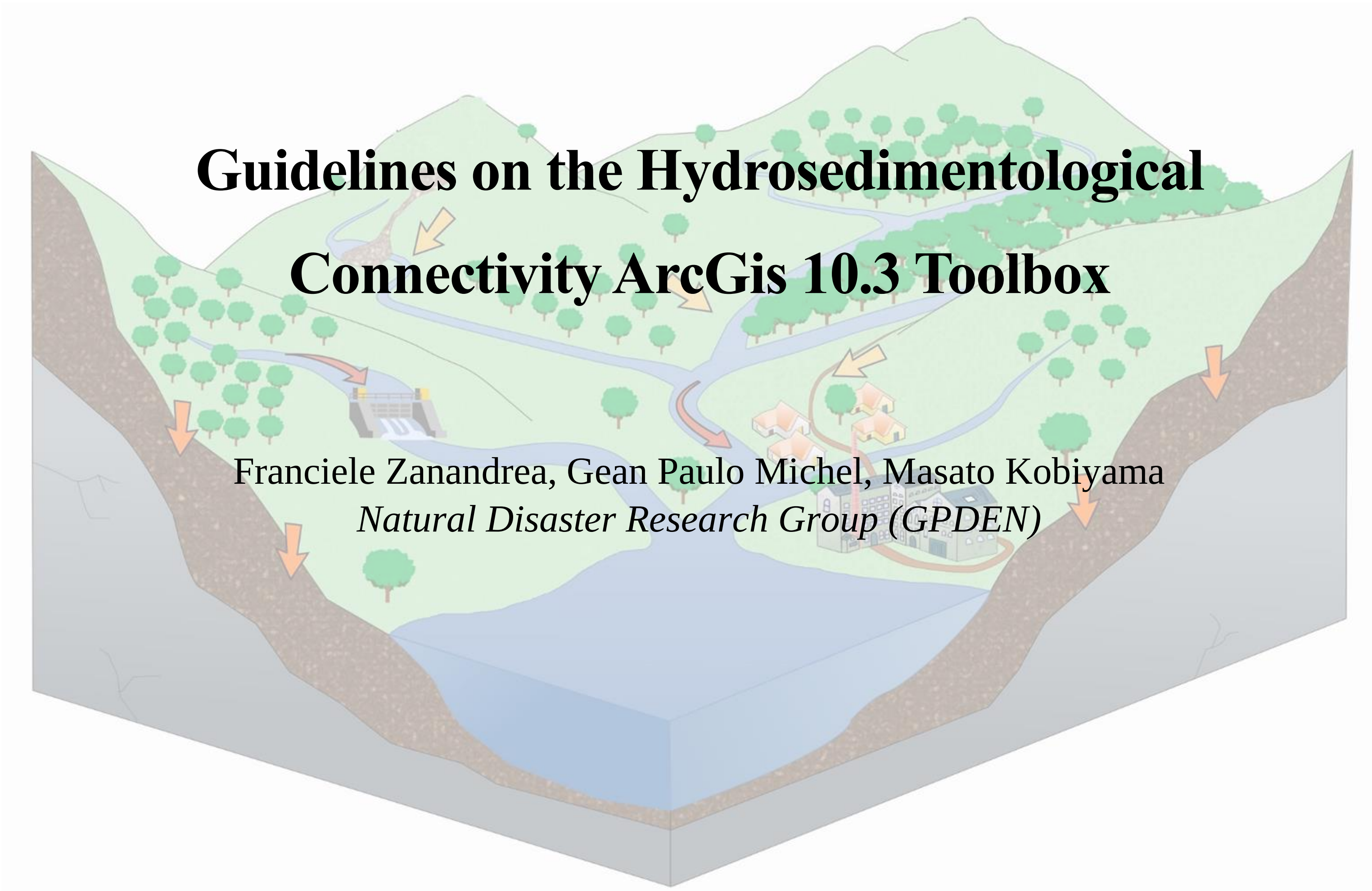

# Guidelines on the Hydrosedimentological Connectivity ArcGis 10.3 Toolbox

Franciele Zanandrea, Gean Paulo Michel, Masato Kobiyama
*Natural Disaster Research Group (GPDEN)*

July 2021

**https://www.ufrgs.br/gpden/**

# Contents

## Abstract

The connectivity support understanding the hydrosedimentological (water and sediments) processes that occur in the watershed and influence the water and sediment transfer at different spatial-temporal scales. This document presents the index of hydrosedimentological connectivity (*IHC*) created from the equation of the connectivity index (*IC*) by Borselli et al. (2008) modified by Cavalli et al. (2013). These guidelines have a brief explanation of the *IHC* conceptualization, as well as a presentation of its equation. The guide also introduces an ArcGis Toolbox for the *IHC* execution, its installation, and how to apply it to watersheds. This Toolbox has created from the ArcGis Toolbox developed by Crema and Cavalli (2018).

**Keywords:** connectivity; index; hydrosedimentology; sediments.

## Abbreviations

*A* – Drainage Area

*C* - Factor *C* of USLE/RUSLE

*CN* - Curve Number

*d* - Length of the flow path

$D_{dn}$ - Downstream component

$D_{up}$ - Upstream component

DTM – Digital Terrain Model

GPDEN – Grupo de Pesquisas em Desastres Naturais/ Natural Disaster Research Group

*Ia* – Initial abstraction

*IC* – Connectivity Index

*IHC* - Index of Hydrosedimentological Connectivity

*Imax* - Maximum intensity of the antecedent precipitation event

*IPS* - Precipitation Index for Sediments

*n* - Manning coefficient

*P* – Precipitation

$Q_{runoff}$ - Surface runoff

*RI* - Residual topography Index

*RS* - Relative Smoothness Index

*S* - Slope

*Sa* - Storage parameter

SCS - Soil Conservation Service

USLE – Universal Soil Loss Equation

RUSLE - Revised Universal Soil Loss Equation

TauDEM - Terrain Analysis Using Digital Elevation Models

*V* - Accumulated precipitation of the antecedent event

*W* - Weighting factor

# 1. Introduction

Connectivity describes the degree to which a system facilitates the transfer of material (e.g., sediment) throughout the landscape components such as hillslopes and river networks. When the sediment transfer occurs by having the water as a vector, we can call Hydrosedimentological Connectivity.

Hydrosedimentological Connectivity is an important concept to better understand processes occurring at a watershed level that impact the water, the sediment dynamics, and other systems (e.g., biological activities) at different spatial temporal scales. Sediment connectivity analysis has often been using spatial indexes that allow estimation of the contribution of a given part of the watershed as sediment source and defines sediment transfer paths. Borselli et al. (2008) proposed a sediment connectivity index (*IC*) based on a geomorphological approach, in which hydrological processes are not explicitly considered. Cavalli et al. (2013) modified this index and Crema and Cavalli (2018) developed a free tool (open source) and stand-alone named SedInConnect for computing *IC*.

Another modification performed in the connectivity formulation proposed by Borselli et al. (2008) was proposed by Zanandrea et al. (2021) by integrating into the original formulation precipitation-derived variables as representative of hydrological processes. This new index is called index of hydrosedimentological connectivity (*IHC*). The index is based on the concept of sediment transport capacity and does not consider the sediment exhaustion in the watershed. The insertion of functional components (surface runoff and antecedent precipitation index) permits obtaining a temporal variation of connectivity in the watershed, which formerly varied only spatially. The *IHC* allows assessing the variation in connectivity over time under different precipitation events, spatialized according to soil/surface characteristics and precipitation.

Thus, this manual presents the background theory about the modifications that make up the *IHC*; the installation steps, and the steps for using the *IHC*, as presented in Zanandrea et al. (2021). The utility presented here is a Toolbox for ArcGis 10.3, generated from the modification of the Sediment Connectivity tool implemented by Crema and Cavalli (2018).

The quantitative estimate of the hydrosedimentological connectivity, which combines functional and structural properties, is important for identifying areas of sediment transfer, flow paths, and deposition, as landslides, debris flow, and deposition areas. The *IHC* map can indicate important places of higher and lower connectivity and precipitation thresholds for the occurrence of (des)connectivity of any areas. Therefore, such a map will be especially useful for watershed management.

## 2. Background theory

The index of hydrosedimentological connectivity (*IHC*) was proposed by Zanandrea et al. (2021) based on the insertion of the precipitation and surface runoff characteristics as functional components in the connectivity index (*IC*) proposed by Borselli et al. (2008) and modify by Cavali et al. (2013). Its main goal is to evaluate the space-time variation of water and sediment connectivity in the watershed, considering the runoff generation and the characteristics of the antecedent precipitation event.

The *IHC* is intended to represent the linkage between different parts of the watershed based on the flow paths. The tool allows estimating hydrosedimentological connectivity as sediment delivery across the flow paths (i.e., the potential connection of sediment between hillslopes and watershed outlet).

The hydrosedimentological connectivity tool has been implemented through the Model Builder application running in ArcGIS 10.3 (ESRI, 2015) modified from the Toolbox proposed by Crema and Cavalli (2018). It uses functionalities and algorithms available in TauDEM 5.3 tool (Tarboton, 2021).

### 2.1. Index of Hydrosedimentological Connectivity

The *IHC* is a modification of the *IC* developed by Borselli et al. (2008) considering the suggestions already incorporated by Cavalli et al. (2013). *IC* determines, at a pixel scale, the degree of connectivity for a given point. The *IC* incorporates the characteristics of the contribution area (upstream component – $D_{up}$), and the characteristics of the flow path to be performed by the sediment to the point of interest (downstream component - $D_{dn}$). The *IC* values are presented in an interval of [-∞, + ∞] and the *IC* representation is shown in Figure 1.

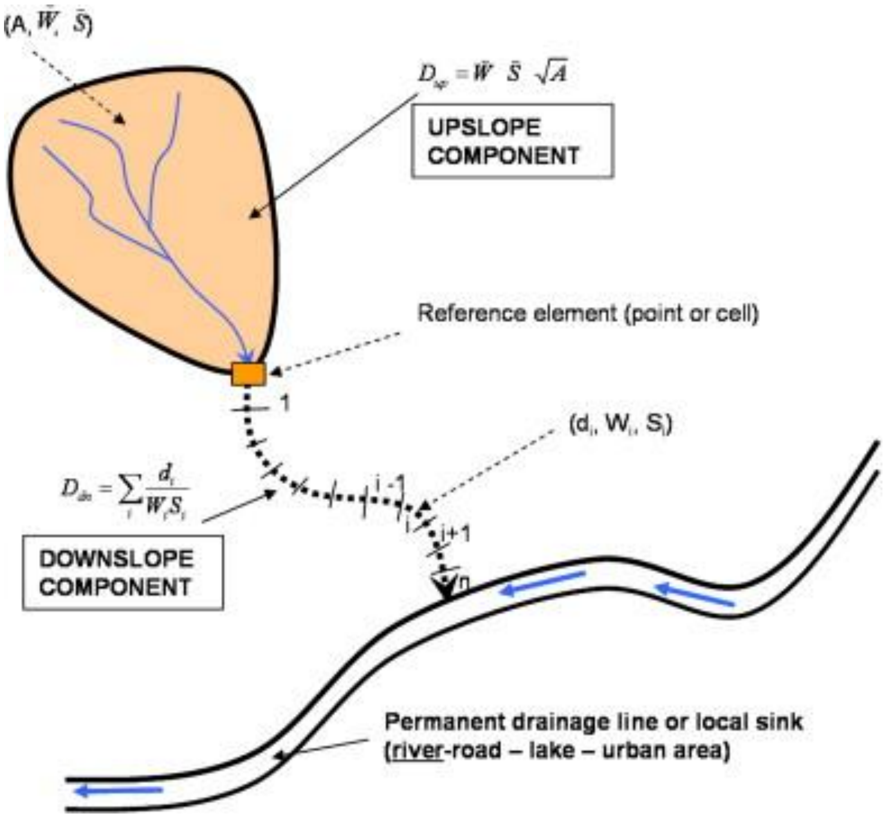


*Figure 1. Definition of the components of the upper and lower part of the hillslope of the connectivity index (IC) (Borselli et al., 2008).*

*W* is the impedance factor; *S* is the slope (m/m); *A* is the contribution area ($m^2$); *d* is the length of the flow path of each pixel (m); *IC* is the connectivity of sediment (dimensionless).

Cavalli et al. (2013) modified *IC* in relation to (i) Slope factor computation, (ii) Contributing area calculation, and (iii) Choice of the Weighting factor (*W*). These modifications were incorporated into the Toolbox proposed by Crema and Cavalli (2018) and are included in the Toolbox presented here.

## 2.2. Framework and formulation of the *IHC* implemented in the Toolbox

The modification of the index is based on insertion of variables (precipitation index for sediments – *Ips* and surface runoff - $Q_{runoff}$) related to functional connectivity into the *IC*, considering the role of water in the sediment connectivity. Functional connectivity is related to the precipitation characteristics, the antecedent conditions (Turnbull and Wainwright, 2019) as well as the flow continuity/discontinuity through a watershed, which brings a temporal feature to connectivity. Considering the magnitude of current and antecedent precipitation events, *IHC* is defined as:

$$IHC = \log_{10}\left(\frac{\overline{W}\,.\,\overline{S}\,.\,Ips\,.\,\sum Q_{runoff}}{\sum \frac{d_i}{W_i\,.\,S_i}}\right) \quad (1)$$

where *Ips* is the precipitation index for sediments (dimensionless); $Q_{runoff}$ is the accumulated surface runoff (m) from the upstream drainage area of the calculated pixel, which is dependent on the pixel size.

The runoff (mm) of each event is calculated at a pixel scale by using the SCS Runoff Curve Number method (NRCS, 1972):

$$Q_{runoff} = \frac{(P-Ia)^2}{P-Ia+Sa} \text{ when } P > Ia\text{, or } Q_{runoff} = 0 \quad (2)$$

$$Sa = \frac{25400}{CN} - 254 \quad (3)$$

$$Ia = 0.2 \cdot Sa \quad (4)$$

where *P* is the total precipitation of the event (mm); *Sa* is the storage parameter (mm); and *Ia* is the initial abstraction (mm). The *Sa* value spatially varies in respect to the soil characteristics and land use through the *CN* value.

The inclusion of *Ips* in the upstream component for the connectivity calculation brings a weighting in relation to the sediment amount that became available at the previous event to be connected during the analyzed event. The *Ips* can be calculated for any specified antecedent precipitation event:

$$Ips(j) = \frac{Imax_{m-j}}{\sum_{i=1}^{j} \frac{V_{m-i}}{\Delta t_{m-i}}} \quad (5)$$

where *m* means the current precipitation event; *j* represents the number of precipitation events between the current one and the antecedent one for which the *Ips* value is calculated; $Imax_{m-j}$ is the maximum intensity of the antecedent precipitation event *m-j* ($mm.d^{-1}$); $V_{m-i}$ is the accumulated precipitation of the antecedent event *m-i* (mm); and $\Delta t_{m-i}$ is the duration of the precipitation event *m-i* (d). The *Ips* use permits considering the antecedent conditions of the watershed and comparing distinct precipitation events.

The *IHC* maintains the first order application, considering three new information, i.e., precipitation, land use and soil characteristics. The impedance factor (*W*) represents the resistance that the land surface imposes to water and sediment flow. The original *IC* uses the USLE/RUSLE factor *C*, proposed by Wischmeier and Smith (1978) and Renard et al. (1997), as the impedance factor. Cavalli et al. (2013) adapted the impedance factor to an exclusively geomorphological approach, using the residual topography (*RI*) and optimizing the *IC* application in mountainous regions, where impedance conditions are better represented by the surface roughness. To be used as *W*, the *RI* value must be normalized. The normalization procedure can be carried out following the approach of Cavalli et al. (2013) or Trevisani and Cavalli (2016). The methodologies that apply *RI* have been developed for use with high-resolution Digital Terrain Models (DTM). Furthermore, the *RI* can be inaccurate for vegetated surfaces because hydraulic roughness does not depend only on the terrain characteristics. For impedance assessment in forested watershed, it is more appropriate to use *W* based on land use because the surface roughness and sediment retention capacity are strongly influenced by the vegetation cover, which can decrease the coupling between landscape units. Zanandrea et al. (2020) proposed the Relative Smoothness (*RS*), which is an impedance factor based on Manning's coefficient that preserves the non-dimensionality of the index:

$$RS = \frac{n_{min}}{n} \tag{6}$$

where $n_{min}$ is the minimum tabulated value; and $n$ is the local Manning coefficient. The value adopted for $n_{min}$ in Zanandrea et al. (2020) was 0.01 which can be seen in Chow (1959). The use of *RS* proved to be advantageous in regions covered by dense forests.

Thus, when applying *IHC*, the *W* value must be defined according to the watershed characteristics. The Toolbox developed by Crema and Cavalli (2018) allows choosing the *W* estimation method for computing *IC*. This option is maintained in the *IHC* Toolbox presented here, as well as the tool for calculating *RI*.

# 3. ArcGIS toolbox

## 3.1. Requirements

The requirements are the same presented by Cavalli et al. (2014). The ArcGIS toolbox requires TauDEM tools installation since several hydrological functions are computed using this tool (Figure 2). The steps for installing TauDEM are specified in the link (https://hydrology.usu.edu/taudem/taudem5/downloads.html). For download of TauDEM 5.3.7 tools, the link is:

https://github.com/dtarb/TauDEM/releases/download/v5.3.7/TauDEM537_setup.exe

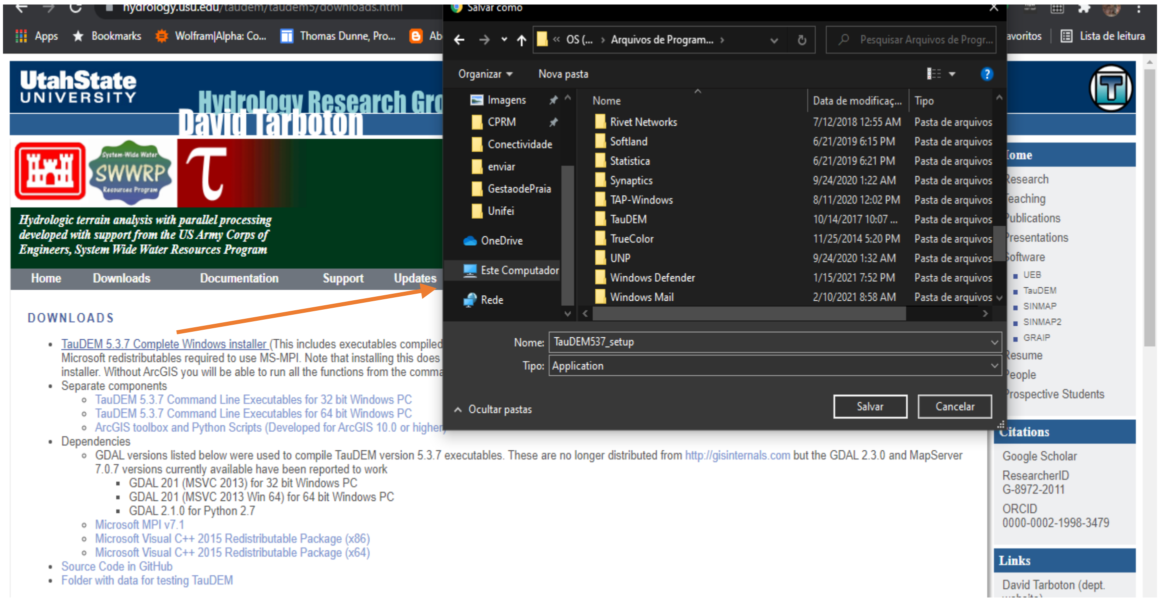


*Figure 2. The download of TauDEM 5.3.7 tool.*

## 3.2. Download and add to workspace

In order to download and use the ArcGis, the toolbox refers to the following steps:

- Download the Hydrosedimentological Connectivity Toolbox (for ArcGis 10.3) in Softwares from the GPDEN website:

  [https://www.ufrgs.br/gpden/softwares](https://www.ufrgs.br/gpden/softwares)

and save it to a permanent folder.

- Open ArcMap 10.3, in the toolboxes section right-click on ArcToolbox top folder and select Add toolbox (Figure 3).

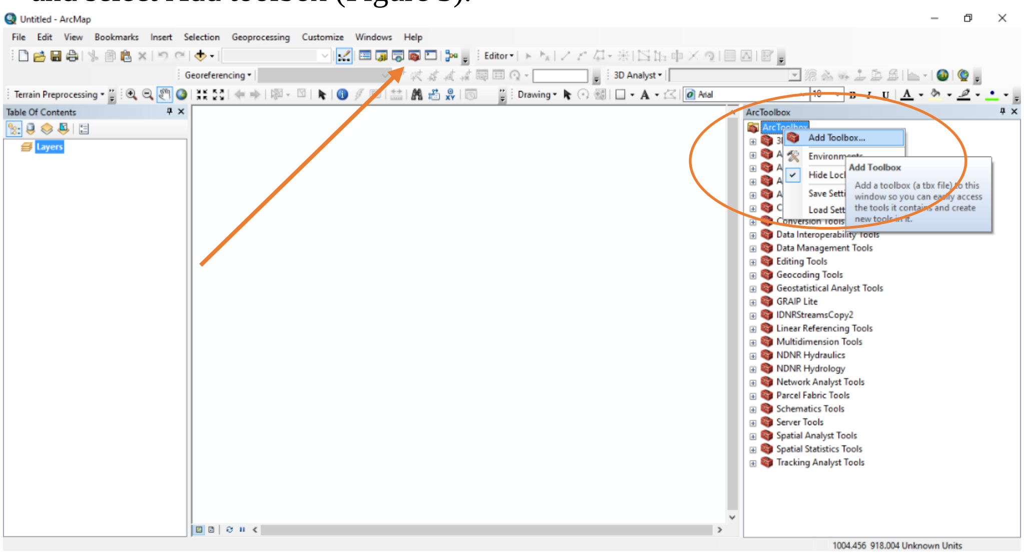


*Figure 3. Adding ArcToolbox to ArcMap 10.3 (Part 1).*

- Browse to your downloaded Hydrosedimentological Connectivity Toolbox, and add it (Figure 4).

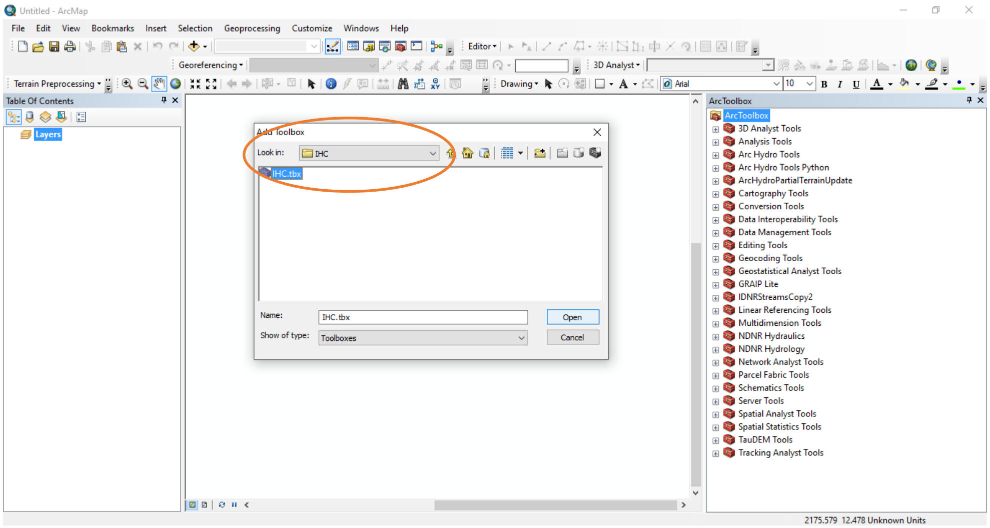

*Figure 4. Adding ArcToolbox to ArcMap 10.3 (Part 2).*

After adding the tool to Arcgis, the Hydrosedimentological Connectivity toolbox should have loaded into the project as shown in the screenshot below (Figure 5). When opening it, three available tools will be visible:

➢ ***IHC* – Index of Hydrosedimentological Connectivity:** implementation of *IHC* computation with respect to the outlet.

➢ **Surface roughness:** Computation of the Surface Roughness (*RI*) as expressed in Cavalli and Marchi (2008) implemented by Crema and Cavalli (2018).

➢ **Weighting Factor:** Computation normalized of the *RI* following the approach of Cavalli et al. (2013) or Trevisani and Cavalli (2016) for use as Weighting Factor (*W*). Surface roughness as a weighting factor (*W*) can be optionally used in the *IHC* computation.

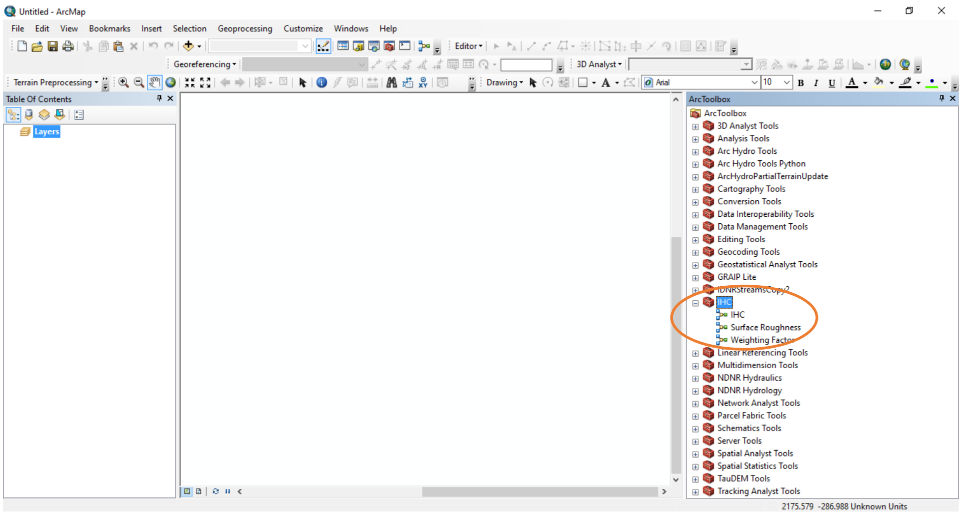


*Figure 5. The IHC ArcToolbox in ArcMap 10.3.*

## 3.3. Calculation of Index of Hydrosedimentological Connectivity

The *ModelBuilder* of the Toolbox that computes *IHC* calculated with respect to the watershed outlet is reported in Figure 6, where it is possible to analyze the sequence of ArcGIS and TauDEM operations modified from Cavalli et al. (2014).

All input raster files must be in GeoTIFF format since TauDEM works only with this format and must have the same extent, origin, size, number of rows, and columns. Moreover, $Q_{runoff}$ depends on the pixel size. The use of a 1m pixel size is indicated.

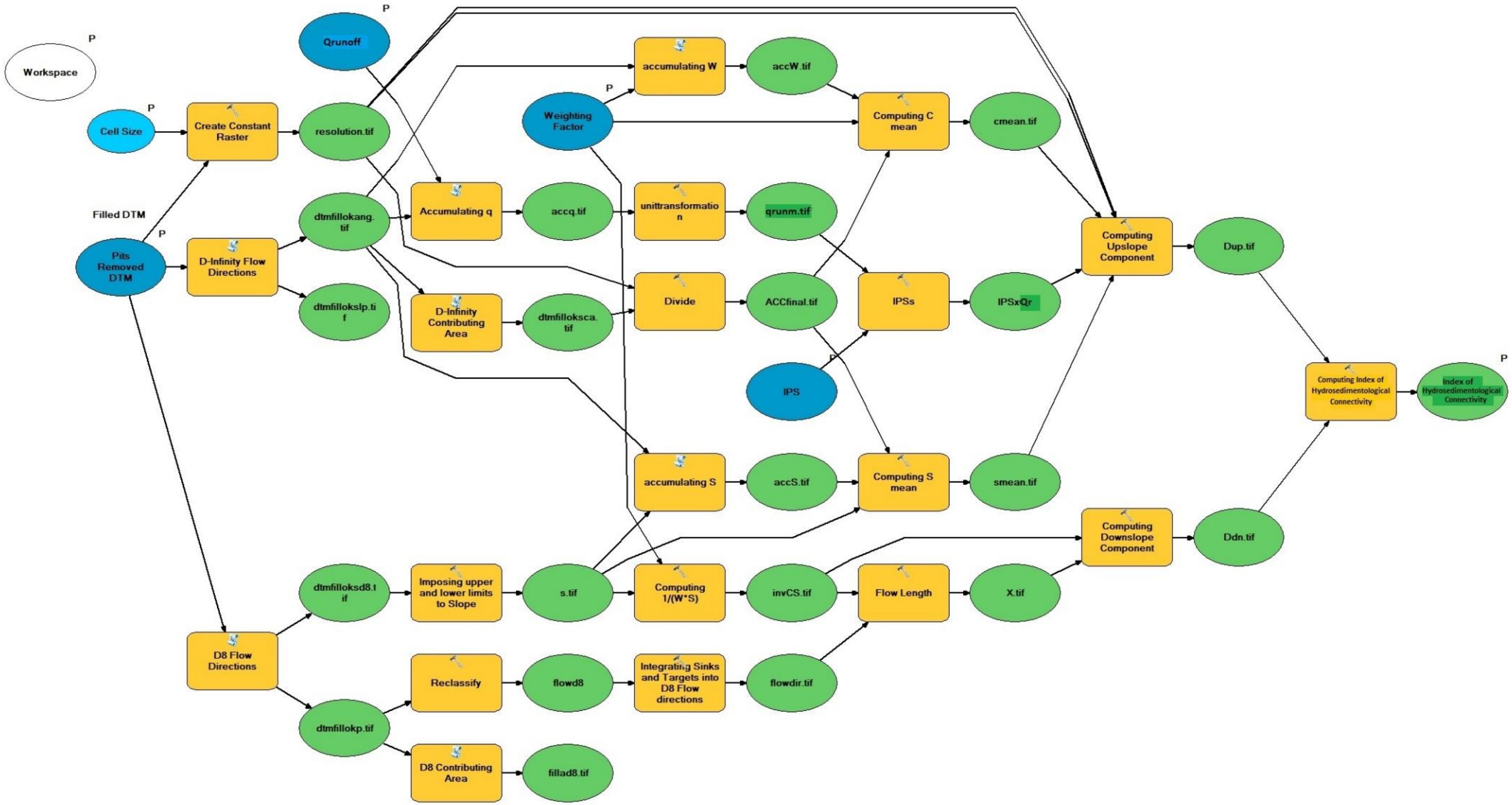


*Figure 6. ModelBuilder of the Index of Hydrosedimentological Connectivity ArcGis toolbox implementation.*

The toolbox window is the following (Figure 7):

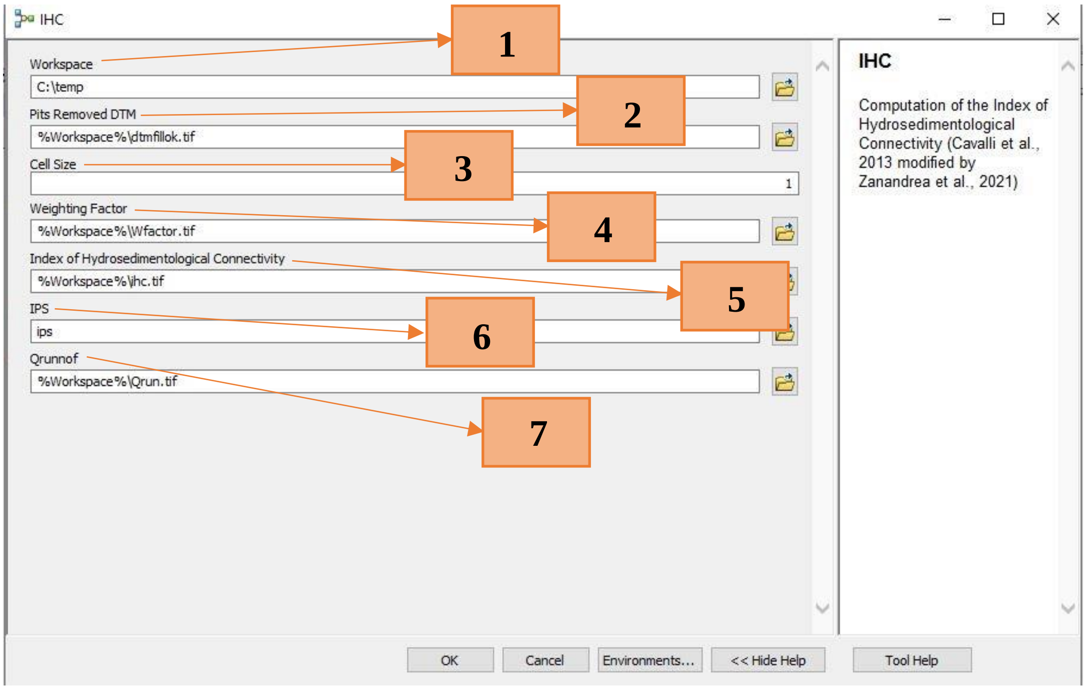


*Figure 7. IHC ArcToolbox.*

The inputs are:

1) **Working directory:** In this box, the directory where ArcGIS will store temporary files has to be selected. It is recommended to clean the directory from any temporary present file related to previous runs of the model. It might occur that, due to the ArcGIS setting, a local default working directory is already set and has the priority (commonly "C:\Users\username\Documents\ArcGIS\Default.gdb"). In this case, you will notice that the input files (DTM, Weighting factor) are not detected inside the working directory (Cavalli et al., 2014).

2) **Input DTM raster:** In this box, the input DTM must be set. The instructions below were taken from the Guidelines on the Sediment Connectivity by Cavalli et al. (2014).

*"The input DTM is usually hydrologically correct (with pits removed) to obtain a catchment-scale connectivity, but it is not compulsory. In case you want to keep the local depressions, each depression will act as a "sink" for upstream sediment in the final map. In this case, the connectivity will be computed with respect to the catchment outlet but all the areas draining to local depressions will report connectivity values with respect to these depressions. Downstream the local depression, the computation restarts until the next depression or the outlet. Running the tool using a DTM without removing local depressions could lead to interesting analyses considering automatically detected*

*sediment sinks. Nevertheless, it is important to point out that local depressions in a DTM are not always real sinks (e.g. dolines) but are generally artifacts of the DEM creation process that interfere with the flow routing and thus need to be removed. For consistency with the algorithms used in the connectivity model, we suggest using the Pit Remove algorithm of TauDEM that identifies all pits in the DEM and raises their elevation to the level of the lowest pour point around their edge.*

*Regarding the extent of the analysis, all the procedures should be carried out over a buffer of the selected catchment. This buffer is necessary to avoid errors or approximations related to border effects. We suggest a buffer of few pixels greater than the basin. At the end of the connectivity assessment, the output connectivity map must be clipped over the catchment mask in order to carry out any analysis on the catchment values distribution.*

*Since the Connectivity Index is numerically computed with respect to all the NoData values, it is a good practice to keep the buffer very close to the outlet (a couple of pixels is enough) while it can be wider in the rest of the study area. This last caution is important to be sure that IC is computed in relation to the desired outlet".*

**3) Input cell size:** In this box, input cell size in map units must be indicated. This value will be used to process drainage data to obtain unit values and to calculate $Q_{runoff}$ for each pixel.

**4) Input Weighting factor raster:** In this box, the weighting factor raster must be entered. The impedance factor must be defined according to the characteristics of the watershed and according to the required analysis. The user must choose which weighting factor is the most suitable for your analysis. If the user chooses to use surface roughness (*RI*) as *W* to represent impedance, the weighting factor can be derived from the Surface Roughness tool elaborated by Crema and Cavalli (2018). The *RI* raster can be normalized by the tool Weighting Factor in this Toolbox. If *RS* values are used as *W*, the *RS* map must be generated from Equation (6) having its values spatially-distributed according to the land use map. The *RS* map inputs directly into the Weighting factor.

**5) Output Index of Hydrosedimentological Connectivity map:** In this box, the path and name of the output *IHC* map are set. The map needs to be clipped with a mask of the watershed to exclude all the values in the buffer area not included in the analysis. The *IHC* maps are generated for each precipitation event.

**6) Input *IPS* raster:** In this box, the input *IPS* map must be set. The *IPS* map must be generated in raster format. The *IPS* values are calculated for each rain gauge analyzed according to Equation (5). The *IPS* values are distributed according to the influence area of each rain gauge evaluated corresponding to the interpolation methodology (e.g., Thiessen-polygon, Kriging). The pixel size of the *IPS* raster must be the same as the other raster's. The *IPS* maps are generated for each precipitation event, as well as the *IHC* map resultant.

**7) Input $Q_{runoff}$ raster:** In this box, the input $Q_{runoff}$ map must be set. The $Q_{runoff}$ values are calculated for each rain gauge and land use/type soil according to Equations (2), (3), and (4). The $Q_{runoff}$ values are distributed according to the influence area of each rain gauge evaluated corresponding to the interpolation methodology (*e.g.*, Thiessen-polygon, kriging) and the land use/type soil maps. The $Q_{runoff}$ values are calculated for each pixel and the generated map must be in millimeters. The conversion of the runoff values of each pixel from millimeters to meters, to maintain the non-dimensionality of the index, takes place within the tool. The pixel size of the $Q_{runoff}$ raster must be the same as the others raster's. The $Q_{runoff}$ maps are generated for each precipitation event, as well as the *IHC* map resultant.

This document is based on the Guidelines on the Sediment Connectivity by Cavalli et al. (2014).

For gaining more explanation on the Hydrosedimentological Connectivity Toolbox usage, please write to Dr. Franciele Zanandrea (franciele.zanan@gmail.com).

## 4. References


Borselli, L., Cassi, P., Torri, D. 2008. Prolegomena to sediment and flow connectivity in the landscape: A GIS and field numerical assessment. CATENA 75: 268–277. DOI: 10.1016/j.catena.2008.07.006.

Cavalli, M., Marchi, L. 2008. Characterisation of the surface morphology of an alpine alluvial fan using airborne LiDAR. Nat. Hazards Earth Syst. Sci. 8: 323–333. DOI: 10.5194/nhess-8-323-2008.

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

Cavalli, M., Crema, S., Marchi, L. 2014. Guidelines on the Sediment Connectivity ArcGis 10.1 and 10.2 Toolbox. CNR-IRPI Padova (PP4), Release: 1.1, 25p. [online] Available from: http://www.sedalp.eu/download/tools.shtml.

Chow, V.T. 1959. Open-Channel Hydraulics. McGraw-Hill, New York.

Crema, S., Cavalli, M. 2018. SedInConnect: a stand-alone, free and open source tool for the assessment of sediment connectivity. Computers & Geosciences. 111: 39-45. DOI: 10.1016/j.cageo.2017.10.009.

ESRI. 2015. ArcGis 10.3. Environmental System Research Institute, Inc, Redlands, CA

Renard, K.G., Foster, G.R., Weesies GA, McCool DK, Yoder DC. 1997. Predicting soil erosion by water: a guide to conservation planning with the Revised Universal Soil Loss Equation (RUSLE). No 703: xix + 384 pp.

Tarboton, D.G. 1997. A new method for the determination of flow directions and upslope areas in grid digital elevation models. Water Resources Research 33: 309–319. DOI: 10.1029/96WR03137.

Tarboton, D.G. 2021. Taudem 5.3, Terrain Analysis Using Digital Elevation Models [online] Available from: http://hydrology.usu.edu/taudem/taudem5/.

Trevisani, S., Cavalli M. 2016. Topography-based flow-directional roughness: potential and challenges. Earth Surf. Dyn. 4, 343 - 358. DOI:10.5194/esurf-4-343-2016.

Turnbull, L., Wainwright, J. 2019. From structure to function: understanding shrub encroachment in drylands using hydrological and sediment connectivity. Ecol. Indic. 98, 608–618. DOI: 10.1016/j.ecolind.2018.11.039.

Zanandrea, F., Michel, G.P., Kobiyama, M. 2020. Impedance influence on the index of sediment connectivity in a forested mountainous catchment. Geomorphology 351. DOI: 10.1016/j.geomorph.2019.106962.

Zanandrea, F., Michel, G.P., Kobiyama, M., Censi, G., Abatti, B.H. 2021. Spatial-temporal assessment of water and sediment connectivity through a modified connectivity index in a subtropical mountainous catchment. CATENA 204: 105380. DOI: 10.1016/j.catena.2021.105380.

Wischmeier, W.H., Smith, D.D. 1978. Predicting rainfall erosion losses - a guide to conservation planning. U.S. Department of Agriculture.