uff TER Departamento de Engenharia Agrícola e do Meio Ambiente

Hydrosedimentological Connectivity Index Guidelines (IHC) - Stand-Alone Version

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https://github.com/artur-cereto/IHC

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Abstract

The connectivity supports 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.

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 address It as 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 used 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 in the original 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 the index of hydrosedimentological connectivity (*IHC*). This 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) allows 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 standalone application not requiring the use of any GIS software.

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, such 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 (dis)connectivity of any areas. Therefore, such maps can 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* intends 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 stand-alone application is based on a Python (3.12.4) script that processes geographical datasets (rasters) in order to generate the hydrosedimentological connectivity index map. It uses functionalities and algorithms available in TauDEM 5.3.7 tool (Tarboton, 1997; Tarboton, 2021), and the following python libraries: os, sys, subprocess, gdal 3.6.2, rasterio 1.3.10, numpy 1.26.4, tkinter 8.6.14.

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 taken by the sediment to the point of interest (downstream component - D_{dn}). The *IC* values are within the range of [-∞, + ∞] and the graphical *IC* representation is shown in Figure 1.

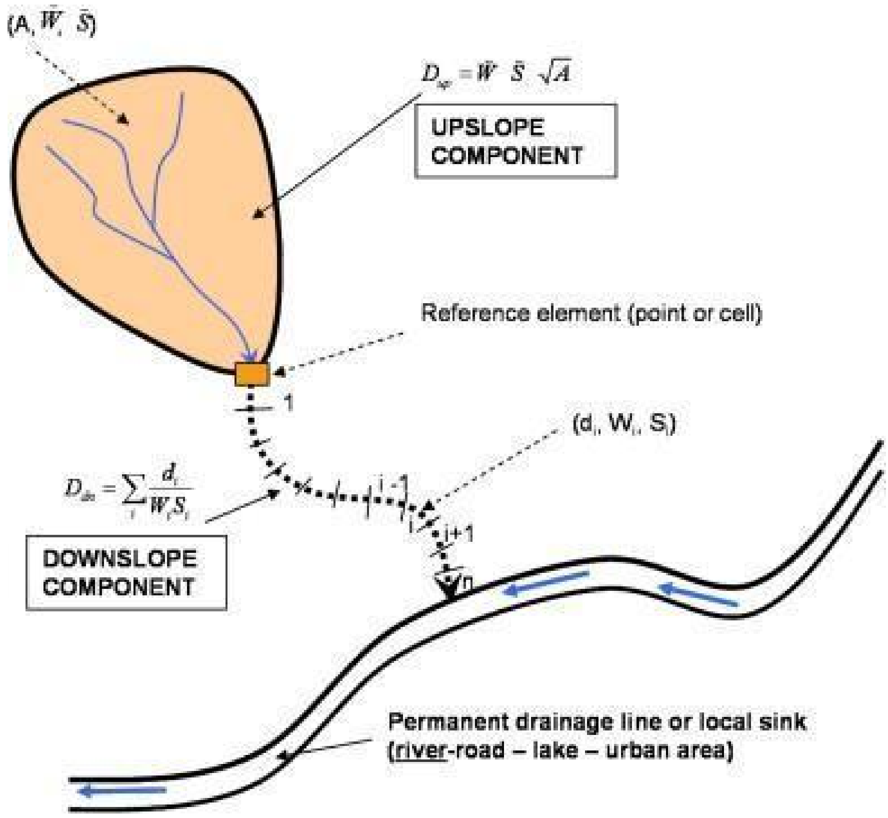

Figure 1. Definition of the components of the upper and lower part of the hillslope of the connectivity index (IC) (Borselli et al., 2008).

W is the impedance factor; *S* is the slope (m/m); *A* is the contribution area (m²); *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 software presented here.

2.2. Framework and formulation of the *IHC* implemented in the software

The modification of the index is based on the insertion of variables (precipitation index for sediments – *Ips* and surface runoff - Q_{runoff}) related to functional connectivity into the *IC*, taking into account 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:

$$IHC = log_{10}\left(\frac{\overline{RS}\times\overline{S}\times Ips\times\sum Q_{runoff}}{\sum\frac{d_i}{RS_i\times S_i}}\right) \quad (1)$$

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 varies spatially due to the soil characteristics and land use, which are related to the *CN* value.

The inclusion of Ips in the upstream component for calculating connectivity adds a weight factor associated with the amount of sediment available for the event studied due to a preceding event. Ips can be calculated for any preceding precipitation event:

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

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 Δt_{m-i} is the duration of the precipitation event *m-i* (d). By using Ips, the previous conditions of the watershed can be taken into account, and it also makes possible to compare different rainfall events.

The *IHC* maintains the original application, considering three new pieces of 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 (Cavalli and Marchi, 2008). . 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 watersheds, 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:

$$RS = \frac{n_{mín}}{n} \tag{6}$$

where n_{min} is the minimum Manning coefficient 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.

3. IHC Stand-alone Application

3.1. Requirements

The requirements are similar to those presented by Cavalli et al. (2014). The software 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 the download of TauDEM 5.3.7 tools, the link is:

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

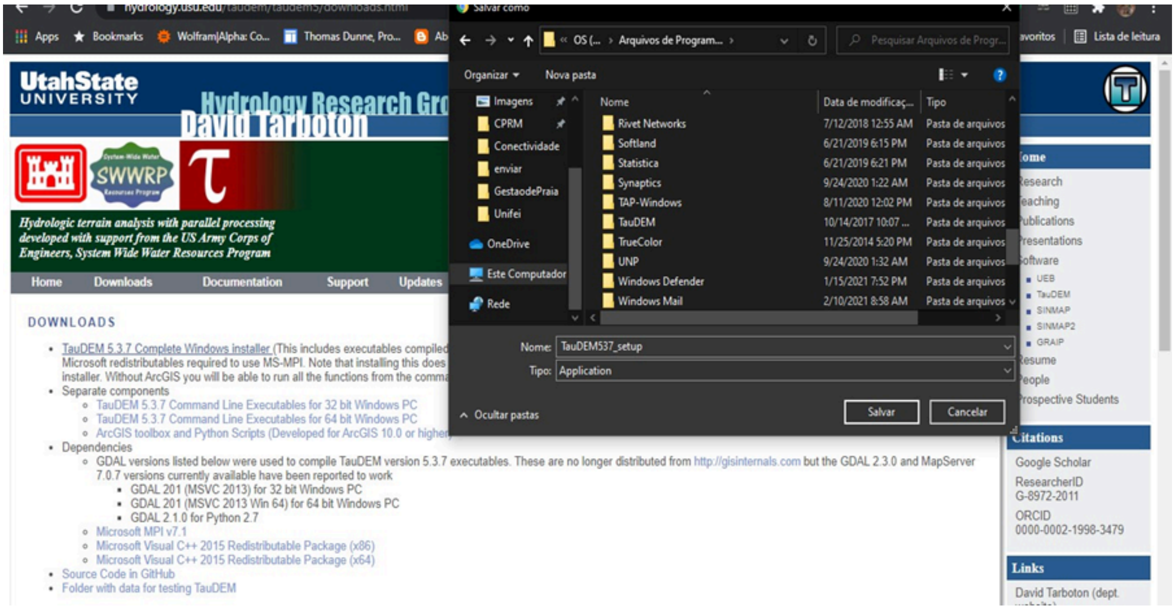

Figure 2. TauDEM 5.3.7 Download

3.2. Calculation of Index of Hydrosedimentological Connectivity

The flow chart of the stand-alone *IHC* calculator is shown in Figure 3, where it is possible to analyze the workings of the script with the TauDEM operation highlighted.

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.

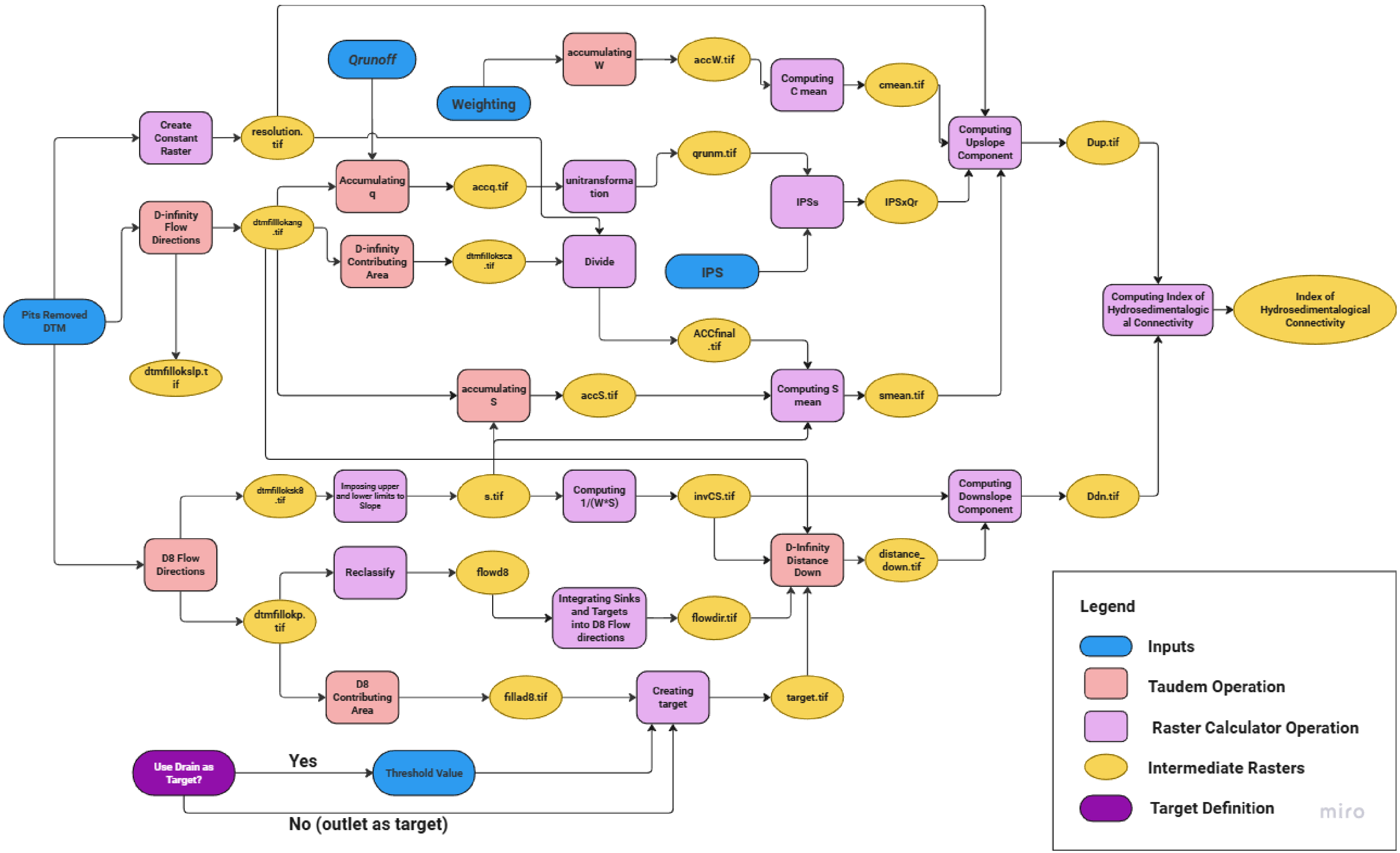

Figure 3. Flowchart of the Index of Hydrosedimentological Connectivity stand-alone implementation.

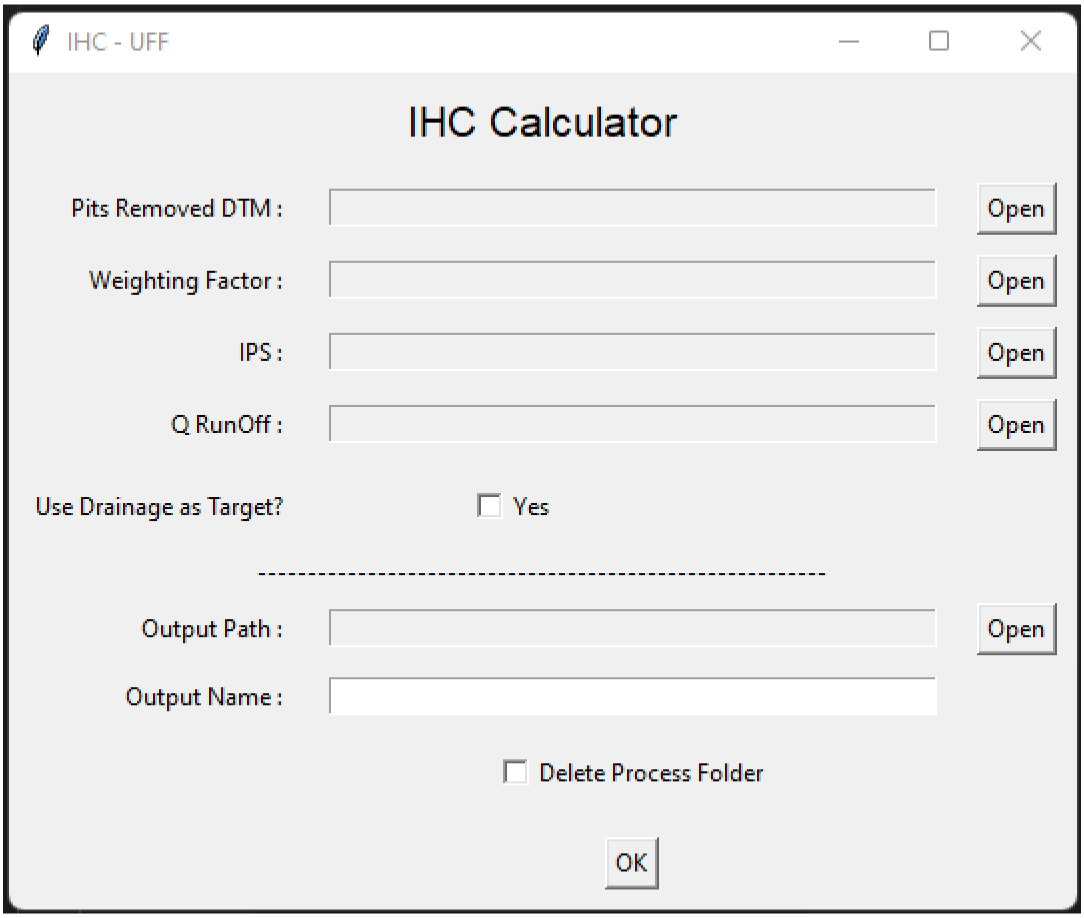

Figure 4. Software stand-alone window

The Figure 4 above presents the stand-alone software user interface, in which it's possible to insert the following input data necessary for the IHC calculation:

1) **Pits Removed DTM:** In order to avoid issues during the calculations we recommend pre-processing the raw DTM using the breach depressions algorithm provided by the WhiteBox tools to get the pits removed DTM (LINDSAY, 2014).

To select the corresponding .tif file, click the "Browse" button and choose the file. The path to the processed DTM will then be displayed in the text box. The pixel size used during the calculations will be automatically set by this input.

2) **Weighting Factor:** In this box, the weighting factor raster must be selected by clicking the "Browse" button and choosing the correspondent .tif file.

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). 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.

3) ***IPS*****:** 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 resultant *IHC* map.

4) $\boldsymbol{Q_{runoff}}$ **:** 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 rasters. The Q_{runoff} maps are generated for each precipitation event, as well as the resultant *IHC* map.

5) **Use Drainage as Target:** If this option is selected, it must be indicated the minimum value for the Threshold that it is going to be used for delimiting the drainage line. All the pixels with higher values than the threshold will compose the drainage line. In case this option isn't selected, the pixel with the highest value will be considered as the target to calculate the index. That is, in this case, the index will be calculated regarding the outlet of the studied watershed.

6) **Output Path:** The path to the folder to store the output files relative to the IHC index map generated.

7) **Output Name:** Finally, the name of the output file that the IHC final map will be stored at must be informed. It is highlighted that the IHC map must be calculated to each precipitation event, for example: *ihc_event1*.

8) **Delete Process Folder:** As the result of the operations needed to calculate the index, intermediate files are generated. These files can be useful to other applications or to extract information (e.g. D8 flow direction, flow accumulation etc.) in addition to enabling troubleshoot issues that may be happening during the processing. In case this option is selected, these files will be stored in a folder named *process_of_<output_name>*, in the case of the previous example *process_of_ihc_evento1*, in the same location of the Output Path (item 6). In case this option is selected, this folder will be automatically deleted after the IHC computations are finished.

3.3 Download the script and add to workspace

In order to correctly run the IHC calculator stand alone application, download both the script and the .yml to set up the virtual environment with the libraries needed to run the computations at https://github.com/artur-cereto/IHC

4. Troubleshoot Issues

Before using the program, ensure that all input files share the same extension, are in the same coordinate system, and have uniform pixel sizes. Inconsistencies in these factors can lead to processing errors, preventing the program from functioning correctly.
In order to avoid issues during the calculations, we recommend pre-processing the raw DTM using the breach depressions algorithm provided by the WhiteBox tools to get the pits removed DTM.

In some isolated cases, edge contamination was observed during the surface runoff accumulation step, resulting in NoData values in regions within the final IHC raster. To verify if this issue occurred, check the intermediate file “accq.tif” to identify any edge contamination. To avoid this problem, it is recommended to use a buffer area around the study area in all input rasters for the IHC calculator.

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

For more explanation on the Hydrosedimentological Connectivity Stand-alone usage, please write to Dr. Franciele Zanandrea (franciele.zanan@gmail.com) or to the developer of this script Artur Cereto (arturcereto@id.uff.br).

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