlas, might be a compromise which increases accuracy of sediment availability values without overcomplicating the method. For example, there could be sought for a sediment availability value per vegetation type, which can be added in the S_0 matrix fairly easily. Also, it would be interesting to see what the effect is of adjusting the distances that are used for the accessibility parameter. Topological distance would not increase the complexity of the method excessively and is a promising next step. However, if method complexity is not an issue, dynamic modelling of the sediment cascades through sediment availability and sediment pathways could complement the approach of this study (e.g. Czuba & Foufoula-Georgiou, 2014). Dynamic modelling could also include the aspect of time, which is considered highly important in dryland systems where the system dynamics are often event-triggered and is not implemented in absolute sense in this study (Puigdefábregas, 1998).

7. Conclusion

The Ounila catchment in Morocco experiences the negative consequences of land degradation firsthand. Therefore, the aim of this thesis was twofold: first, to get insight in the functioning of the Ounila catchment and second, to locate hotspots of connectivity. Sediment cascades, responsible for the relocation of water and sediment, were addressed through a connectivity-network framework. Connectivity was addressed through indices derived from graph theory, based on the intrinsic properties of the network. The results show that the connectivity index is an appropriate method to address the functioning of the catchment and to locate hotspots.

First, the spatial patterns of connectivity were analyzed. The adjustment of sediment availability through the S_0 matrix was found to increase representativity of the area without over complicating the method. Hotspots are found at sub-catchments with relatively low potential flow and a low accessibility index. Second, it is found that accessibility and therefore spatial extent play an important role in the assessment of connectivity. The distance to the outlet plays an important role on the spatial structure, when distance is decreases more details in connectivity is found. This detail is important for the relocation of restoration practices. Lastly, the functioning of the catchment is assessed through the flow matrix, which is part of the potential flow parameter. The flow matrix contains information on the location of sediments for each time step and can therefore be used in sediment flux analyses. This thesis shows that the sediment flux at the outlet is reduced by 8% when restoration practices are done in sub-catchments with low vegetation cover and high connectivity, compared to restoration on sub-catchment with solely low vegetation cover.

This study shows that the addition of graph theory, through a connectivity-network approach, contributes to our understanding of catchment functioning. Also, it shows that the NSC index is an appropriate method to locate areas were geomorphic change affects the entire system. However, before this method can be applied to relocate catchment restorations, specifics of the sediment cascades, the spatial extent and the impact on the applied method should be researched in more depth.

References

Baartman, J. E. M., Masselink, R., Keesstra, S. D., & Temme, A. J. A. M. (2013). Linking landscape morphological complexity and sediment connectivity. *Earth Surface Processes and Landforms*, *38*(12), 1457–1471. https://doi.org/10.1002/esp.3434

Beck, H. E., Zimmermann, N. E., McVicar, T. R., Vergopolan, N., Berg, A., & Wood, E. F. (2018). Present and future köppen-geiger climate classification maps at 1-km resolution. *Scientific Data*, *5*, 1–12. https://doi.org/10.1038/sdata.2018.214

Benda, L., Poff, N. L., Miller, D., Dunne, T., Reeves, G., Pess, G., & Pollock, M. (2004). The network dynamics hypothesis: How channel networks structure riverine habitats. *BioScience*, *54*(5), 413–427. https://doi.org/10.1641/0006-3568(2004)054[0413:TNDHHC]2.0.CO;2

Borselli, L., Cassi, P., & Torri, D. (2008). Prolegomena to sediment and flow connectivity in the landscape: A GIS and field numerical assessment. *Catena*, *75*(3), 268–277. https://doi.org/10.1016/j.catena.2008.07.006

Bracken, L. J., & Croke, J. (2007). *The concept of hydrological connectivity and its contribution to understanding runoff-dominated geomorphic systems*. *2274*(November 2008), 2267–2274. https://doi.org/10.1002/hyp

Bracken, L. J., Wainwright, J., Ali, G. A., Tetzlaff, D., Smith, M. W., Reaney, S. M., & Roy, A. G. (2013). Concepts of hydrological connectivity: Research approaches, Pathways and future agendas. *Earth-Science Reviews*, *119*, 17–34. https://doi.org/10.1016/j.earscirev.2013.02.001

Bracken, L. J., Turnbull, L., Wainwright, J., & Bogaart, P. (2014). Sediment connectivity: A framework for understanding sediment transfer at multiple scales. *Earth Surface Processes and Landforms*, *40*(2), 177–188. https://doi.org/10.1002/esp.3635

Cavalli, M., Trevisani, S., Comiti, F., & Marchi, L. (2013). Geomorphometric assessment of spatial sediment connectivity in small Alpine catchments. *Geomorphology*, *188*, 31–41. https://doi.org/10.1016/j.geomorph.2012.05.007

Cossart, E. (2016). L'(in) efficacité géomorphologique des cascades sédimentaires en question: les apports d'une analyse réseau. Cybergeo: European Journal of Geography.

Cossart, É., & Fressard, M. (2017). Assessment of structural sediment connectivity within catchments: Insights from graph theory. *Earth Surface Dynamics*, *5*(2), 253–268. https://doi.org/10.5194/esurf-5-253-2017

Cossart, E., Viel, V., Lissak, C., Reulier, R., Fressard, M., & Delahaye, D. (2018). How might sediment connectivity change in space and time? *Land Degradation and Development*, *29*(8), 2595–2613. https://doi.org/10.1002/ldr.3022

Council, A. W. (2009). Vulnerability of arid and semi-arid regions to climate change–Impacts and adaptive strategies. In *Perspective Document for the 5th World Water Forum, World Water Council, Marseille, Co-Operative Programme on Water and Climate (CPWC).*

Czuba, J. A., and E. Foufoula-Georgiou (2014), A network-based framework for identifying potential synchronizations and amplifications of sediment delivery in river basins, Water Resour. Res., 50, 3826–3851, doi:10.1002/ 2013WR014227.

Diekkrüger, B., & Busche, H. (2012). Impact of global change on hydrology and soil degradation-scenario analysis for the semi-arid Drâa catchment (South Morocco). *Editors: Janos J. Bogardi, Jan Leentvaar, and Hans-Peter Nachtnebel*, 21.

Dregne, H. E. (2002). Land degradation in the drylands. In *Arid Land Research and Management* (Vol. 16, Issue 2). https://doi.org/10.1080/153249802317304422

Ducruet, C., & Rodrigue, J. P. (2011). Graph theory: Measures and indices. *The geography of transport systems*.

FAO. 2019. Trees, forests and land use in drylands: the first global assessment – Full report. FAO Forestry Paper No. 184. Rome.

Foerster, S., Wilczok, C., Brosinsky, A., & Segl, K. (2014). Assessment of sediment connectivity from vegetation cover and topography using remotely sensed data in a dryland catchment in the Spanish Pyrenees. *Journal of Soils and Sediments*, *14*(12), 1982–2000. https://doi.org/10.1007/s11368-014-0992-3

Francis C.F., Thornes J.B. (1990) Runoff hydrographs from three Mediterranean vegetation cover types, in: Thornes J.B. (Ed.), Vegetation and Erosion, Processes and Environments, Wiley, Chichester, UK, pp. 363–384

Fressard, M., & Cossart, E. (2019). A graph theory tool for assessing structural sediment connectivity: Development and application in the Mercurey vineyards (France). *Science of the Total Environment*, *651*, 2566–2584. https://doi.org/10.1016/j.scitotenv.2018.10.158

Fryirs, K. (2013). (Dis)Connectivity in catchment sediment cascades: A fresh look at the sediment delivery problem. *Earth Surface Processes and Landforms*, *38*(1), 30–46. https://doi.org/10.1002/esp.3242

Fryirs, K. A., Brierley, G. J., Preston, N. J., & Kasai, M. (2007). Buffers, barriers and blankets: The (dis)connectivity of catchment-scale sediment cascades. *Catena*, *70*(1), 49–67. https://doi.org/10.1016/j.catena.2006.07.007

Grauso, S., Pasanisi, F., Tebano, C., Grillini, M., & Peloso, A. (2018). Investigating the sediment yield predictability in some Italian rivers by means of hydro-geomorphometric variables. *Geosciences (Switzerland)*, *8*(7). https://doi.org/10.3390/geosciences8070249

Gyssels, G., Poesen, J., Bochet, E., & Li, Y. (2005). Impact of plant roots on the resistance of soils to erosion by water: A review. *Progress in Physical Geography*, *29*(2), 189–217. https://doi.org/10.1191/0309133305pp443ra

Heckmann, T., Cavalli, M., Cerdan, O., Foerster, S., Javaux, M., Lode, E., Smetanová, A., Vericat, D., & Brardinoni, F. (2018). Indices of sediment connectivity: opportunities, challenges and limitations. *Earth-Science Reviews*, *187*(September), 77–108. https://doi.org/10.1016/j.earscirev.2018.08.004

Heckmann, T., & Schwanghart, W. (2013). Geomorphic coupling and sediment connectivity in an alpine catchment - Exploring sediment cascades using graph theory. *Geomorphology*, *182*, 89–103. https://doi.org/10.1016/j.geomorph.2012.10.033

Heckmann, T., Schwanghart, W., & Phillips, J. D. (2015). Graph theory-Recent developments of its application in geomorphology. *Geomorphology*, *243*, 130–146. https://doi.org/10.1016/j.geomorph.2014.12.024

Heckmann, T., & Vericat, D. (2018). Computing spatially distributed sediment delivery ratios: inferring functional sediment connectivity from repeat high-resolution digital elevation models. *Earth Surface Processes and Landforms*, *43*(7), 1547–1554. https://doi.org/10.1002/esp.4334

James, J. J., Sheley, R. L., Erickson, T., Rollins, K. S., Taylor, M. H., & Dixon, K. W. (2013). A systems approach to restoring degraded drylands. *Journal of Applied Ecology*, *50*(3), 730–739. https://doi.org/10.1111/1365-2664.12090

Marchi, L., & Dalla Fontana, G. (2005). GIS morphometric indicators for the analysis of sediment dynamics in mountain basins. *Environmental Geology*, *48*(2), 218–228. https://doi.org/10.1007/s00254-005-1292-4

Mayor, Á. G., Bautista, S., Small, E. E., Dixon, M., & Bellot, J. (2008). Measurement of the connectivity of runoff source areas as determined by vegetation pattern and topography: A tool for assessing potential water and soil losses in drylands. *Water Resources Research*, *44*(10), 1–13. https://doi.org/10.1029/2007WR006367

Medeiros, P. H. A., Güntner, A., Francke, T., Mamede, G. L., & de Araújo, J. C. (2010). Modélisation des patrons spatio-temporels de la connectivité et de la production de sédiments dans un bassin versant semi-aride à l'aide du modèle WASA-SED. *Hydrological Sciences Journal*, *55*(4), 636–648. https://doi.org/10.1080/02626661003780409

Najafi, S., Dragovich, D., Heckmann, T., & Sadeghi, S. H. (2021). Sediment connectivity concepts and approaches. *Catena*, *196*(August 2020), 104880. https://doi.org/10.1016/j.catena.2020.104880

Parish, R., & Funnell, D. C. (1999). Climate change in mountain regions: Some possible consequences in the Moroccan High Atlas. *Global Environmental Change*, *9*(1), 45–58. https://doi.org/10.1016/S0959-3780(98)00021-1

Pastor, A., Babault, J., Teixell, A., & Arboleya, M. L. (2012). Intrinsic stream-capture control of stepped fan pediments in the High Atlas piedmont of Ouarzazate (Morocco). *Geomorphology*, *173–174*, 88–103. https://doi.org/10.1016/j.geomorph.2012.05.032

Perma Atlas, (z.d), retrieved 04 January 2021 from https://www.perma-atlas.com/en/approach/

Poeppl, R. E., Keesstra, S. D., & Maroulis, J. (2017). A conceptual connectivity framework for understanding geomorphic change in human-impacted fluvial systems. *Geomorphology*, *277*, 237–250. https://doi.org/10.1016/j.geomorph.2016.07.033

Poeppl, R. E., & Parsons, A. J. (2018). The geomorphic cell: a basis for studying connectivity. *Earth Surface Processes and Landforms*, *43*(5), 1155–1159. https://doi.org/10.1002/esp.4300

Prăvălie, R. (2016). Drylands extent and environmental issues. A global approach. *Earth-Science Reviews*, *161*, 259–278. https://doi.org/10.1016/j.earscirev.2016.08.003

Pringle, C. (2003). What is hydrologic connectivity and why is it ecologically important? *Hydrological Processes*, *17*(13), 2685–2689. https://doi.org/10.1002/hyp.5145

Puigdefábregas, J. (1998). Ecological impacts of global change on drylands and their implications for desertification. *Land Degradation and Development*, *9*(5), 393–406. https://doi.org/10.1002/(SICI)1099-145X(199809/10)9:5<393::AID-LDR301>3.0.CO;2-F

Sandercock, P. J., & Hooke, J. M. (2011). Vegetation effects on sediment connectivity and processes in an ephemeral channel in SE Spain. *Journal of Arid Environments*, *75*(3), 239–254. https://doi.org/10.1016/j.jaridenv.2010.10.005

Schilling, J., Freier, K. P., Hertig, E., & Scheffran, J. (2012). Climate change, vulnerability and adaptation in North Africa with focus on Morocco. *Agriculture, Ecosystems and Environment*, *156*(January 2018), 12–26. https://doi.org/10.1016/j.agee.2012.04.021

Schulz, O., & de Jong, C. (2004). Snowmelt and sublimation: field experiments and modelling in the High Atlas Mountains of Morocco. *Hydrology and Earth System Sciences*, *8*(6), 1076–1089. https://doi.org/10.5194/hess-8-1076-2004

SWAT+ | SWAT | Soil & Water Assessment Tool. (z.d.). Retrieved on 9 december 2020, from https://swat.tamu.edu/software/plus/

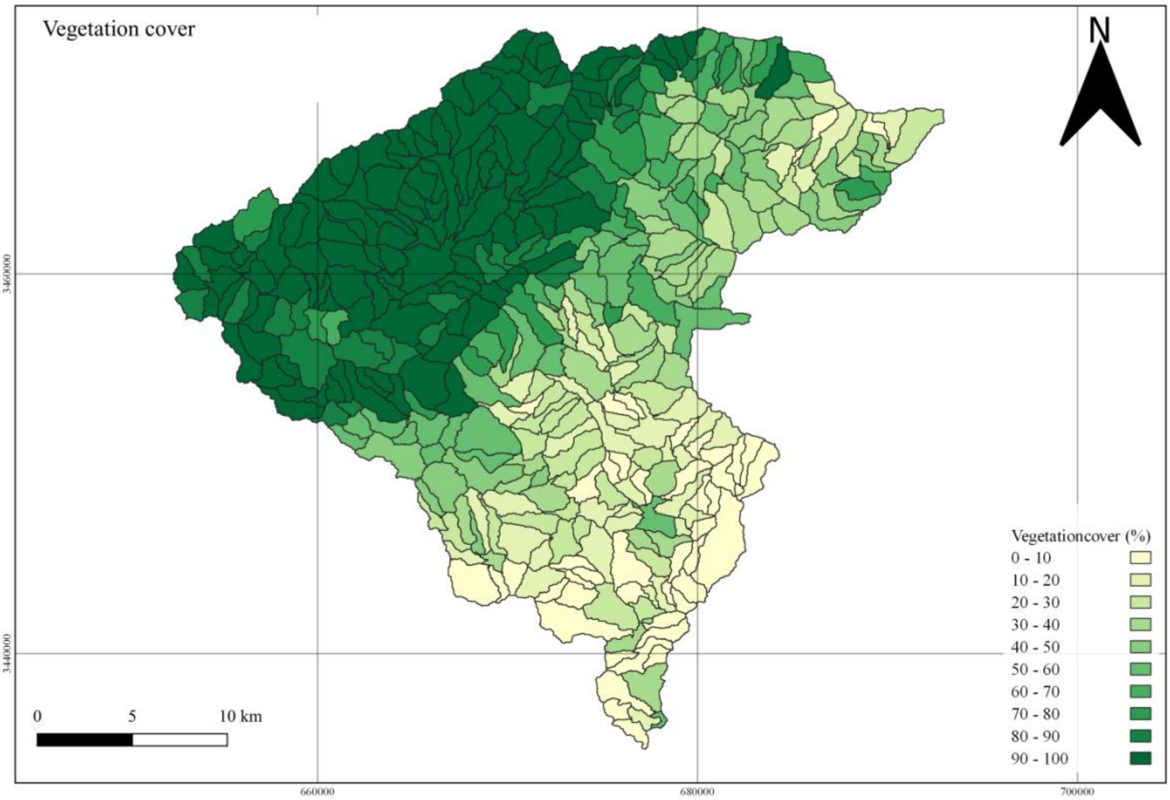
Wohl, E., Gerlak, A. K., Poff, N. L., & Chin, A. (2014). Common core themes in geomorphic, ecological, and social systems. *Environmental Management*, *53*(1), 14–27. https://doi.org/10.1007/s00267-013-0093-x

Wyss, M., Matile, L., & Zierhofer, W. (2016). *Compendium of cultural landscapes in the High Atlas Mountains and in the Antiatlas Mountains of Morocco*.

Zuazo, V. H. D., & Pleguezuelo, C. R. R. (2008). Soil-erosion and runoff prevention by plant covers. A review. *Agronomy for Sustainable Development*, *28*(1), 65–86. https://doi.org/10.1051/agro:2007062

Appendices

1. Vegetation cover: everything but bare soil is assumed vegetation



2. Sediment availability as fraction compared to that of erosion on bare soil (1)