**Guidelines on the Sediment Connectivity ArcGis 10.1 and 10.2 Toolbox**

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# Introduction

Sediment connectivity, i.e. the degree of linkage that controls sediment fluxes throughout landscape, and, in particular, between sediment sources and downstream areas, is a key issue in the study of sediment transfer processes in mountainous catchments. The spatial characterization of connectivity patterns in the catchment allows estimation of the contribution of a given part of the catchment as sediment source, and defines sediment transfer paths. A reliable assessment of sediment connectivity is especially useful for giving management priorities. The assessment of sediment connectivity is of particular importance in alpine headwaters, in which both complex and rugged morphology, and heterogeneity in type, extent and location of sediment sources cause large variability in the effectiveness of sediment transport processes. The control of morphology on spatial sediment connectivity acts through sediment transfer on hillslopes and unchanneled valleys, hillslope-channel coupling and decoupling, and sediment transfer along the channel network.

In this document, background theory, installation steps and user guidelines of two utilities for the derivation of the Index of Connectivity (IC), as expressed in Cavalli et al. (2013), developed in the frame of the SedAlp project are presented. The utilities are: (i) a Toolbox for ArcGis 10.1 and 10.2 and, (ii) a standalone application not requiring the use of any GIS software.

The need for the development of such tools comes from the increasing interest in sediment connectivity issues (Fryirs 2013; Baartman et al. 2013) and its semi-quantitative assessment (Heckmann and Schwanghart 2013; Cavalli et al. 2013; Meßenzehl et al., 2014) to estimate the effectiveness of sediment transport processes at catchment scale.

Moreover, the possibility to relate a quantitative estimate of sediment connectivity to sediment sources databases can improve hazard and risk assessment in order to mitigate the effects of dangerous phenomena like debris flows. With an integrated approach, which encompasses sediment sources mapping and connectivity assessment, it is indeed possible not only to evaluate the general availability of sediment but also to estimate the potential for this sediment to reach specific targets.

# Background theory

The index of sediment connectivity IC, as proposed by Cavalli et al. (2013) based on the work of Borselli et al. (2008), is a distributed geomorphometric index that can be easily derived from a Digital Elevation Model (DEM). Thus, it mainly focuses on the influence of topography on sediment connectivity, whereas other aspects such as type, extent and location of sediment sources are not taken into account.

IC is intended to represent the linkage between different parts of the catchment and aims, in particular, at evaluating the potential connection between hillslopes and features of interest (e.g. catchment outlet, main channel network, a given cross section along the channel) or elements acting as storage areas (sinks) for transported sediment (e.g., lake, retention basin). In particular, the developed tools allow estimating sediment connectivity considering two aspects: (i) sediment delivery across the whole drainage system (i.e. the potential connection of sediment between hillslopes and catchment outlets), and (ii) sediment coupling-decoupling between hillslopes and selected targets or sinks. The choice of modeling these two aspects stems from the need to address two main sediment management issues: (i) what is the probability that sediment from a certain sediment source will reach the catchment outlet? (ii) what is the probability that sediment eroded from the hillslopes will attain the target of interest?

The connectivity tool has been implemented through the Model Builder application running in ArcGIS 10.1 (ESRI 2012), and it uses functionalities and algorithms available in TauDEM 5.2 tool (Tarboton 2013).

## Index of sediment connectivity

IC is derived following the approach of Borselli et al. (2008), who defined the Index of Connectivity as:

 (1)

where *Dup* and *Ddn* are the upslope and downslope components of connectivity (Fig. 1), respectively. *IC* is defined in the range of [-∞, +∞], with connectivity increasing for larger *IC* values.

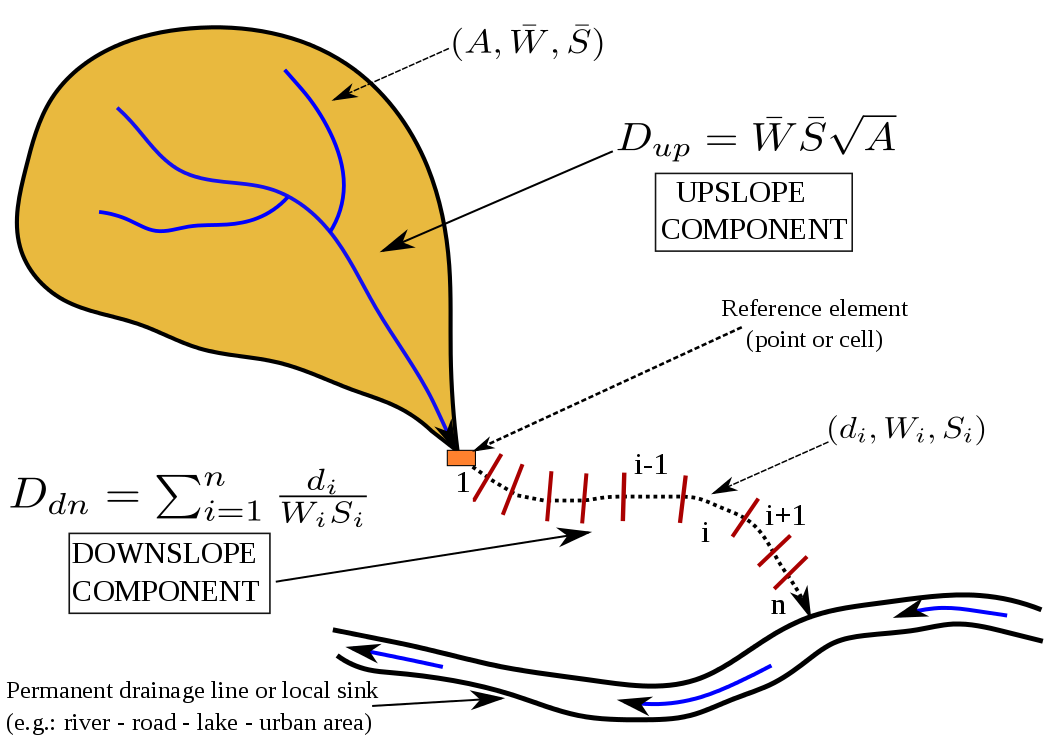


Figure 1. Connectivity index upslope and downslope components (modified after Borselli et al., 2008).

The upslope component *Dup* is the potential for downward routing of the sediment produced upslope and is estimated as follows:

 (2)

where  is the average weighting factor of the upslope contributing area (see later), is the average slope gradient of the upslope contributing area (m/m) and *A* is the upslope contributing area (m2).

The downslope component *Ddn* takes into account the flow path length that a particle has to travel to arrive to the nearest target or sink. Therefore, *Ddn* can be expressed as:

 (3)

where *di* is the length of the flow path along the *i*th cell according to the steepest downslope direction (m), *Wi* and *Si* are the weighting factor and the slope gradient of the *i*th cell, respectively. It is worth noting that *di* can assume two values: cell size (*l*) in the case of cardinal direction and *l√2* in the case of diagonal direction.

## Refinement of the index of sediment connectivity implemented in the tools

The changes made to the original model by Borselli et al. (2008) have been devised to adapt the model to mountain catchments and to its use with High Resolution Digital Terrain Models (HR-DTMs). The changes can be grouped under the following categories: (i) Slope factor computation, (ii) Contributing area calculation, and (iii) Choice of the Weighting factor (W).

### Slope

In the original connectivity model (Borselli et al., 2008), a value of 0.005 m/m was added to the computed value of slope in order to avoid infinites in Eq. 3. In this modified version of the model, we preferred to preserve the slope values calculated directly from the HR-DTM setting a lower limit of 0.005 m/m, for the same reason just explained, and an upper limit of 1 m/m. The upper limit in slope parameter is introduced to limit the bias due to very high values of IC on steep slopes. The setting of a slope upper limit of 1 m/m has also a physical reason: in alpine environment very high slopes are typical of near-vertical rocky cliffs or very steep hillslopes and bedrock channels where sediment storage is difficult. In such a context, processes related to sediment mobilization are mainly represented by rockfalls and not by the processes the proposed sediment connectivity index intends to investigate (i.e. debris flows, bedload transport).

### Contributing area

The tools uses the multiple flow D-infinity approach (Tarboton 1997) to calculate contributing area, instead of the single-flow direction algorithm (O’Callaghan and Mark 1984) applied in the original model.

The advantages of D-infinity over the methods that restrict flow to eight possible directions introducing grid bias (i.e. single-flow direction method) or proportioned flow according to slope introducing unrealistic over-dispersion (i.e. multiple flow direction method) are well known (Tarolli and Dalla Fontana 2009; Hengl and Reuter 2009). In order to correctly model sediment fluxes in mountain catchments, it is fundamental to capture the real flow paths especially on hillslopes where divergent flow predominates. The choice of a reliable algorithm modeling divergent flow is thus reckoned necessary. Another reason that leads to the choice of the D-infinity approach is related to the cell size of HR-DTMs. If the cell size is smaller than the width of the channels in the study area, the use of the single-flow algorithm to derive flow accumulation would limit high-drainage areas (i.e. the channel network) to sequences of single cells, thus underestimating channel widths. In contrast, the D-infinity algorithm better approximates channel width by partitioning flow over the entire cross section. Therefore, the D-infinity algorithm produces a more representative pattern of sediment connectivity through the basins.

### Weighting factor

The weighting factor W, which appears in upslope and downslope components of IC (Eqs. 2 and 3), was introduced by Borselli et al. (2008) to model the impedance to runoff and sediment fluxes due to properties of the local land use and soil surface. Borselli et al. (2008) used the C-factor of USLE-RUSLE models (Wischmeier and Smith 1978; Renard et al. 1997) as weighting factor W. The C-factor, related to vegetation cover and management, attains its maximum value when the soil is more at risk of erosion and approaches zero when the soil is more protected. However, the same authors stressed that W should be derived from the surface characteristics that influence runoff processes and sediment fluxes within a watershed or on a hillslope. Manning’s *n* roughness coefficient meets these requirements; it could be especially suitable, as an alternative to the C-factor, in areas with a great heterogeneity of land use or in the case of a study aiming at evaluating the role of different vegetation covers on sediment dynamic).

LiDAR-derived HR-DTMs permit the computation of geomorphometric indices able to represent fine-scale topographic variability, thus furnishing valuable information on the surface roughness. Accordingly, we decided to propose a local measure of topographic surface roughness, i.e. a roughness index (*RI*), as the weighting factor W. The roughness index is calculated as the standard deviation of the residual topography at a scale of few meters (Cavalli et al. 2008; Cavalli and Marchi 2008). The residual topography is computed as the difference between the original DTM and a smoothed version derived by averaging DTM values on an *nxn* cells moving window. The averaged DTM is necessary to avoid the effect of large scale topography (i.e. slope gradient). Finally, the standard deviations of residual topography values are computed in an *n**n* cells moving window over the residual topography grid. The roughness index is then defined as:

 (4)

where *n2* is the number of the processing cells within the *nxn* cells moving window, *xi* is the value of one specific cell of the residual topography within the moving window, and *xm* is the mean of the *n2* cells values.

The weighting factor is expressed as follow:

 (5)

where *RIMAX* is the maximum value of *RI* in the study area. To avoid infinites or close-to-infinite ratios in Eq. 3, all the values in *W*  that fall in the range 0-0.001 are set to 0.001. This standardization of roughness value, which causes *W* to range from 0.001 to 1, is introduced for three reasons: (i) to have the same range of variation as for S factor in order to weight them equally in the model; (ii) to remove the bias due to high *RI* values, and (iii) to provide comparable values with USLE C-factor and therefore with the original model by Borselli et al. (2008).

The use of a roughness index as weighting factor in the IC has several advantages: i) the weight is estimated objectively; ii) it avoids the use of tabled data such as those used for the C-factor of USLE, which are essentially devised for agricultural environments; iii) it allows the model to be applied straightforwardly, requiring only the DTM as an input. Furthermore, the model by Borselli et al. (2008) focuses on environments that justify the use of the USLE C-factor. Vegetation cover and land use management data used to determine the C-factor are suitable to describe impedance to runoff and sediment fluxes process in agricultural and forest environments. In Alpine catchments, large unvegetated areas are present with different surface roughness depending on the characteristics of outcropping rock and debris cover. In these bare areas, the C-factor would not provide differences in the impedance to sediment transport, which can be better represented by a proxy based on topographic roughness. Moreover, a roughness-based index is more suited for modeling sediment transfer by debris flows, which have a major role in sediment-related processes in Alpine basins. In such a context, we argue that the characterization of surface roughness represents a better proxy for sediment transport impedance compared to the C-factor.

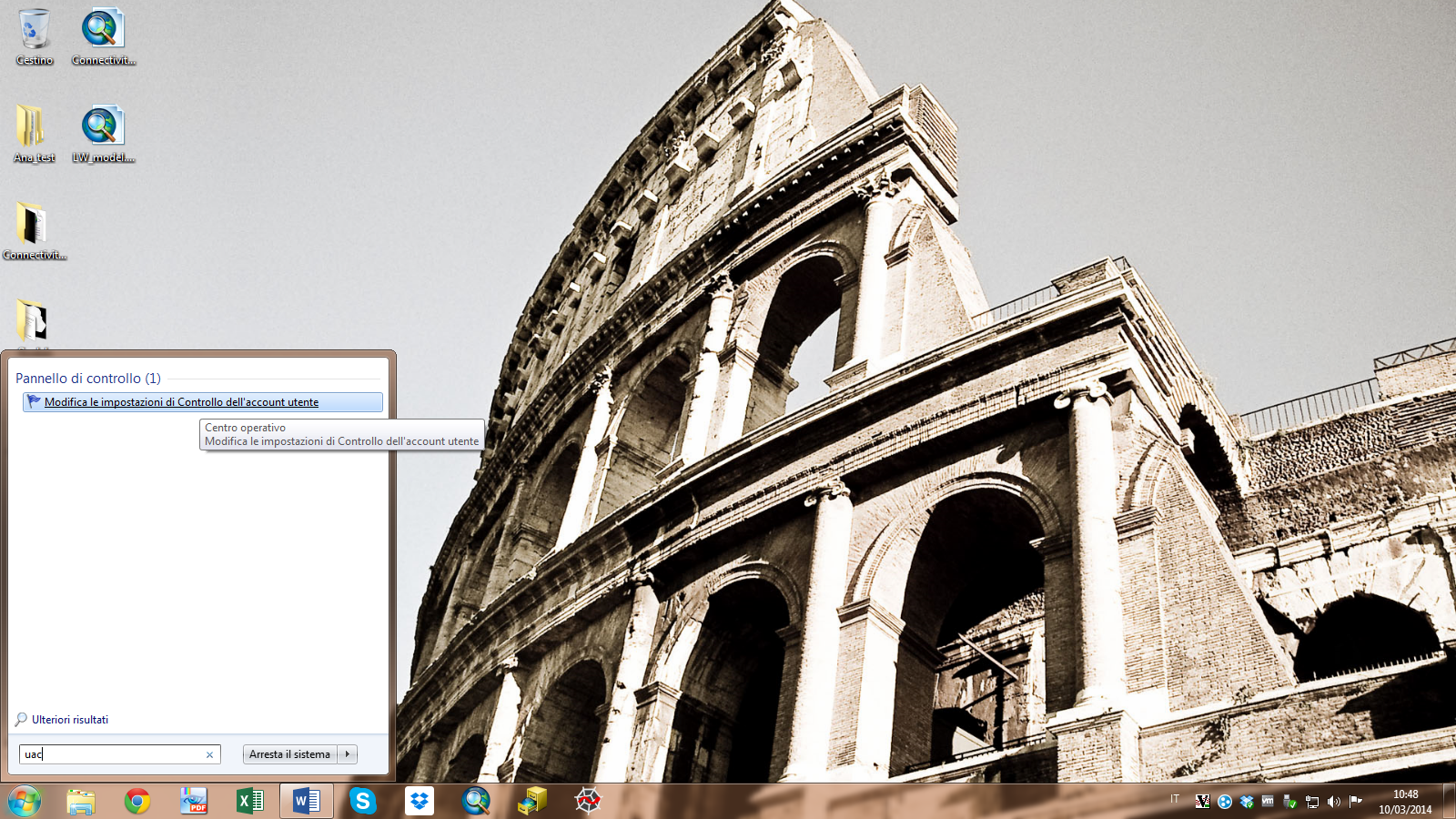
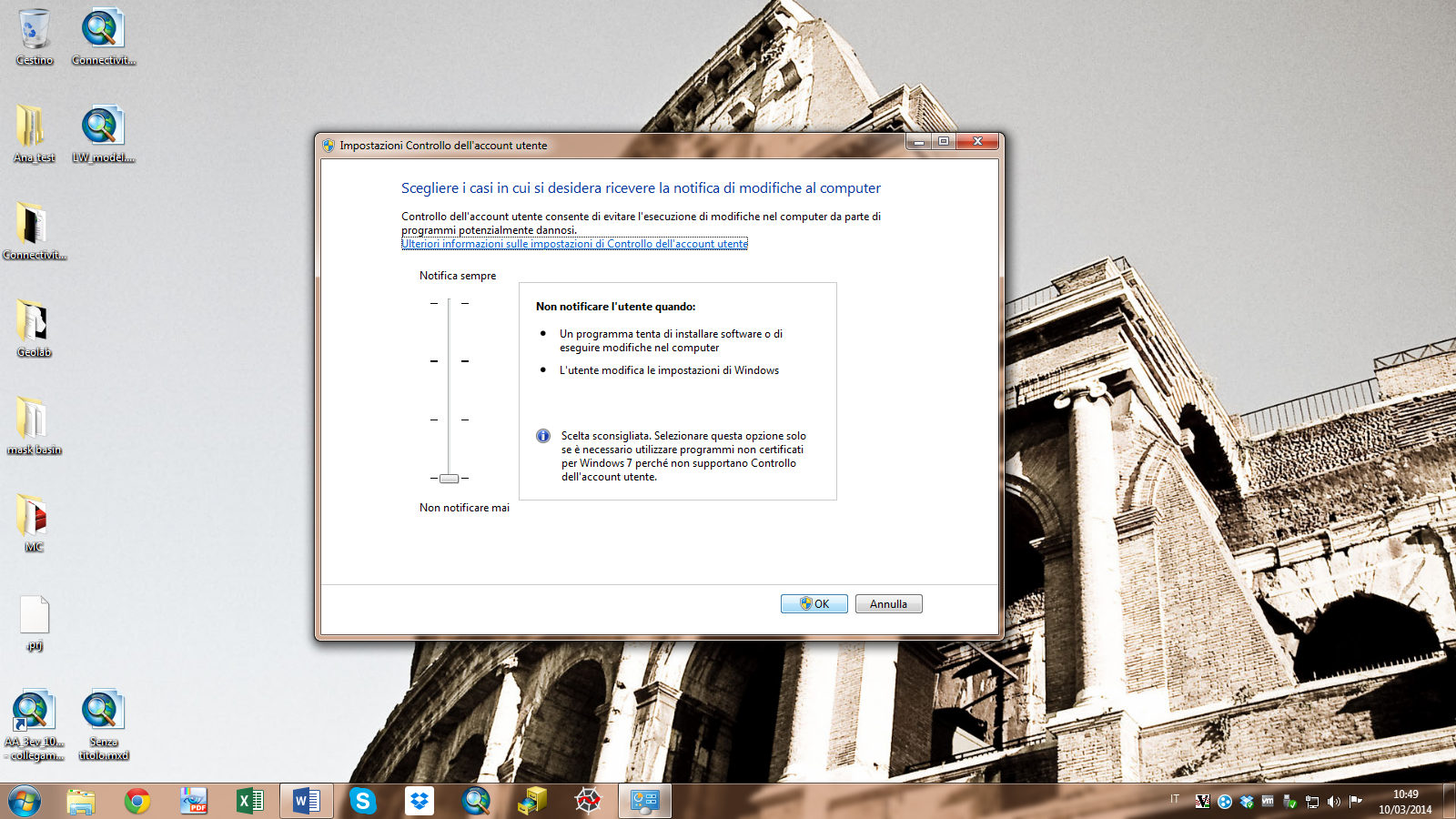
It is important to emphasize that the choice of the weighting factor W related to the impedance to sediment fluxes is free. This means that, according to the objective of the study, the user can use different parameters expressing the impedance to sediment fluxes (e.g., C-factor of the USLE as in the Borselli et al., 2008, Manning’s n, or topographic roughness computed on a high-resolution DTM). A basic requirement to be met is that the weighting factor varies on the range >0 to 1.

# ArcGIS toolbox

## Requirements

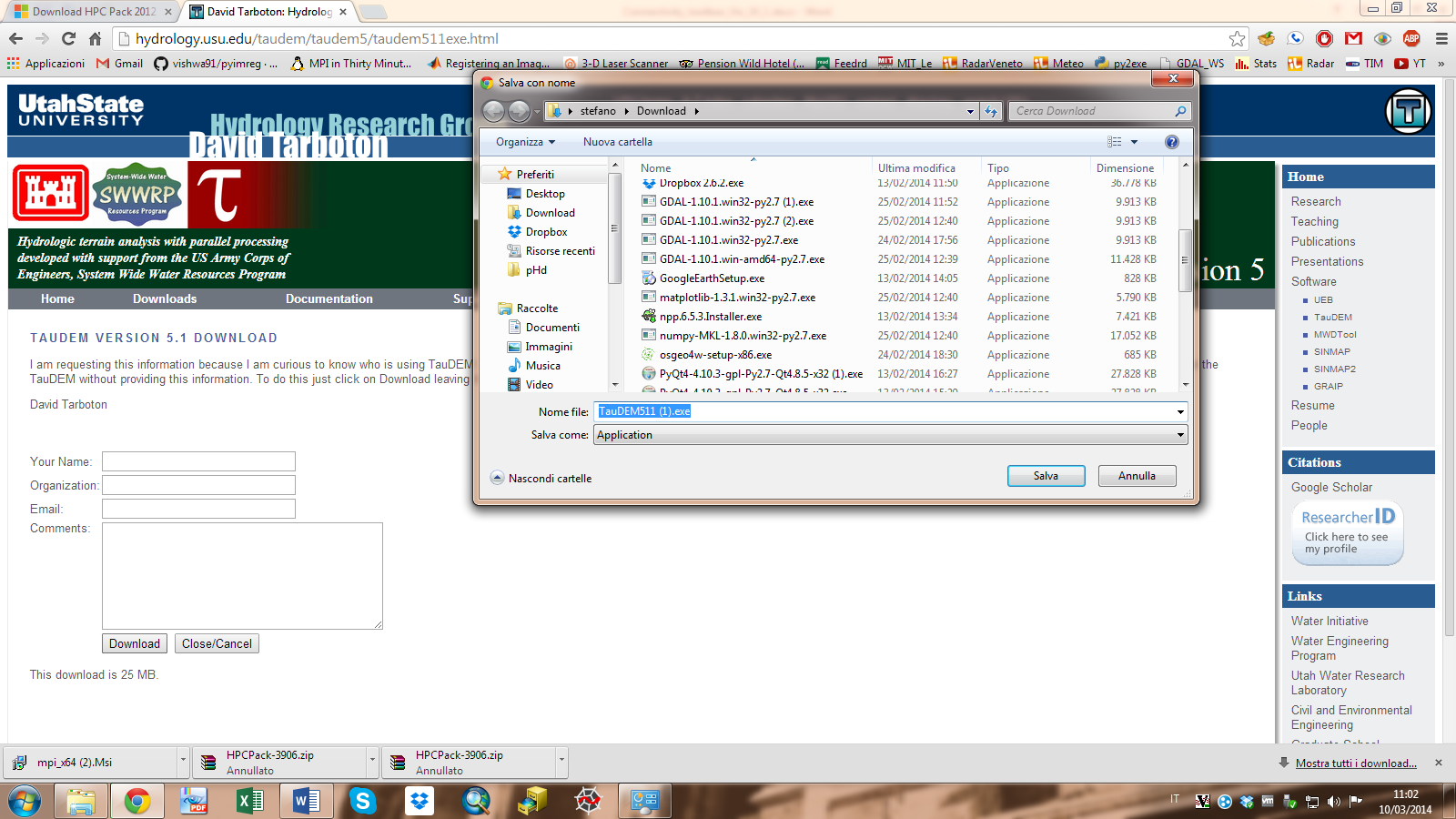
The ArcGIS toolbox requires TauDEM tools (http://hydrology.usu.edu/taudem/taudem5/index.html) installation since several hydrological functions are computed exploiting this suite. For TauDEM tools installation refer to the following steps:

* Recommendation: turn UAC (User Account Control) to the lowest value to prevent Windows from blocking MPI activity. To do this type “*uac”* in the start dialogue, turn the level low and confirm.

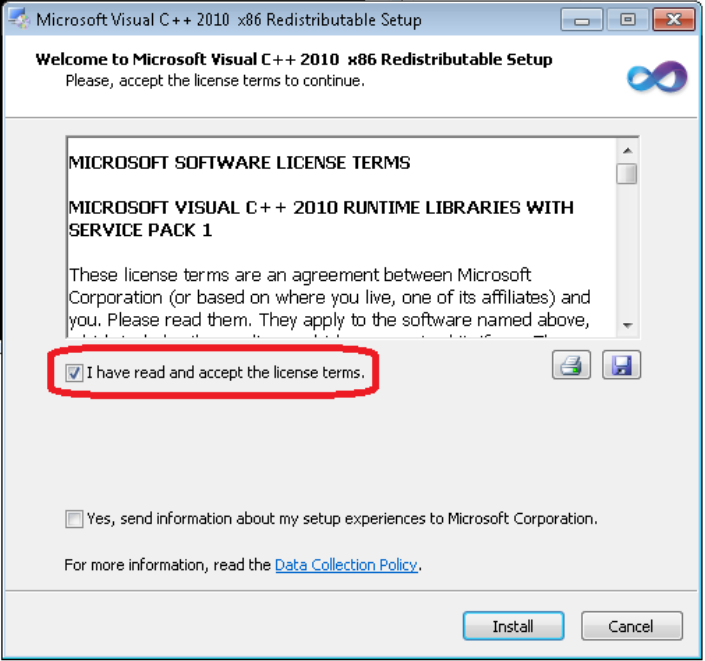
* Download and install TauDEM 5.1.1 (tested version) from:

<http://hydrology.usu.edu/taudem/taudem5/taudem511exe.html>

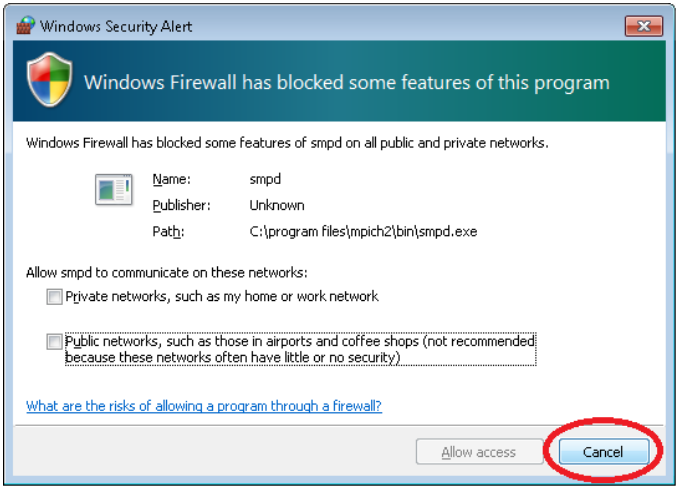


* It is recommended to install TauDEM with administrative privileges. To do this right-click on the downloaded file and select ***Run as administrator***.

TauDEM installation requires [HPC Pack 2012](http://www.microsoft.com/en-us/download/confirmation.aspx?id=36045) and [Microsoft visual C++ 2010](http://www.microsoft.com/it-it/download/details.aspx?id=5555) runtime libraries. During the installation, their presence in the system will be automatically checked. In the negative case, you will have to install the proposed dependencies following the installer suggestions.



* If at any time during the installations (HPC, Visual C++ or TauDEM) you receive a firewall message like the following:



click *Cancel* and continue because the utility does not need to communicate with external resources.

## Download and add to workspace

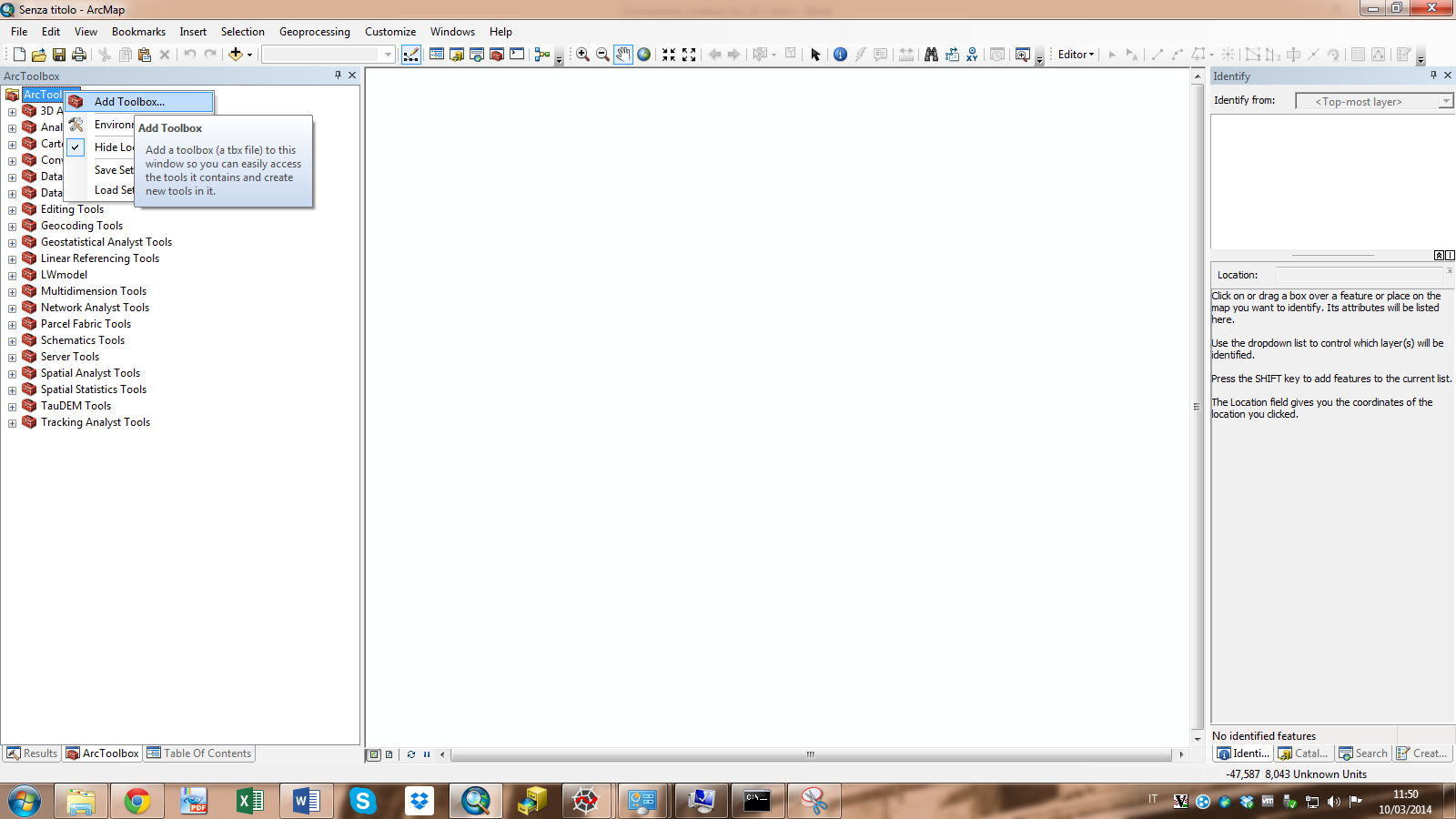
In order to download and use the ArcGis toolbox refer to the following steps:

* Download the Connectivity Toolbox (for ArcGis 10.1 and 10.2) from the SedAlp website:

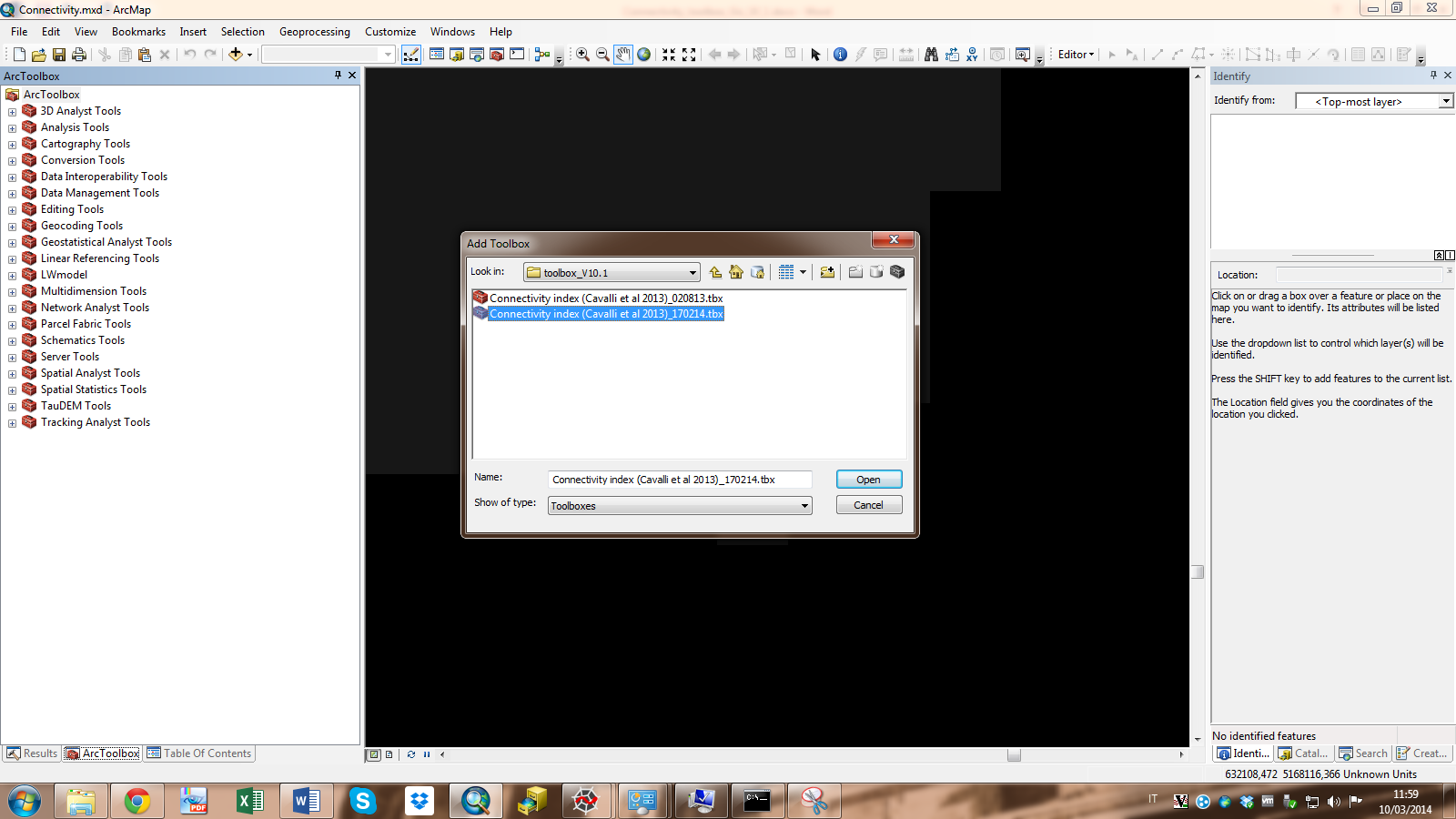
<http://www.sedalp.eu/download/tools.shtml>

and save it to a permanent folder.

* Open ArcMap 10.1/10.2, in the toolboxes section right-click on ArcToolbox top folder and select Add toolbox.



Browse to your downloaded Connectivity Toolbox and add it.

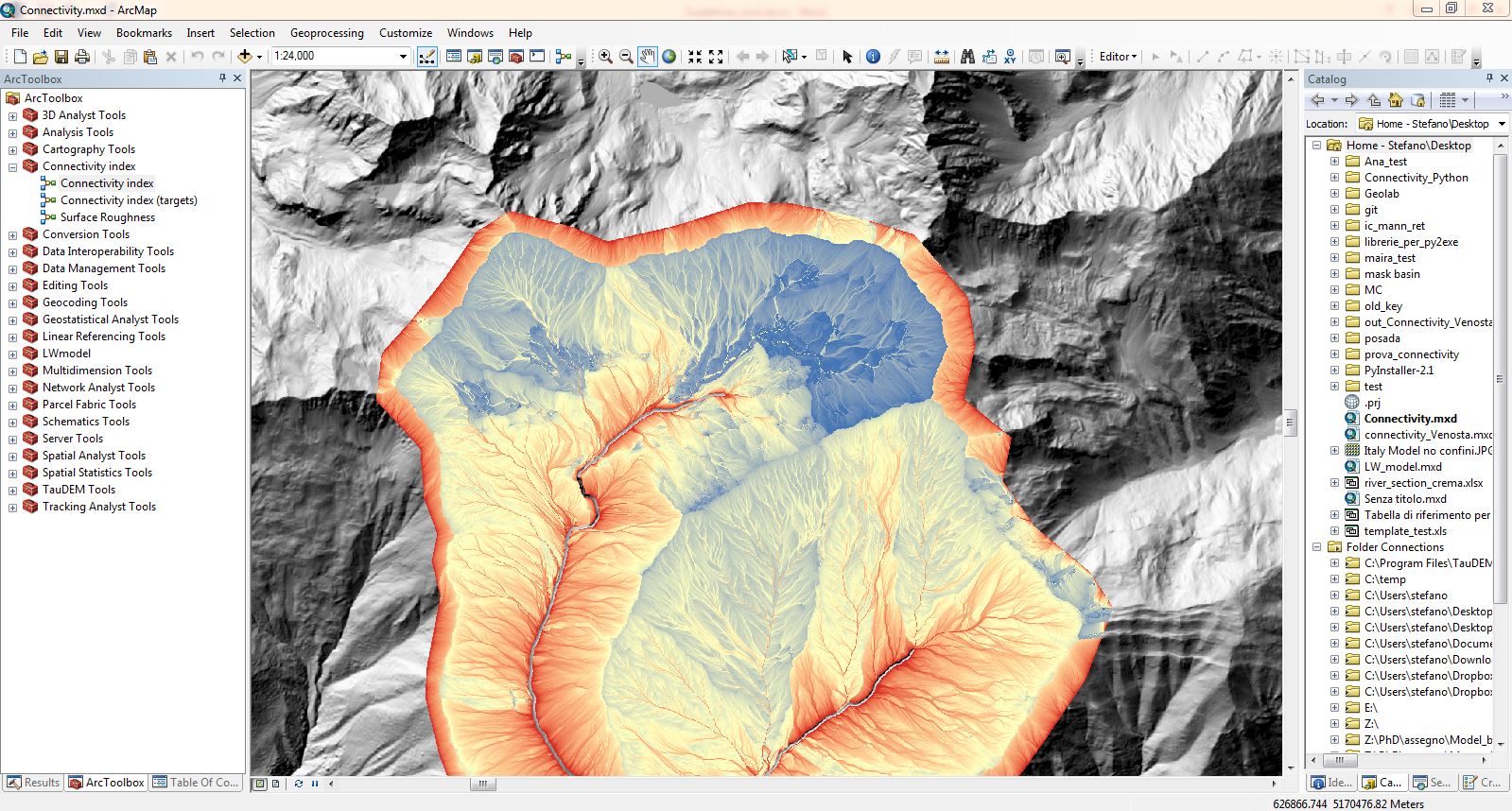


At the end of the procedure, you should have the Connectivity toolbox loaded into your project as shown in the next screenshot. If you open it three available tools should be visible (the possible presence of a red cross on a tool means that it is not working. Usually this occurs because some paths to the linked files are not properly set or read).

The three tools are:

* Connectivity index: implementation of IC computation with respect to the outlet;
* Connectivity index (targets): implementation of IC computation with respect to a selected feature
* Surface roughness: Computation of the Surface Roughness as expressed in Cavalli et al. (2008); the surface roughness here is obtained computing the standard deviation of residual topography (difference between original DTM and a smoothed DTM calculated with a user selected moving window).

Surface roughness as weighting factor can be optionally used as a proxy of the impedance to the flow in the IC computation.



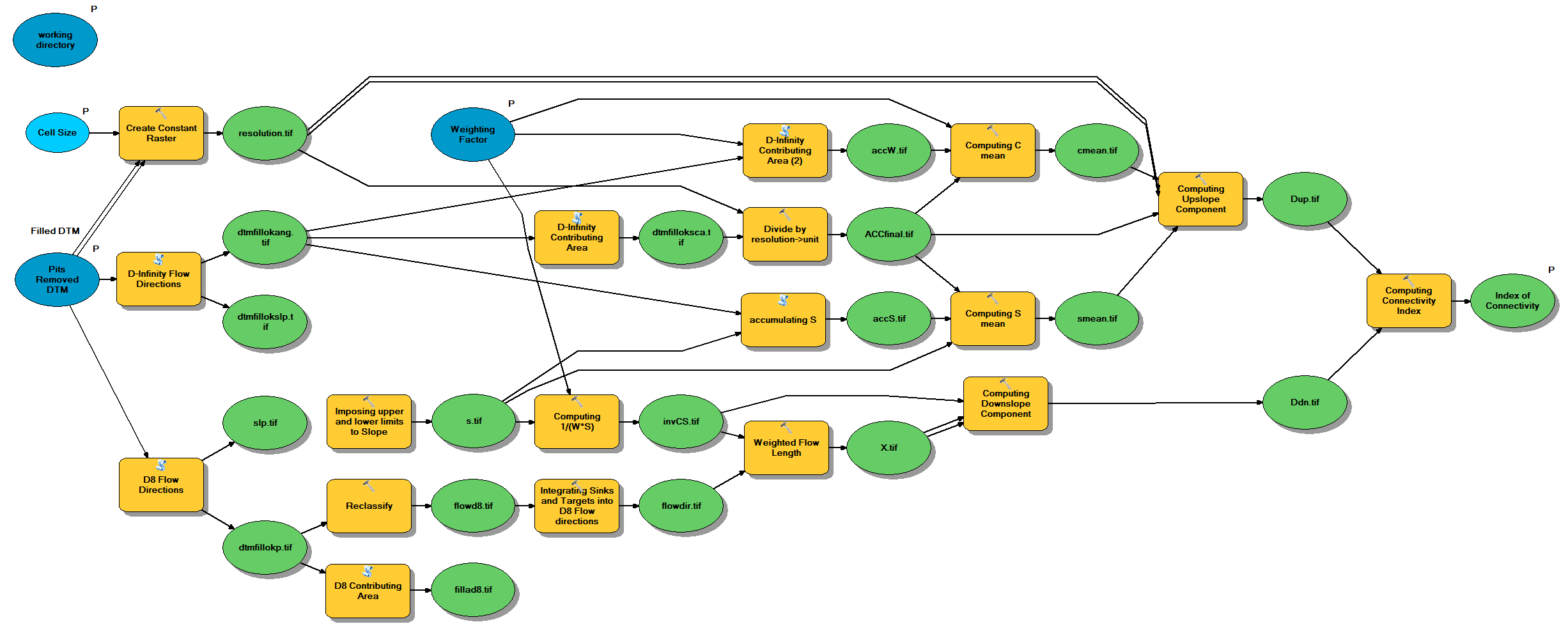
### Connectivity index calculated with respect to the catchment outlet

The workflow of the toolbox that computes IC with respect to the main outlet of the catchment is reported in Fig. 2 where it is possible to analyze the sequence of ArcGIS and TauDEM operations.

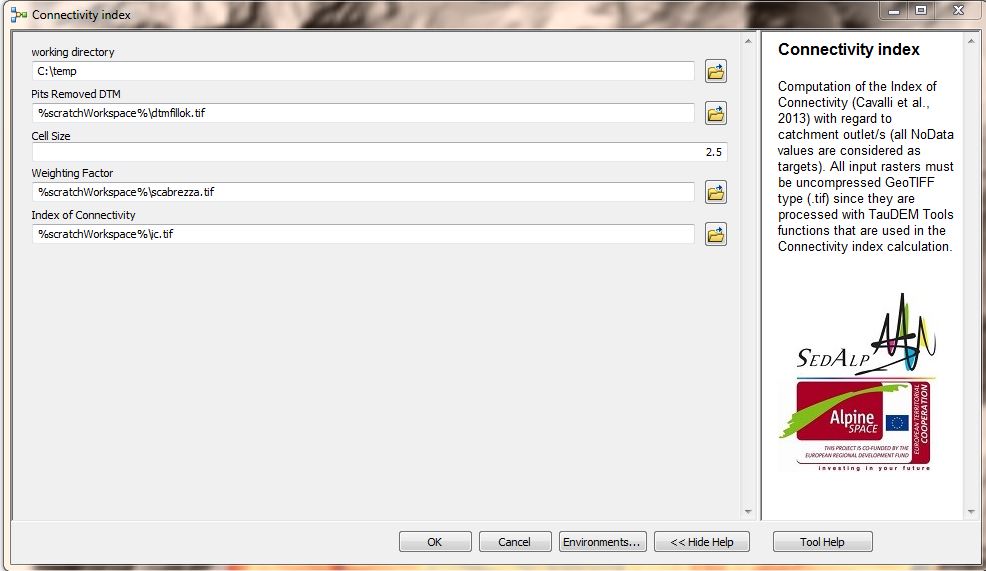
**All input raster files have to be in GeoTIFF format** since TauDEM works only with this format and **must have** **the same extent, origin, number of rows and columns**. The first release of ArcGis 10.1 had several bugs on working with this files, all of them have been resolved in the **ArcGis Desktop 10.1 Service Pack 1** that you need to download and install from the following link:

<http://support.esri.com/en/downloads/patches-servicepacks/view/productid/189/metaid/1913>

Figure 2. Workflow of the Connectivity Index ArcGis implementation, computation with respect to the main outlet.



The toolbox window is the following:



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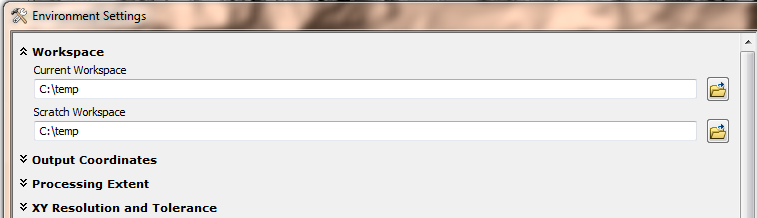
2

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The inputs are:

1. Working directory: here 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. To correct this error click on the Environments \\vmware-host\Shared Folders\PhD\assegno\Guidelines_tool\environments.JPG button on the tool window and under Workspace and set your working directory.



1. Input DTM file: here the input DTM must be set.

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 to use 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 procedure 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 pixel 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.

1. Cell size: here the input cell size in map units must be indicated. This value will be used to process drainage data to obtain unit values.
2. Weighting factor raster: here the weighting factor raster must be set.

In case the user wants to adopt surface roughness as a proxy to impedance to the sediment fluxes, the weighting factor can be derived from the Surface Roughness provided tool. Then, following Eq. 5, the raster can be normalized into the actual weighting factor to be used in the IC model. As already mentioned in the background theory section, **according to the required analysis and to the characteristics of the study area, the user can choose which weighting factor is the most suitable**

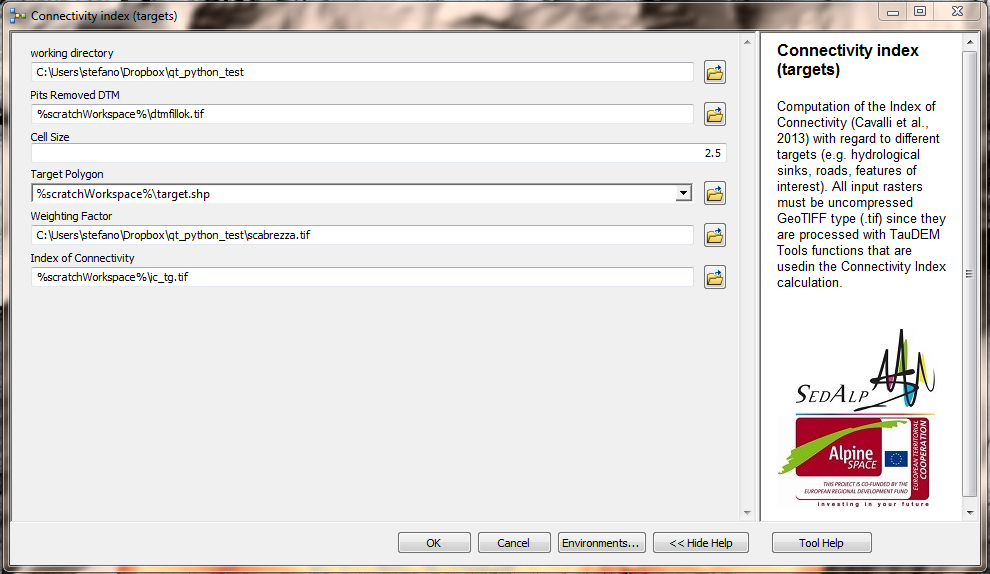
1. Output Connectivity Index map: here path and name of the output IC map are set.

The map needs to be clipped with a mask of the catchment in order to exclude all the values in the buffer area not included in the analysis.

### Connectivity index calculated with respect to selected targets

The workflow of the toolbox is reported in the annex 1.2 where it is possible to analyze the sequence of ArcGIS and TauDEM operations.

The following screenshot reports the toolbox window with its inputs/outputs:



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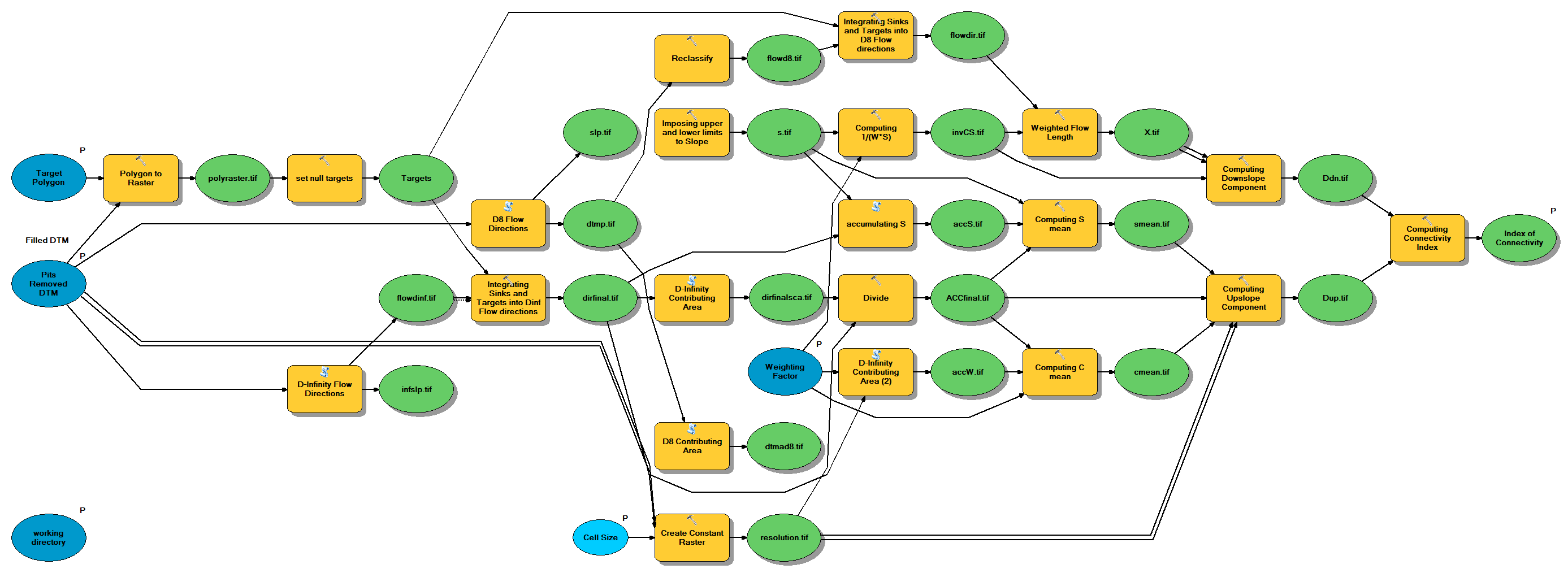
1

* Points **1-2-3-5** are equivalent to the ones described in sec. 3.2.1
* **Input 4** is a polygon feature/s (in .shp format) identifying the selected targets.

In case the target is the channel network and the user has already available a polyline shapefile, it is sufficient to make a buffer of similar size to the channel width to obtain the target polygon. The output connectivity map will report in this case values referred to the selected target feature. From the processing point of view the output map will have *NoData* over the input target polygon.

As in the case of the model calculating IC with respect to the catchment outlet (sect. 3.2.1) the output map (output 6 in the screenshot above) needs to be clipped with a mask of the catchment in order to exclude all the values in the buffer area not included in the analysis.

Figure 3. Workflow of the Connectivity Index ArcGis implementation, computation with respect to user-selected targets.



* For **more information** on TauDEM installation, see also the following:

<http://hydrology.usu.edu/taudem/taudem5/TauDEM51GettingStartedGuide.pdf>

and/or:

<http://hydrology.usu.edu/taudem/taudem5/TauDEM51CommandLineGuide.pdf>

* For **troubleshooting on TauDEM** installation/working check also:

<http://hydrology.usu.edu/taudem/taudem5/support.html>

and:

<http://hydrology.usu.edu/taudem/taudem5/troubleshooting.html>

* For **troubleshooting on the Connectivity ToolBox or stand-alone application** usage write to:

[stefano.crema@irpi.cnr.it](mailto:stefano.crema@irpi.cnr.it)

or:

[marco.cavalli@irpi.cnr.it](mailto:marco.cavalli@irpi.cnr.it)

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