RESPONSES TO EDITOR AND REVIEWERS COMMENTS (colored text)

I have examined the manuscript as well as the reviewers' comments and authors' reply of these. I do think that a set of revisions is advised. During this round of reviewers is it not my intention to discount any of the comments raised by Reviewers.

> Authors warmly appreciate and thank the editor.

Referee n. 1

-The authors give proper credit to the related hydrological work with clear indication of their new contribution, but some theoretical background about object-based image analysis and multi-resolution segmentation as well as some previous work related to the application of this method in geomorphology or geomorphometry should be mentioned (e.g. important papers which encouraged authors to apply it). Suggested literature is mentioned in the Potentially useful literature section".

> We introduced in the chapter "Introduction" (page 2 lines 15-17, marked-up manuscript) the theoretical background that you have suggested.

The title clearly reflects the contents of the paper, however, I might suggest for consideration adding the term "object-based" before "geomorphometry" for more precise specification.
> We added to the title the term "object-based" before "geomorphometry"

Specific comments:

1. Fig. 1 is a bit difficult to read and understand, especially some features of the "Monitoring system". Adding colours at least to these symbols would improve the readability.

> We improved the readability of the features in the map, by changing the colours and the shapes of the monitoring stations (Fig. 1 new)

2. Although, according to the authors and the stated reference (Peckham, 2009), use of grid spacing of 5 meters seems suitable (page 7, line 18), in the Results section the authors state that contribution area anomaly of the riparian corridor could be attributed also to the DEM resolution (page 16, line 8). There are other methods how to correctly determi ne DEM resolution (e.g. Hengl, 2006). Resolution of 2.5 meter could be calculated using the simplest equation in Hengl (2006) based on the working scale. Of course, increased resolution would increase computation time of other analyses (especially segmentation), but this anomaly might be avoided this way. I would suggest to at least mention it in the discussion.

> We added this concept on page 11 line 17-18 and page 12 line 1 (in the marked-up manuscript)
> In the scientific literature some methods are known for a more suitable grid resolution (Hengl, 2006) based on the properties of the input data (i.e complexity of the terrain), but the grid spacing used seemed suitable for hydro-geomorphological applications since it follows the general rule that it should be adequately sufficient at the local hillslope scale, marking the transition in process dominance from hill slope to channel (Peckham, 2009)."

3. Page 7, line 24 as well as page 16, line 29: Was the mentioned expert-based geomorphological map created based on the segmentation input layers or taken from a previous study? Either way, it would be useful to have it described there and perhaps even more useful to display it as a figure to directly see the mentioned agreement between these two maps.

> The expert-based geomorphological map was created by direct field surveys of an expert geomorphologist. We displayed the expert-based geomorphological map in the fig. 7 new (ex fig. 7) where in the previous version only the object-based morphological map was shown.

4. Several crucial pieces of information about the performed multi-resolution segmentation (page 7, starting in line 25) are missing, especially the value of scale parameter and a method of its determination. For readers would be also useful to know the used values of shape and compactness parameters. Were the spect layers used as an input into the segmentation or only the plan and profile curvature, whose values were later used in the classification? It is not clear from the text.

> We added all this information on page 12 from line 10 in the marked-up manuscript and we added a new table 1

5. Are the objects resulting from segmentation displayed in Fig. 7 (A) classified based on a sum of plan and profile curvature? If yes, I would suggest to mention it in the figure caption.

> For classification was used only plan curvature see Fig. 7a

6. I would suggest to use darker tone of colour for "contributing area" or perhaps to add black outline to make it more readable in Fig. 9 - 13.

> We used darker tone of colour for "contributing area"

Technical corrections:

- page 1, line 20: I would replace "plane" with "plan" to have the correct term for this curvature. Please apply also in the rest of the text
> We replaced "plane" with "plan"

- page 6, line 3: I would replace abbreviation "zob" with full "zero order basin" as it is in the figure under it or in page 3, line 14 or page 11, line 5

> We replaced the abbreviation "zob" with "zero order basin"

- page 7, line 5: typing error "." at the end of the first sentence should be removed

> Removed

- page 7, line 16: I suggest to replace "5 mt. cell size" with "5-meter cell size"
> Done

- page 7, line 17: I suggest to replace "Arc-Gis" with "ArcGIS" as it is the official name
> Done
- page 7, line 20: there is a reference to (Peckam, 2011) but in the list of references is (Peckam, 2009), please correct it; I would replace "Starting from this DEM" with e.g. "This DEM was used in"

> Done

- page 7, line 25: I suggest to replace "e-Cognition" with "eCognition Developer" as it
is the official name

    Done

- page 8, line 4: caption for Fig.7, please be consistent with the name of the segmentation.
Here is "multi-resolution", in the previous text is "multiresolution"

    Done

- page 8, Table 1: I think that in the last row it should be "SPPC" instead of "SP=C"

    Done

- page 9, line 5: I suggest to replace "Saga" with "SAGA" and "QGis" with "QGIS" as
these are the official names

    Done

- page 10, Fig. 8: I would say there is one extra "Transition-Wet" in the legend, otherwise
it is not recognisable in the figure if it should represent other type of transition
area

    There was an error in the figure 8. We cancelled the second "Transition-wet" legend (fig. 8 new)

- page 11, line 16: I think there should be "Table 3" instead of "Table 1"

    In the new version of the paper we added a new table, for this reason we changed in "Table 4"
    (there is a new renumbering).

- page 12, line 1 and 2: caption of Fig. 10, there should be added "approximately" before Q and EC values as
it is in captions of Fig. 11 – 13

    Added

- page 16, line 30: typing error "," at the end of sentence should be removed

    Removed

Referee n. 2

1. "The process of used land surface segmentation is not sufficiently explained and justified………….as well as specifications of the multisegmentation alghoritm…."

   - We optimized this part of the text see page 10 from line10 and added a new Table 1 (marked-up manuscript)
   -

2. "Production of flow accumulation maps is unclear too"

   The flow accumulation map was obtained using "Catchment area" algorithm available in the SAGA module implemented in QGIS;

3. Criterion of accordance between expert based mapping and multiresolution segmentation

   With the term "Expert based geomorphological map" we mean a traditional "geomorphological map" performed by geomorphologist, who drawn polygonal features on a topographic map (CTR 1:5.000 vector data map).
   Thus, the criterion of accordance between the geomorphological map and multiresolution segmentation is the training-target procedure proposed in the section "Methodology" of Guida et al.2015 (see reference).

4. "Majority variable are not explained in the table 3".

   The Table 3 is now renumbering in Table 4. We explained the variables in the caption of the table.

5. "Systematic shift of extreme value in fig 14 could point to systematic underestimation of contributing area in the 5th scenario".

   We tried different curves according to Fig. 15 a in order to compare our results to the others cited studies.
   In particular, the curve adopted is comparable with that of Dunne et al., 1975 and Dunne, 1978.

6. Quality of geomorphometric procedure:
   The quality of the geomorphometric procedure will be improve using a DEM with a higher resolution than that used in this study.

Answers to some marked questions in the pdf:

Page 3 Fig. 1: It is problematic to distinguis colluvial and alluvial soils in the map. No Main station and only one Sub station is in the map following legend (control size of symbols in the map and in the legend, please).

   We improved the readability of the features in the map, by changing the colours and the shapes of the monitoring stations (Fig. 1 new).

Page 4 line 10: Grey columes are not explained (wet periods?) as well as full black and gray lines (Q and EC?). Scale on the left y axis is (I suppose) for log Q. Where is scale for Specific Electrical Conductivity?

   Grey columes are introduced only for a clear visualization of the events
   The significance of the full black and gray lines correspondent to Q and EC respectively and are shown in the legend that is inside the fig. 2

The scale on the left y axis is for Log Q as indicated in the figure 2
The scale for the Specific Electrical Conductivity is the same of the Discharge.

Page 5 line 6: sEC? - abbrev EC was only established above.

we added statement "(we used either sEC or EC in the following)" on page 5 lines 6 in the marked-up manuscript

Page 5 line 9: Please, define / quote this algorithm

The statement "hydrologically-corrected DEM was obtained by means of the D∞ algorithm" is not corrected
We replaced the above sentence in " hydrologically-corrected DEM was obtained by means of the "Fill" tool of ESRI's ArcInfo software.

Page 5 line 10: they are not mentioned in Fig. 3 and anywhere above - add it ?into second middle block: "DEM (5x5) hydrological D∞corrected, flow accumulation maps

We modify the flow chart and added the "flow accumulation map" in the second middle block.

Page 6 line 3: What is "zob springs"? Zero Order Basin springs - after Fig. 4? Do not use abbrev uselessly.

Changed the "Zob spring" in "Zero order basin spring"
Page 6 line 4: Dot

Done

Page 6 Fig. 4: Complete captions for second photo, distinguish a) and b).

We completed the caption

Page 6 Fig. 5: Only abbrev EC was introduced

Corrected in the caption

Page 6 line 15: It is not fully correct to quote not published paper introducing a new concept.

The paper is now accepted for publication

Page 7 line 5: ?? formulation

Cancelled

Page 7 line 11: a)

Done
Page 7 line 12 : b); Change of colour of the line could show rising and recession limbs of the cycle.

Done

We changed the colour of the line (Fig. 6 new)

Page 7 lines 15-17: Does it means by digitizing of contourlines ot this map?

The CTR (regional thecnical map) 1:5000 is a CTR 1:5.000 is a vector data (CAD format) topographic map with contour lines provided of z coordinates (elevation values).

Page 7 lines 22-23: Please explain choice of this variables. Why you consider aspect as more important as e.g. slope gradient?

We didn't consider slope gradient because, a part for the valley bottom and hilltop, it is quite constant and didn't give additional information to the segmentation procedure.

Page 7 lines 23-24: Why only curvatures were used in following analysis? Why not aspect?

The aspect was not processed in the Landserf free Gis because we just obtained a good accordance between the training and the target segments by using the sine and cosine aspect parameters in addition to the curvatures analyses.

Page 7, line 25: Is it Expert-based contributing area map from Fig 3? Please, be terminologically consistent

in the text there is an error. In order to be terminologically consistent we revised the flow chart and the correct term is "expert based geomorphological map"

Page 7, line 25-26-27: How was the multisegmentation algorithm used, what variants were tested and what was a criterion of agreement of expert based mapping and multiresolution segmentation?

We have tested the algorithm trying different incremental weight (1, 2, and so on) for the plan and profile curvatures (i.e for incremental weight of 1 of plane/profile curvature with cell window 5 – weight 1; cell window 7- weight 2 …. Cell window 21- weight 10).
We added a new table where are listed all the weight (Tab. 1 new)
the criterion of accordance between the geomorphological map and multiresolution segmentation is the training-target procedure proposed in the section "Methodology" of Guida et al.2015 (see reference).

Page 8 line 28: How was the sum of plane curvature classes computed? Why only plane and not profile curvature was used
We used E-Cognition to sum, for each segment derived from the segmentation, the plane curvature computed with different windows.
Was used only the plane curvature in the classification because was enough to classify the hydro-geomorphotype

Page 9 lines 5-7: Not clear. Please, describe in more detail.

We changed the statement in: More precisely, the log-values of the flow accumulation map was reclassified according to the real conditions observed in streamflow and in each hydro-geomorphotypes during five different scenarios of the training storm event.

Page 9 line 24: ?LHg
Corrected
Page 10 line 10: LHg in the Figure?

Page 10 line 11: Dry-Wet in the Figure?

Dry-Wet in the Figure is the shared line between the Dry and the Wet areas. In the text we means the Dry area

Page 10 line 12: Transition-Wet in the Figure? There are two symbols for it! (first and last but one)

Transition-Wet in the Figure is the shared line between the Wet and the Tansition areas. In the text we means the transition area

Page 12 figures 10: It could be usefull mark it in the map - Contributing area seems to be same as in Fig. 9.

We used darker tone of colour for "contributing area" and orange colour for the riparian corridor.

Page 14 Table 3: From what values of area was computed? (Evidently no from Contributing area)?

q is the specific discharge calculated respect the area of the catchment
Use km^2 to be comparable with specific discharge.
Done

What is AREA 1 and AREA 2? Is there any relation with wet area 1 and wet area 2 in Fig. 8 (also not explained)? How they are computed? Are they really %? (very small values)
The AREA 1 and AREA 2 haven't any relation with the areas of fig.8

The AREA 1 and AREA 2 are used for comparison with others studies and to explain the saturation state both for each hydro-geomorphotype and the catchment

AREA 1: is the ratio (it is not in %) between the contributing area and the area of each hydro- geomorphotype.
This ratio is used in the fig. 15b (there is an error in the figure 15 b the area is A1 and not A2)

AREA 2: is the ratio (it is not in %) between the contributing area and the area of the basin.
This ratio is used in the text page 24 line 15.

Pag24 line 9: Used exponential relation evidently systematically overestimate extreme values. Because extremely low number of values high R2 cannot be substantive. Were tested another types of relationships? If the exponential relationships result from the hydrological theory assesment of contributing area could be questionable.

We tried different curves according to Fig. 15 a in order to compare our results to the others cited studies.
The exponential law was used because described better than the linear and others curves the five scenarios.

Page 15 line 2: French written publication - the principle should be briefly repeated.
The correct reference is Latron and Gallart (2007)

Page 15 Line 15: No intersection is on the figure unless extrapolation the curves behind measured values.

removed

Page 16 line 29: No info about weighted profile and plan curvature sum computation. Moreover on p. 8 only plan curvature is mentioned as used for segmentation!!

We cancelled "weighted profile and plan curvature sum computation"
We rewrote this part of the text see page 12 line 6 of the marked-up manuscript. Please see the new table 1

Page 16 Line : Where is it documented?

We used the logarithm of flow accumulation to scale it to a more condensed and linear range. An example is the "Topographic Index" (Quinn et al., 1991, 1995).

Page 16 line 33: Not documented

- The sentence "this parameter provided better statistical fit with the observed contribution areas detected during the event by means of direct surveys and discharge/groundwater measurements" is modify in " spatial distribution of this parameters offered a good accordance with the observed contribution areas detected during the event by means of direct surveys and ischarge/groundwater measurements"

The authors thank referees for the suggestions.

Using object-based geomorphometry for hydro-geomorphological analysis in a Mediterranean research catchment

Domenico Guida[1], Albina Cuomo[1], Vincenzo Palmieri[2]

[1]Department of Civil Engineering, University of Salerno, Fisciano, 84084, Italy
5   [2]ARCADIS, Agency for Soil Defense of the Campania Region, Naples, Italy

Correspondence to: A. Cuomo (acuomo@unisa.it)

Abstract. The aim of the paper is to apply an object-based geomorphometric procedure to define the runoff contribution areas and support a hydro-geomorphological analysis on a 3-km^2 Mediterranean research catchment (southern Italy). Daily and sub-hourly discharge and electrical conductivity data were collected and recorded based on three-year monitoring activity. Hydro-
10   chemograph analyses on these data revealed a strong seasonal hydrological response in the catchment that were different from the stormflow events that occurred in the wet periods and in dry periods. This analysis enabled us to define the hydro-chemograph signatures related to increasing flood magnitude, which progressively involves various runoff components (base flow, subsurface flow and surficial flow) and an increasing Contributing Area to discharge. Field surveys and water table/discharge measurements carried out during a selected storm event enabled us to identify and map specific runoff source
15   areas with homogeneous geomorphological units previously defined as hydro-geomorphotypes (spring points, diffuse seepage along the main channel, seepage along the riparian corridors, diffuse outflow from hillslope taluses and concentrate sapping from colluvial hollows). Following the procedures previously proposed and used by authors for object-based geomorphological mapping, a hydro-geomorphologically-oriented segmentation and classification was performed with an e-Cognition (Trimble, Inc) package. The best agreement with the expert-based geomorphological mapping was obtained
20   with weighted plane curvature at different-size windows. Combining the hydro-chemical analysis and object-based hydro-geomorphotype map, the variability of the contribution areas was graphically modelled for the selected event which occurred during the wet season by using the log values of flow accumulation that better fit the contribution areas. The results enabled us to identify the runoff component on hydro-chemograph for each time step and to calculate a specific discharge contribution from each hydro-geomorphotype. This kind of approach
25   could be useful applied to similar, rainfall-dominated, forested and no-karst catchments in the Mediterranean eco-region.
Keywords: geomorphometry, hydro-geomorphology, runoff Contributing Area, Cilento Global Geopark

1 Introduction

In order to gain a better understanding of hydrology, it is essential to study the complex interactions and linkages between watershed components, such as drainage network, riparian corridors, headwaters, hillslopes and aquifers and related processes
30   operating at multiple scales (National Research Council, 1999). Hydrological science plays an important and fundamental role only when it provides an integrated knowledge and understanding of the forms and processes that operate in watershed at multiple, space-time scales in the landscape (Marcus et al., 2004). A useful way of understanding the response of catchments to rainfall events is to analyze stream discharge vs rainfall per unit of time, plotted as a storm flow hydrograph and hyetograph, respectively. In recent decades, hydrologists have carried out numerous studies on catchment and hillslope hydrology in order
35   to define when, how and where runoff is produced and how it progressively increases along the drainage network. Hydrologists generally agree that following rainfall, new-event water components are added, through various hydrological mechanisms to

the old, pre-event water components which are generally referred to as base flow components that derive from deep and shallow aquifers, expanding and reducing the runoff-Ceontributing Aareas (Betson, 1964). The most common general concept that explains the above-mentioned hysteretic behavior is the Variable Source Area (VSA) concept. This concept was originally proposed by Hewlett (1961) and later adopted by other authors (Dunne and Black, 1970; Dunne and Leopold, 1978, Huang and Laften 1996, Vander Kwaak and Loague 2001, Zollweg et al. 1995, Pionke et al. 1996). Despite its early formulation, it represented the hydrological background for more recent research studies (Lyon et al. 2004, Easton et al. 2007, 2008, Buchanana et al. 2012, Moore et al. 1988, Barling et al. 1994, Kwaad 1991, Easton et al. 2010, White et al. 2011). Contemporarily, the "hydro-geomorphic paradigm" was proposed by Sidle et al. (2000) in order to discriminate the VSA hydrologic sources and pathways, which refers to the connected hydro-geomorphic components of the catchments (hollow, hillslope and riparian corridor). Within a more general program for flood hazard assessment procedures, the hydro-geomorphic paradigm will bewas used to generalize at basin and regional scale in southern Italy by Cuomo (2012), by means of hydro-geomorphology (Okunishi, 1991; Okunishi, K., 1994; Babar, 2005; Sidle and Onda, 2004; Goerl, Kobiyama, dos Santos , 2012). Cuomo (2012) introduced and applied a new hydro-geomorphological basic unit: the *hydro-geomorpho-typehydro-geomorphotype*, by using the Salerno Geomorphological Mapping System (Dramis et al., 2011; Guida et al., 2012; Guida et al., 2015), as a framework for object-based geomorphological mapping. Based on the up-to-date and shared theoretical geomorphometric background (Baatz and Schäpe 2000, Dragut and Blaschke 2006, van Asselen and Seijmonsbergen 2006, Anders et al. 2011, Dragut et al. 2013, Dragut et al. 2014, Eisank et al. 2014), tThis proposal is currently under experimental calibration as an effective, object-based geo-morphometryic procedure for spatial individuation, objective delimitation and automatic recognition of the hydro-geomorpho-typehydro-geomorphotypes, in the perspective of an object-based distributed hydrological modelling (Cuomo et al., 2012).

Linking geomorphometry with hydrology toward the hydro-geomorphology gives consistency to the suggestion made by Peckham (20109±) with the aim of simplifying the issue of the computational cost and time of a fully distributed model.

In the past, many authors made extensive use of chemical and isotopic tracers in order to separate the runoff components recorded in the hydrographs and pinpoint distinctive sources and pathways by using the geochemical and isotopic signature of water at parcel scale or for small catchments (Klaus and McDonnell, 2013). However, applying only the hydro-chemograph and isotopic separation methods to an experimental parcel cannot provide sufficient information on the spatial distribution of runoff sources and paths for basins as a whole, due to their spatial heterogeneity structure and time process variability.
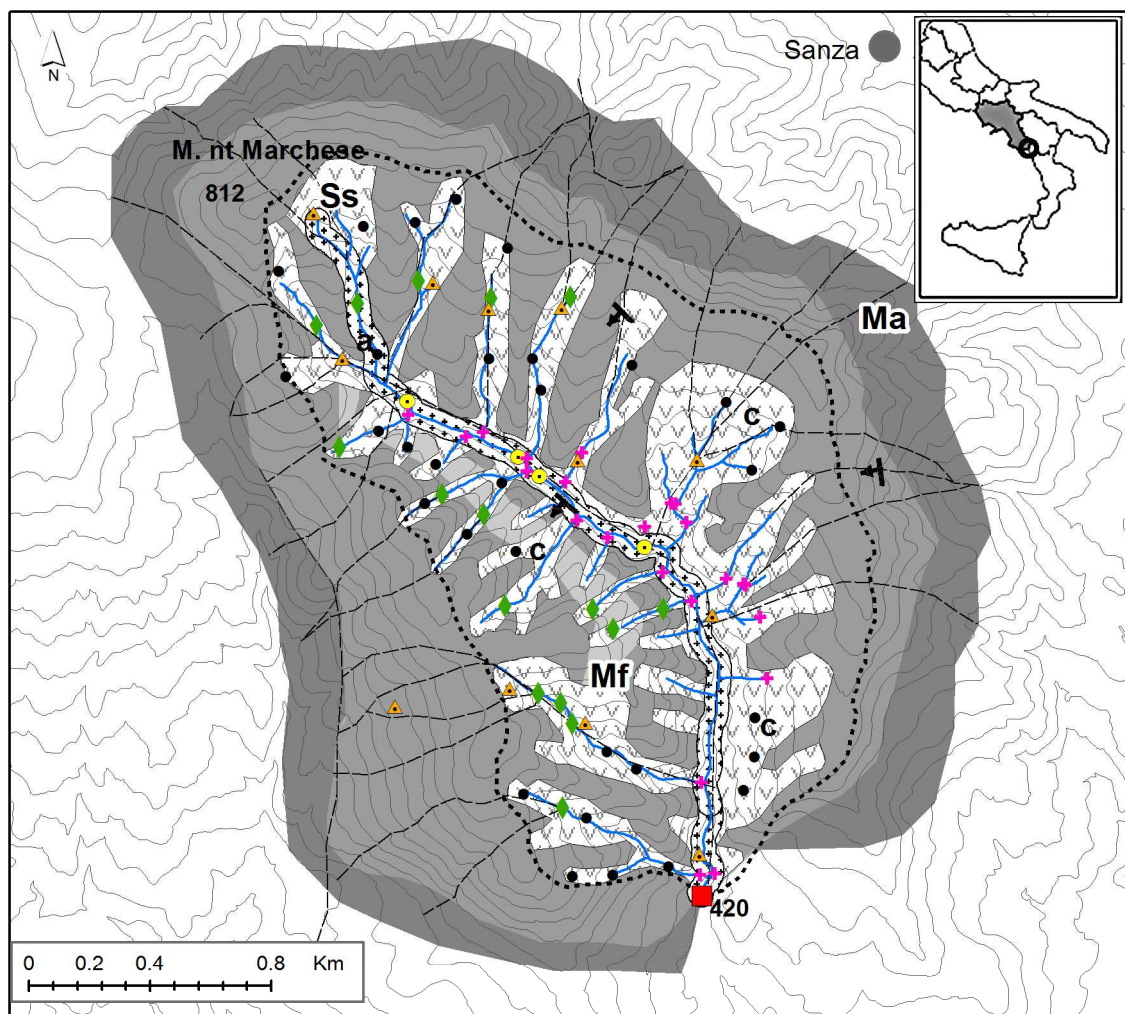
Moreover, extensive use of the above-mentioned methods is more expensive and time-consuming than the quantity and quality of the data collected and the knowledge gained. As stated by Ladouche et al. (2001), with these methods alone it is possible to identify type, timing and volume of the runoff components, but it is impossible to define the spatial origin and related pathways during storm events accurately. In order to overcome these difficulties and by following the general approach used by Latron and Gallart (2007), we used an integrated, hydro-geomorphological approach for studying a Mediterranean research catchment in southern Italy. This approach is based on detailed geomorphological surveys, mapping and three-year hydro-chemical monitoring. It integrates a new procedure for identifying and separating hydro-chemical runoff components and a geomorphometric application for the objective delimitation of the source areas, where each runoff component is generated (Cuomo and Guida, 2013, Guida and Cuomo, 2014). Starting from these premises, the paper describes the study area as a Mediterranean research catchment and presents the hydro-chemical dataset recorded during the monitoring activity carried out in the 2013-2014 calibration period. In the next section an original procedure is explained for discriminating timing, type and hydro-chemical signature of the runoff components involved during storm events. With the aim of spatially defining these

2

runoff sources, an object-based hydro-geomorphological map was then set by a hydrological-oriented segmentation and classification. Finally, the results of combined hydro-chemical and object-based hydro-geomorphometric analysis are discussed in order to determine the variability of the contribution area during a significant storm event.

2 Hydro-geomorphology and monitoring activity of the study area

5   The study area is a forested and hilly catchment located in the Bussento River drainage basin, the $3Km^2$ Ciciriello catchment, located in the Cilento and Vallo di Diano National Park-UNESCO Global Geopark, Southern Italy (Fig. 1).

At the base the terrigenous bedrock is composed of a lower Tertiary, marly-clayey formation passing in unconformity upward to middle Miocene, a westward-dipping sandstone strata and pelitic intervals. A lenticular 10 m thick marly layer ("Fogliarina Marl" geosite) outcrops along the right hand side of the valley. Regosols, regolite and gravelly slope deposits up to 5 meters

10   thick, cover the bedrock mentioned above. The mainstream bed, rectilinear and dipping strata subsequent to main faults is incised in alluvial gravelly and smooth deposits and partly in bedrock; the secondary streambed is exclusively in bedrock, subsequent to minor fault systems. From a hydro-geomorphological perspective, the groundwater circulation is controlled by the litho-structural arrangement of the above-mentioned bedrock formations, where the marly-clayey formation constitutes the local aquitard below the sandstone aquifer. The westward dipping of the permeability boundary causes a general westward

15   groundwater flow, convergent toward the lower apex of the wedge-like hydro-structures ("*hydro-wedge*" in Cascini at al., 2008, Guida and Cuomo 2016), where the main permanent springs are located. In the headwaters, colluvial hollows are situated at the bottom of the zero-order basins, and are considered to be the main headwater hydro-geomorphotypes by Cuomo (2012), where dominant saturation excess runoff occurs mainly during the wet season. The stream flow of both permanent springs from the bedrock aquifers and seasonal springs from colluvial headwater increase down -valley.

Basin
- - - - - Watershed

Bedrock

Mf	Marl
Ss	Sandstone
Ma	Marly-clay

Soil

| c | Colluvial |
| a | Alluvial |

Strata attitude
- - - Fault

Monitoring system

■ Main station

◉ Sub - station

✚ Secondary station

◆ Zob/riparian station (V-notch/ piezometer)
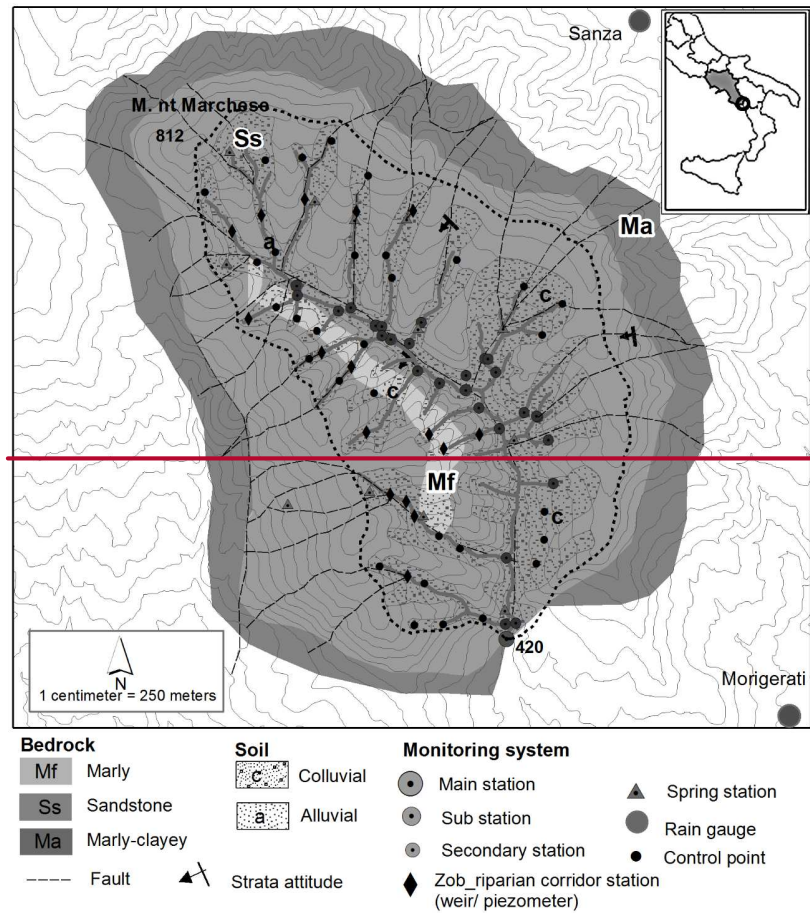
▲ Spring station

⬤ Rain gauge

● Control point

Figure 1. ~~Location and geomorphological~~ Hydrogeological ~~map~~ map of the Ciciriello Experimental Catchment ~~(from Cuomo and Guida, 2016 under revision)~~ and location of the monitoring stations (modified from Cuomo and Guida, 2016). Legend: Bedrock lithology~~:~~; Ma~~:~~, Marly-clay~~ey~~ and ~~argillitic~~ argillite ~~tertiary~~ Tertiary formation, base aquiclude; Ss~~:~~, Sandstone

5 Miocene formation, fractured general aquifer; Mf~~:~~, Marl~~y limestone~~, interlayered and perched aquifer.

Since December 2012, water depth (D), discharge (Q) and specific electrical conductivity (we used either sEC or EC in the following) were measured daily at the main station, hourly during the floods and weekly at the sub-stations during the inter-storm periods (Fig. 1). The Q measurements were obtained with the Swoffer 3000 current meter (Swoffer Inc., USA), and the

10 EC parameter was measured with the multi-parametric probe HI9828 (Hanna Instruments Inc., Romania). The monitoring year 2013-2014 (Fig. 2) provided a complete hydro-chemical dataset, which enabled us to carry out the analysis at seasonal and event time scales (Cuomo and Guida 2014).
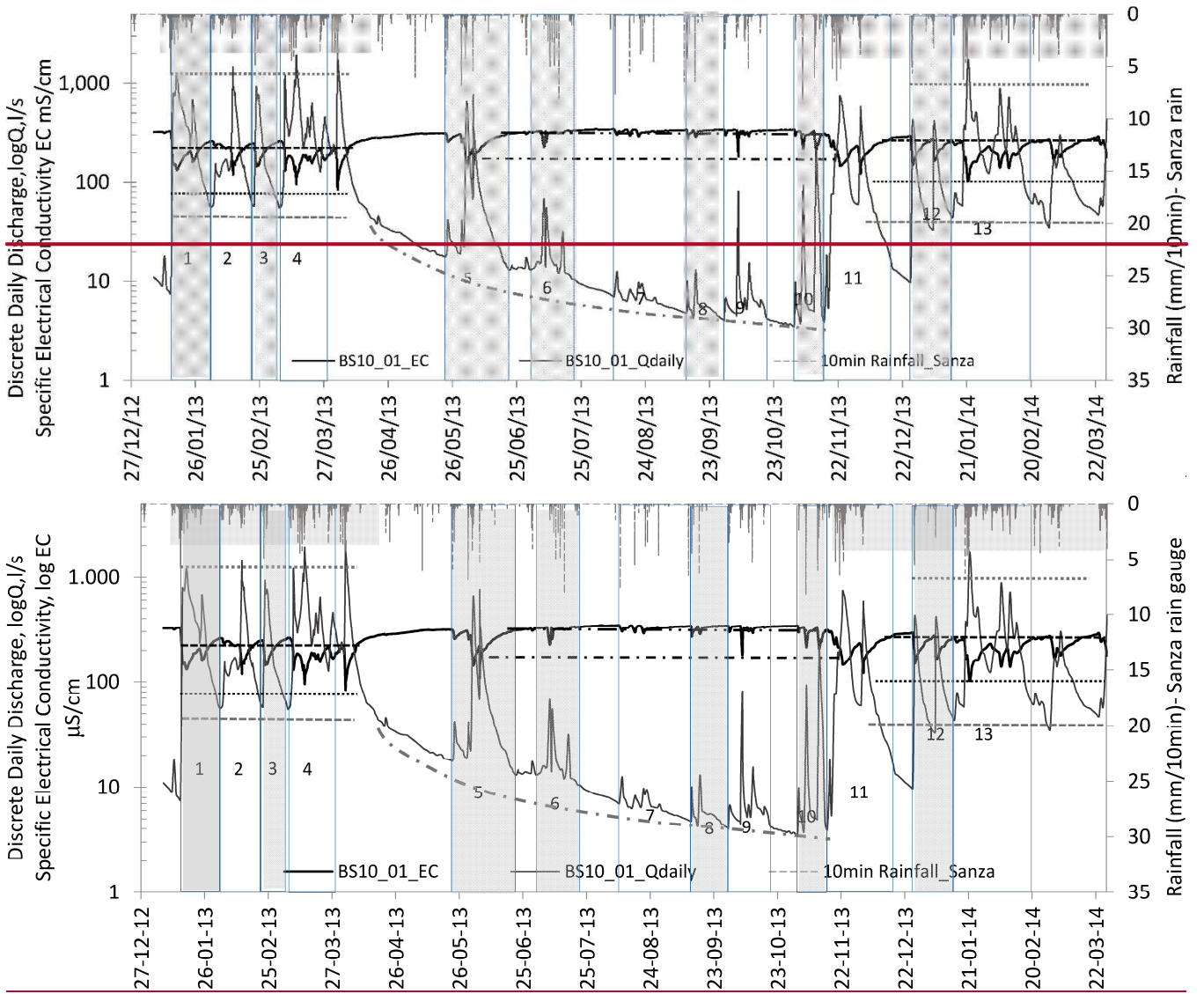
Figure 2. Plot of the hydro-chemograph dataset recorded at the main monitoring station (BS16_01) and the 10-min rainfall plot at the Sanza rain gauge (from Guida and Cuomo, 2016 under revision). Legend: Numbers indicate the selected events; horizontal lines are representative of the reference parameter ranges; black dashed-double dot lines indicate EC maxima in the dry period; black dashed-dot line represents EC minimum during the dry period; black dashed line indicates EC maximua in the wet period; black dotted line represents EC minimum in the wet period; gray dashed line indicates the Q minima in the wet period; gray dotted line indicates the average Q maximum in the wet period; finally, the gray dashed-dot curve indicates the theoretical annual base flow curve of the catchment during the period under consideration.

3. Hydro-geomorphological procedure for the contribution areas individuation

The Ceontributing Aarea is a dynamic hydrological concept because it may vary seasonally. The extension of the Ceontributing Aarea is strongly influenced by various static factors such as topography and soils, and dynamic factors such as antecedent moisture conditions, rainfall characteristics (Dunne and Black, 1975).

6

In the following sections, an integrate procedure is proposed that uses simple geomorphometric tools to take into account various hydrological and geomorphological factors which cause runoff variability on the catchment case study.

The flow chart in Fig. 3 shows the three integrated approaches used in the application.
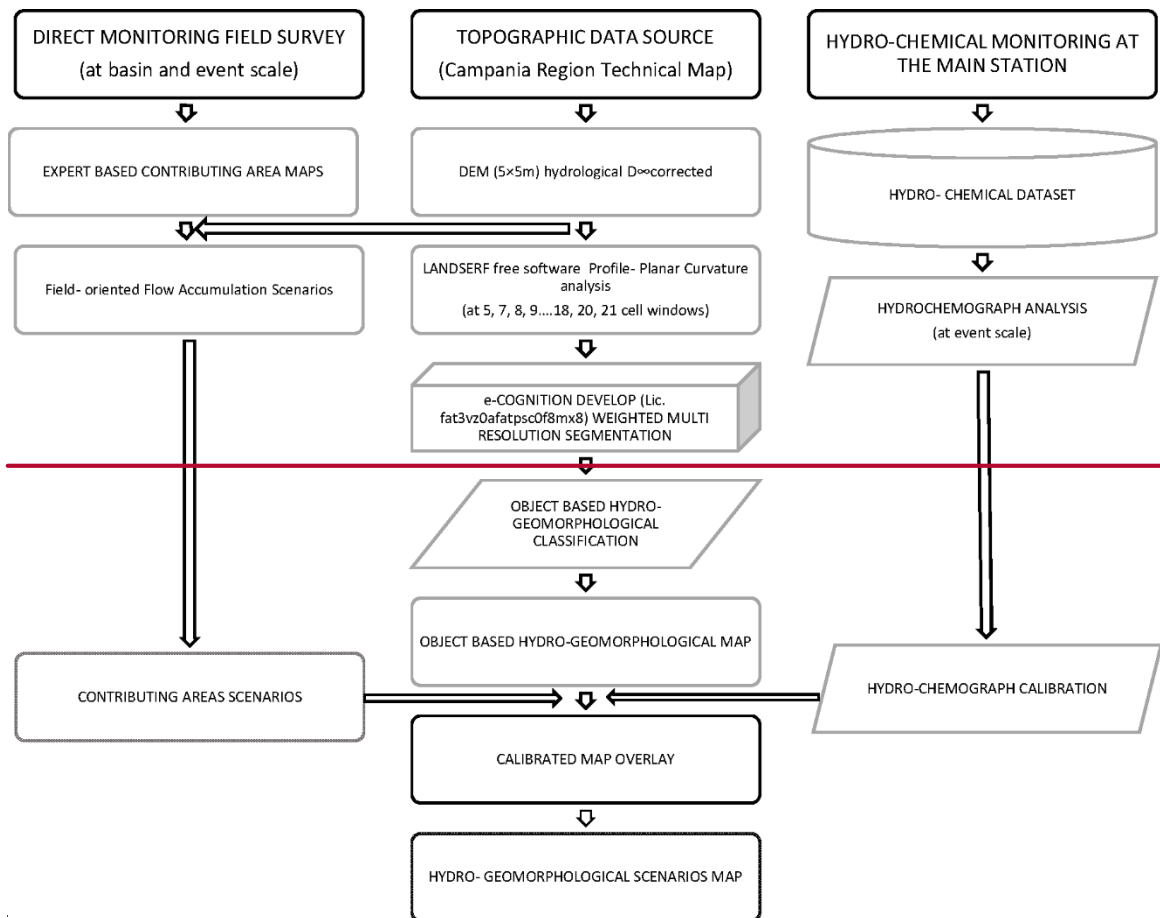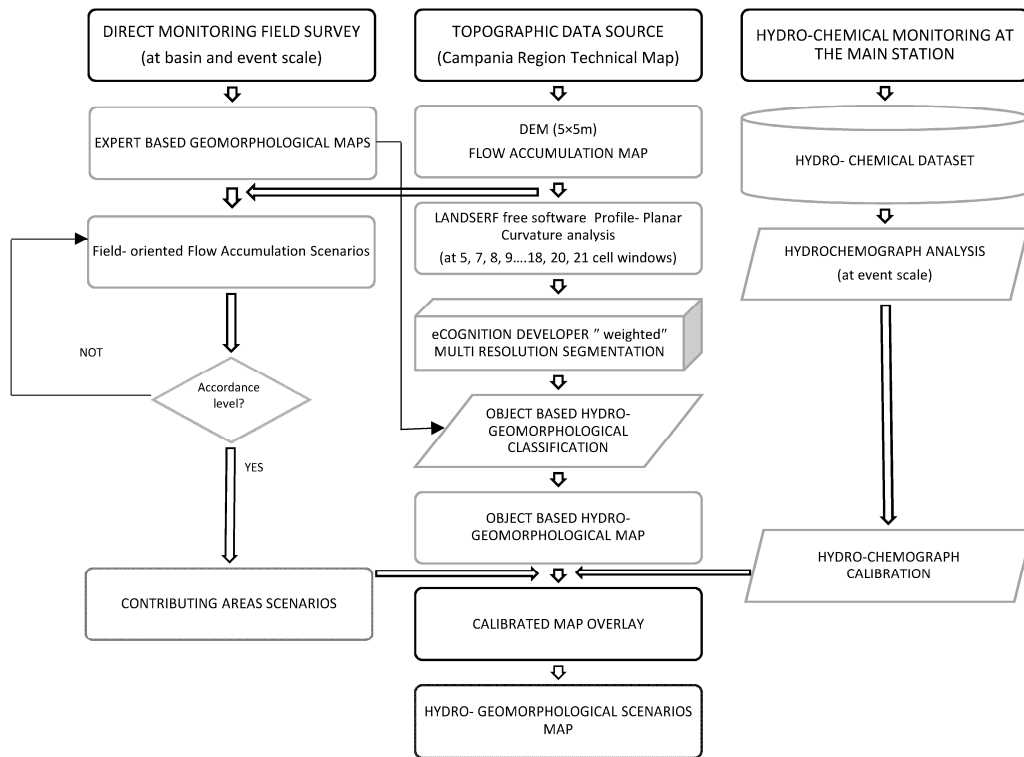
Figure 3. Flow chart procedure for identifying Contribution Areas

The first approach on the left hand side highlights the expert-based activities by geomorphological surveys and direct monitoring carried out at basin scale before and during the application event and the derivation of traditional, hand-draw, expert-based ~~contribution area~~geomorphological maps. The field- oriented flow accumulation ~~maps~~scenarios were obtained by ~~linking Q and sEC~~ data collected at the control points (Fig. 1) for each event time step (five time step) and for each hydro-geomorphotype and by using the flow accumulation map derived by the following explained second step. The expert-based activities are illustrated in Sect. 3.1. ~~—~~The second approach (see the flow chart at the center) shows the geomorphometric routine activities performed during the application, as illustrated in Sect. 3.2. ~~—~~Starting from the topographic data source ~~(Technical of the Campania region)~~, a hydrologically-corrected DEM was obtained ~~obtained by means of the D∞ algorithm~~ and the log of the flow accumulation map was derived. This last was reclassified in the first approach in order to obtain the~~the~~ best agreement ~~between the~~ with -field evidence highlighted during the storm event at each hydro-geomorphotype. The ~~above expert-based maps and~~ the flow accumulation maps ~~enabled us to obtain the~~ field-oriented flow accumulation maps were obtained ~~,~~as a proxy for the ~~five~~ Contributing Aarea scenarios. As better explained in Sect. 3.2, after five elaboration steps ~~of elaborations~~, the geomorphometric analysis provided ~~us with~~ the Object-based Hydro-geomorphological map of the catchment, quantitatively defining spatial extension of the basic hydro-geomorphotypes. The hydro-geomorphotype map, was calibrated by the hydro-chemical analysis illustrated in Sect. 3.3 and was then overlaid with the five Contributing Aarea scenarios thus obtaining the final hydro-geomorphological scenarios maps.

3.1 Direct survey on the catchment during a storm event

Before and during the storm event in the period from 29 to 31 Jan 2015, one of the authors carried out direct field surveys by measuring EC and, wherever possible, Q parameters on the control points in Fig. 1, and repeated them at each time-step of the storm event. The pre-event conditions were detected at 5:15 pm on 29 Jan 2015 by carrying out systematic surveys and taking measurements from the main stream and secondary channel stations (Fig. 4a), where only groundwater feeds the discharge along the riparian corridors. After the beginning of rainfall, measurements were taken from 7:20 am to 9:10 am on 30 Jan 2015 at the ~~zob~~ zero order basin springs and hollow stations (Fig.4b~~–~~), where the soils became more and more saturated and contemporarily new water was added from the riparian corridor downstream.
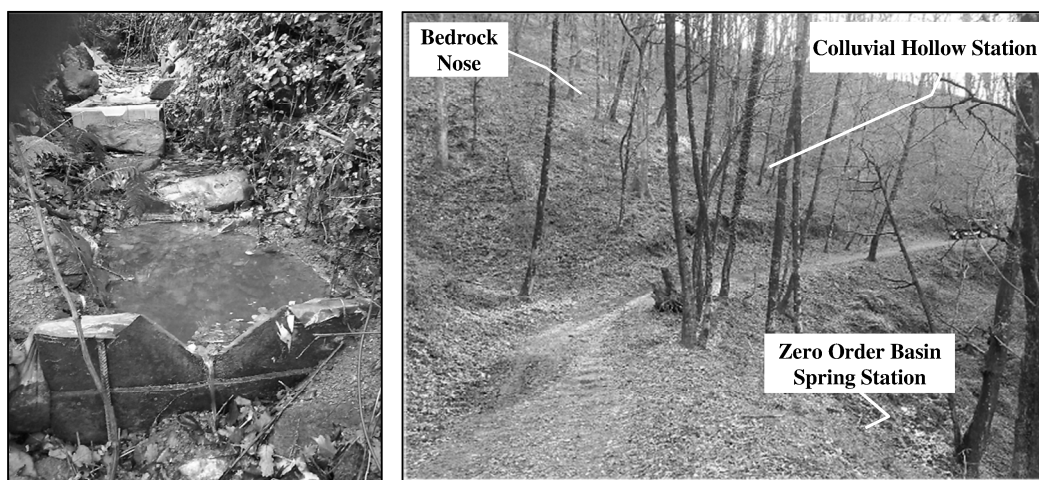

Figure 4. a) The V-notch weir at the BS16_01_01dx ~~end~~ and b) stations.

9

At During the storm event peak, repeated measurements at the same control points were taken from 11:30 to 1:00 pm, which detecteddetecting direct runoff (-Fig. 5a) and soil pipe contribution (figFig. 5b)–.
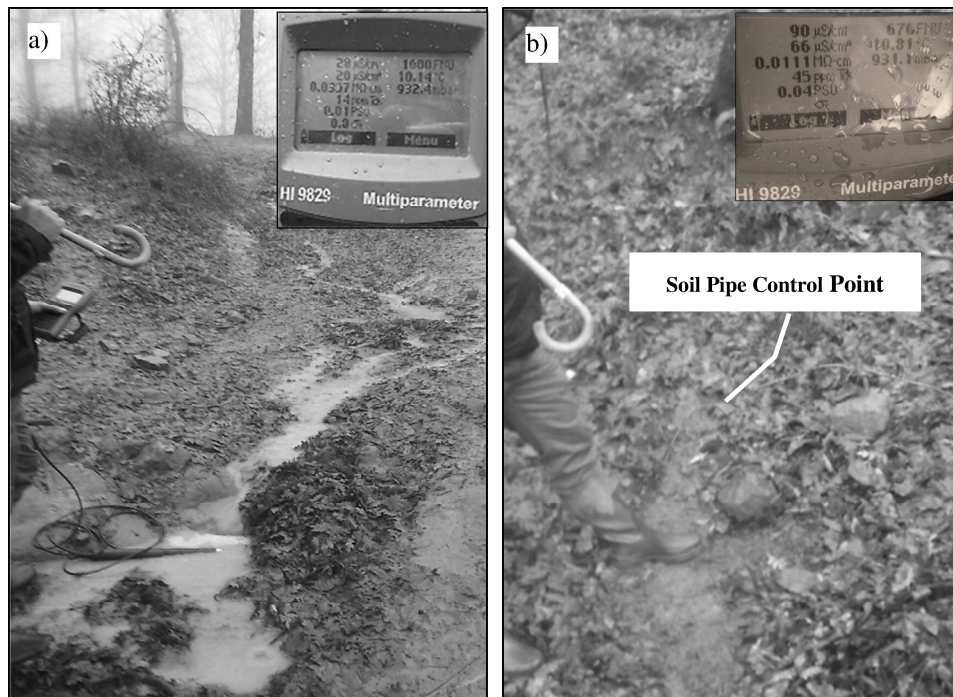

Figure 5. Measurements at 12:00 am in the dirty road point controls (a) and the soil pipe (b) with respective sEC measurementsvalues.

Figure 6a shows the hydro-chemograph of the storm event recorded at the main station and cumulative rainfall measured at the nearest rain gauge station near the catchment. On the plot, the phases of hydrological response in the catchment were determined by means of the progressive runoff generation activation, identified with the above-mentioned field measurements. In Fig.6b, the hysteretic Q-EC cycle (Cuomo and Guida, 2016, under revision) of the event demonstrate homogeneity in hydro-chemical response in the rising and recession limbs. At 20.00 hrs on 29 Jan 2015, the field measurements at piezometers and Q-sEC values (approximately 60 l/s and 240 µS/cm) recorded at the main station were typical of pre-event conditions occurring during the wet period, as found by Cuomo and Guida (2016, under revision). After it started raining, in addition to the direct rainfall in main streamflow, the contribution from groundwater ridging along the riparian corridor and floodplain began to feed the total discharge, the direct field evidence.. With continual rainfall, the contribution area expands and excess saturation runoff is progressively added to the discharge from colluvial hollows up to approximately Q=1000 l/s and sEC=100-120 µS/cm. In addition to these values, firstly the macropore contribution is added. Finally excess infiltration runoff from the saturated areas becomes dominant, which progressively increases the discharge, but reaches asymptotical sEC=80 µS/cm values.
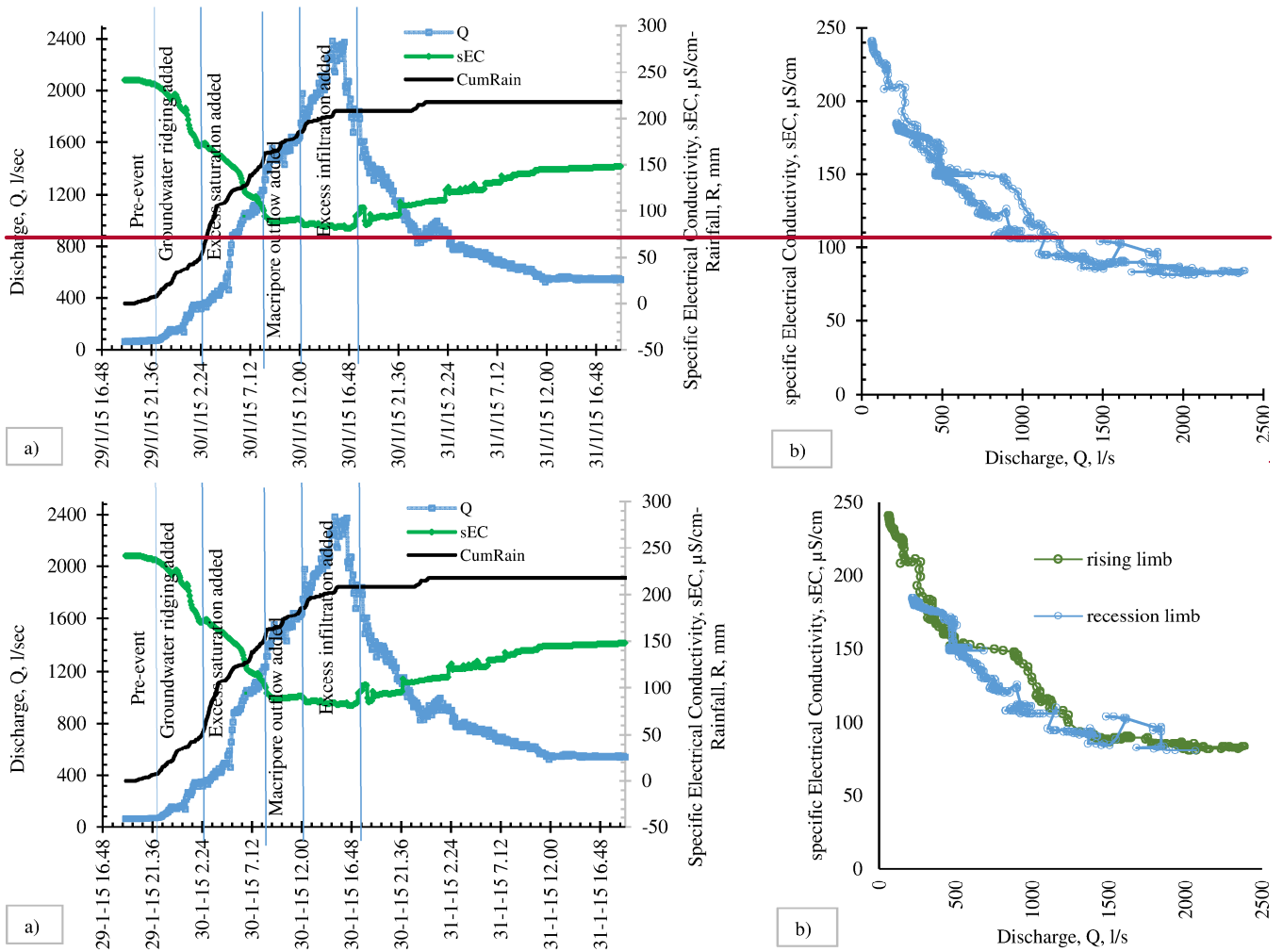
Figure 6. a) Hydro-chemograph plot of the 29-31 January 2015 storm event and related hydro-geomorphological phases, during which the runoff components are progressively added, according to Table 3; b) Q-EC hysteretic cycle of the storm event.

In order to obtain the Contribution area scenarios the flow accumulation map by means of the SAGA module implemented in QGIS was product. More precisely, the log-values of the flow accumulation map was reclassified according to the real conditions observed in streamflow and each hydro-geomorphotypes during five different scenarios occurred during the training storm event. The best accordance between the reclassified log-values of the flow accumulation map and the field evidences represents the final Contributing Area scenarios map.

3.2 Object-based hydro-geomorphological mapping

In order to quantitatively define the runoff source areas, an object-based hydro-geomorphological map of the Ciciriello catchment was created using an original, automatic spatial analysis procedure. Starting from the Campania Region Technical Map at 1:5.000 scale (CTR), a vector map provided of elevation values), at 1:5.000 scale, a Digital Elevation Model (DEM) with a 5- mteter cell size was obtained by means of the Topo-To-Raster tool (TOPOGRID) in Arc GisGIS. This algorithm provides an interpolation method specifically designed for creating hydrologically corrected DEM. Moreover, further spurious sinks have been removed by means of Fill tool. In the scientific literature some methods are known for a more suitable grid

11

resolution (Hengl, 2006) based on the properties of the input data (i.e complexity of the landsurface), but ~~T~~the grid spacing used seemed suitable for hydro-geomorphological applications since it follows the general rule that it should be adequately sufficient at the local hillslope scale, marking the transition in process dominance from hill slope to channel (Peckham, ~~2011~~2009). ~~Starting from this DEM~~This DEM was used in~~,~~ an "object-based" hydro-geomorphological map that was obtained using a step-by-step rule set.

~~At~~At the first step, a geomorphometric analysis was performed calculating ~~by combining the sine and cosine of aspect,~~ ~~plane~~plan and profile curvatures ~~calculated~~ at ~~various~~ increasing cell windows: 5, 7, 9, 11, 13, 15, 17, 19 and 21 cells. The multi–scale ~~based~~ analysis of curvatures was performed with Landserf free GIS software, thus obtaining a raster layer for each geomorphometric calculation.

During the second step the best agreement with expert-based geomorphological mapping was achieved with eCognition Developer software by means of an original multiresolution segmentation algorithm, using appropriates land-surface parameters.

The multiresolution segmentation algorithm merges spatially contiguous pixels or cells into "image objects" (segments) based on local homogeneity criteria of the input parameters. These segments, bounded by discontinuities in the input variables, are used further as building blocks in classification, based on attributes such as average values of input variables, shape indexes, and topological relations of segments (Dragut et al., 2013).

More precisely, morphometric parameters obtained in the previous step (plan and profile curvatures at various cell windows) are used with a proportional increased weight to the increasing cell window size for each raster layer (Table 1); as input parameters also sine and cosine of aspect were used. We didn't consider slope gradient because, a part for the valley bottom and hilltop, it is quite constant and didn't give additional information to the segmentation procedure.

Table 1: Weights assigned to each layer implementes in the eCognition developer software for the multiresolution segmentation algorithm.

Layer (cells window)	Plan curv (5)	Plan curv (7)	Plan curv (9)	Plan curv (11)	Plan curv (13)	Plan curv (15)	Plan curv (17)	Plan curv (19)	Plan curv (21)	Prof curv (5)	Prof curv (7)	Prof curv (9)	Prof curv (11)	Prof curv (13)	Prof curv (15)	Prof curv (17)	Prof curv (19)	Prof curv (21)	Aspect Cos	Aspect Sin
Weight	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9	10	10

Other settings used for this algorithm are: scale 7, shape 0.0002, compactness 0.0002.
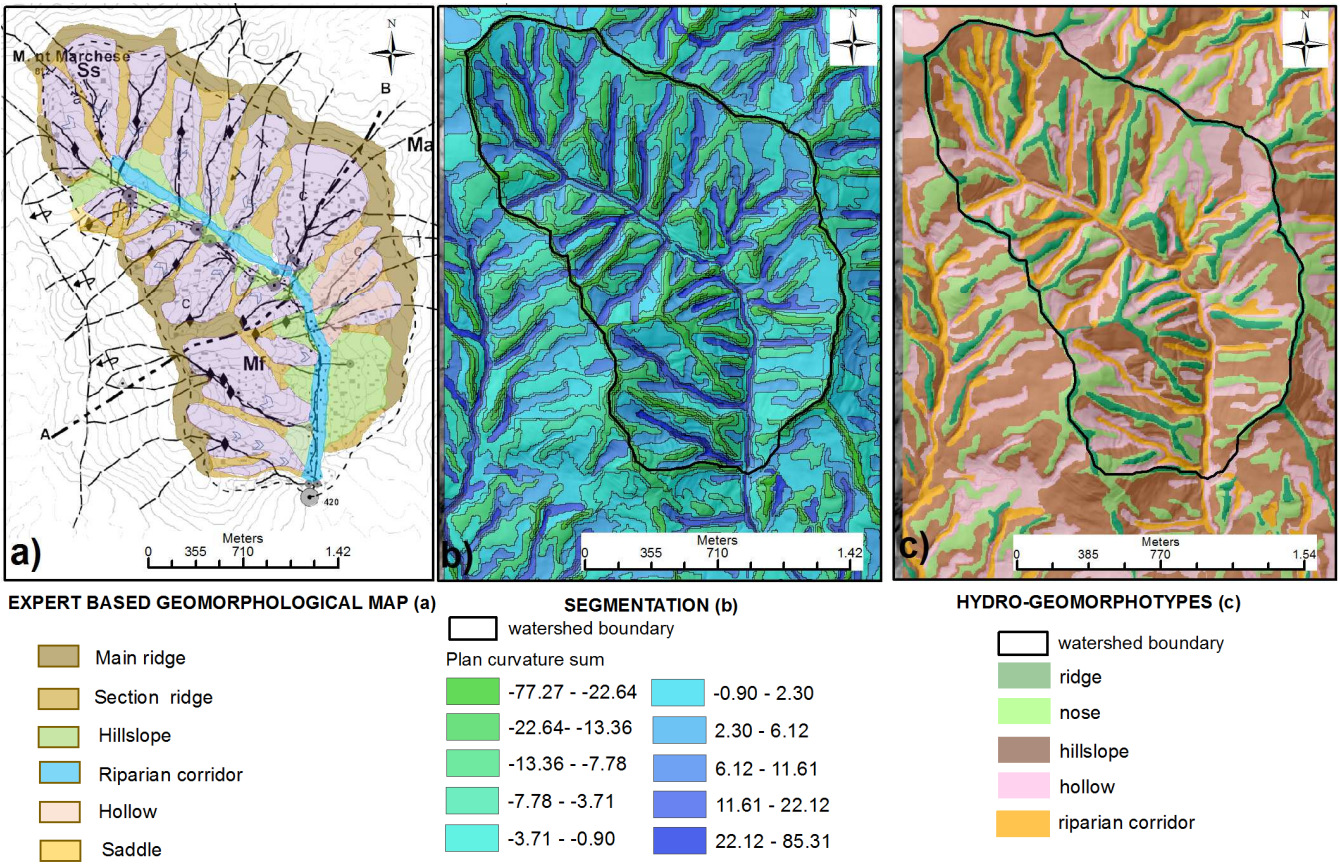
During this procedure, the segments obtained were compared to the expert-based geomorphological mapping by using the target-training procedure proposed in Guida et al. (2015) (Fig. 7a).

The image objects derived from the segmentation are shown in Fig. 7b.

In the third step, the classification of the objects, obtained in the previous step, was performed. The classification procedure followed the criteria proposed by Hennrich et al. (1999), whose conceptual background was the 'landscape catena' (Conacher and Dalrymple, 1977), which combines surface form and pedo–hydro–geomorphological processes at hill-slope scale.

In particular, the classification was based on the sum of the planimetric curvatures that were re-classified according to the threshold values listed in the Table 2. The interval values listed in the Table 2 were achieved by a supervised classification.

The use of only the plane curvature sum, computed with different windows, allow to obtain an object-based hydro-geomorphological map (Fig. 7c) with a good accordance with the expert based geomorphological map.

EXPERT BASED GEOMORPHOLOGICAL MAP (a)

- Main ridge
- Section ridge
- Hillslope
- Riparian corridor
- Hollow
- Saddle

SEGMENTATION (b)

☐ watershed boundary

Plan curvature sum

- -77.27 - -22.64
- -22.64 - -13.36
- -13.36 - -7.78
- -7.78 - -3.71
- -3.71 - -0.90
- -0.90 - 2.30
- 2.30 - 6.12
- 6.12 - 11.61
- 11.61 - 22.12
- 22.12 - 85.31

HYDRO-GEOMORPHOTYPES (c)

☐ watershed boundary

- ridge
- nose
- hillslope
- hollow
- riparian corridor

During the second step the best agreement with expert based geomorphological mapping was achieved with e Cognition software by means of an original multiresolution segmentation algorithm, by assigning a proportional increased weight to the increasing cell window size used for each raster layer (Fig. 7a). The hydro-geomorphological map (Fig. 7b) was obtained by expert based re-classification of the sum of plane curvature classes, choosing threshold values according to the hydrological components (hydro-geomorphotypes) listed in Table 1.
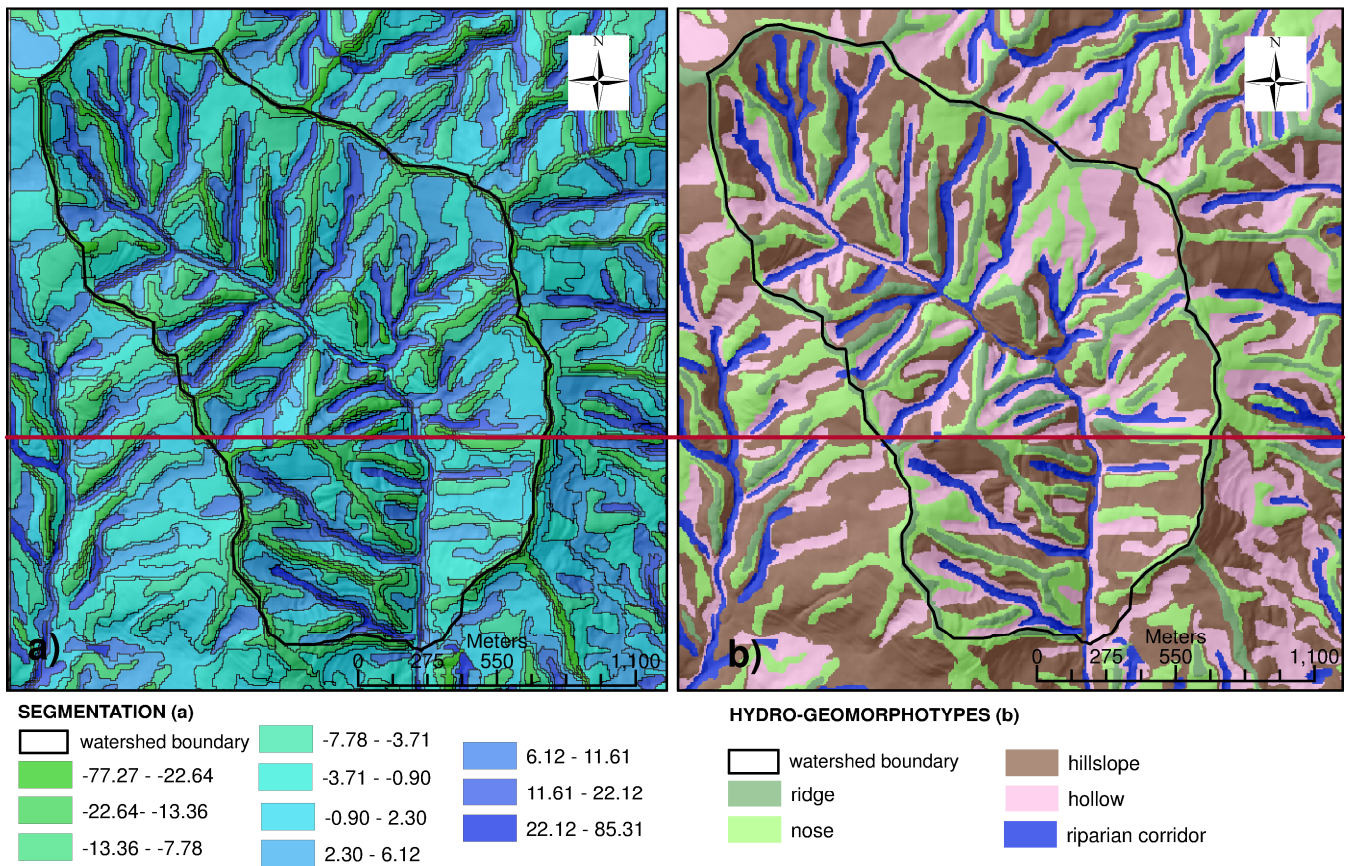
Figure 7. a) Expert- based hydro-geomorphological map; ab) Multi-resolution segmentation map; bc) Object-based hydro-geomorphological map obtained classifying the Multiresolution segmentation map by using only the plan curvature sum.

5   Table 12: Geomorphometric classification, geomorphological correspondence, hydro-geomorphotype definition and hydro-geomorphological behavior for each hydro-geomorphotype.

Sum of Plan-Profile Curvature Class (PPCSSPC)	Geomorphometric parameters and topographic position	Landform, Component or Element (Dramis et al., 2011)	Hydro-geomorphotype (HGT in Cuomo, 2012)	Hydro-geomorphological behaviour
SPPC < -13,4	Convex, divergent flow-like, upslope	Upland, summit, peak, crest	Ridge	Groundwater recharge on bare bedrock and dominant excess infiltration runoff after storm
-13,4 >= SPPC < -3,76	Light convex-divergent flow-like, up to midslope	Shoulder, side slope	Nose	Shallow soil, groundwater recharge area, prevalently excess infiltration runoff
-3,76 >= SPPC < 2,3	Light convex-planar, parallel flow-like, midslope	Scarps, back-slope, foot-slope, wash-slope, talus,	Hillslope	Debris, deep soil, shallow aquifer, excess saturation excess and sub-surficial runoff
2,3 >= SPPC < 11,6	Planar to light concave, convergent flow-like, upslope	Glen, swallet, scar	Hollow	Deep soil, shallow aquifer, prevalently excess saturation, delayed runoff production
SP=C => 11,6	Concave, convergent mid- to downslope	V-shaped stream, gully, bank, stream bed	Riparian corridor	Shallow soil, groundwater discharge, prevalently sub-surface, delayed return flow and groundwater ridging

14

The classification procedure followed the criteria proposed by Hennrich et al. (1999), whose conceptual background was the 'landscape catena' (Conacher and Dalrymple, 1977), which combines surface form and pedo hydro geomorphological processes at hill slope scale.

In the third step, a hydrologic analysis was performed on the catchment, obtaining the contributing area map by means of the Saga module implemented in QGis. More precisely, the log values of the contributing area map were reclassified according to the real condition of streamflow along the drainage network, observed in field during the training storm event, showed five different scenarios. Finally, a spatial statistical analysis was applied to the data fromperformed on the object based hydro-geomorphotype map shown above(Fig. 7c) and the five Contributing Area scenarios mapsscenarios, in order to evaluate their spatial relationships for the training storm event that occurred on January 2015 (Fig. 6). The application at storm event time scale is described on in the next section.

3.3 Dynamic hydro-chemograph separation

In order to understand the runoff generation that occurs during distinctive storm events for each period (wet/dry), we used the Q-EC relationship data analysis proposed by Cuomo and Guida (2013) and Guida and Cuomo (2014), considering the good accordance between the hydro-chemograph separation and the hydrograph filtering comparative procedure introduced by Longobardi et al. (2014). In particular, Cuomo and Guida (2016, under revision) subsequently proposed a modified mass balance procedure based on a "step-like", recursive, two-component hydrograph separation for the Ciciriello Catchment. The authors associated a correspondent mechanism of runoff generation to each component and the Q-EC threshold values for each mechanism in that Ceontributing Aarea started to enlarge and expand.

In this study, we used these values for each phase during the field survey, verifying the correspondence between the end-members hydro-chemograph signature proposed by Cuomo and Guida (2013, 2016 under revision and Guida and Cuomo, 2014) and the starting runoff contributing area.

Cuomo and Guida (2016, under revision) adopted the daily dataset illustrated in Sec. 2 (Fig. 2), using the end-members that the authors measured at the specific stormflow components by carrying out direct surveys and taking piezometric measurements. They obtained three upper and one lower boundary curves (Fig. 8), each representative of a specific mechanism, source area and timing of runoff production. The lower hyperbolic curve (LHg) delimits all the Q-EC values recorded during the dry period. The upper hyperbolic (UH) curves delimit the Q-EC values that are typical of groundwater and groundwater ridging for the UH1 curves. The second upper hyperbolic curves (UH2) starts when the UH1 reaches its horizontal asymptote and the sub-surface mechanism starts. Following which the upper linear curve (UL) starts when the direct runoff and soil pipe mixes with the previous components. The estimated intersection points between the three upper consecutive curves are the Q-EC threshold values for which another mechanism starts and hydro-dynamically interacts with the previous mechanism. In this way, the waters join together before reaching the streamflow. Successively, the authors carried out the same procedure on the 13 storm events shown in Fig. 2. The events n. 1-2-3-4-10-11-12-13 were assigned to the wet recharging period while events n. 5-6-7-8-9 were assigned to the dry discharging period. Moreover, the Q-EC relationship highlights three different types of hydrologic behavior occurring in the three hydrologic periods: wet (W), dry (D) and transition (T). In this way, the boundary curves between the dry-wet and wet-transition events were obtained in order to define further inner fields. Figure 8 shows a typical "threshold hydro-geomorphological system", where each source runoff remains independent during low magnitude events, but interacts physically and functionally with other sources at higher event magnitudes, inducing superposed hydrological mechanisms and complex hydro-chemical water mixing by dilution, dispersion and diffusion. By identifying

15

these five areas in respect to the hydrologic behavior of the catchment, it was possible to carry out the analyses for delimiting the Ceontributing Aarea in the next section using the thresholds listed in Table 23.
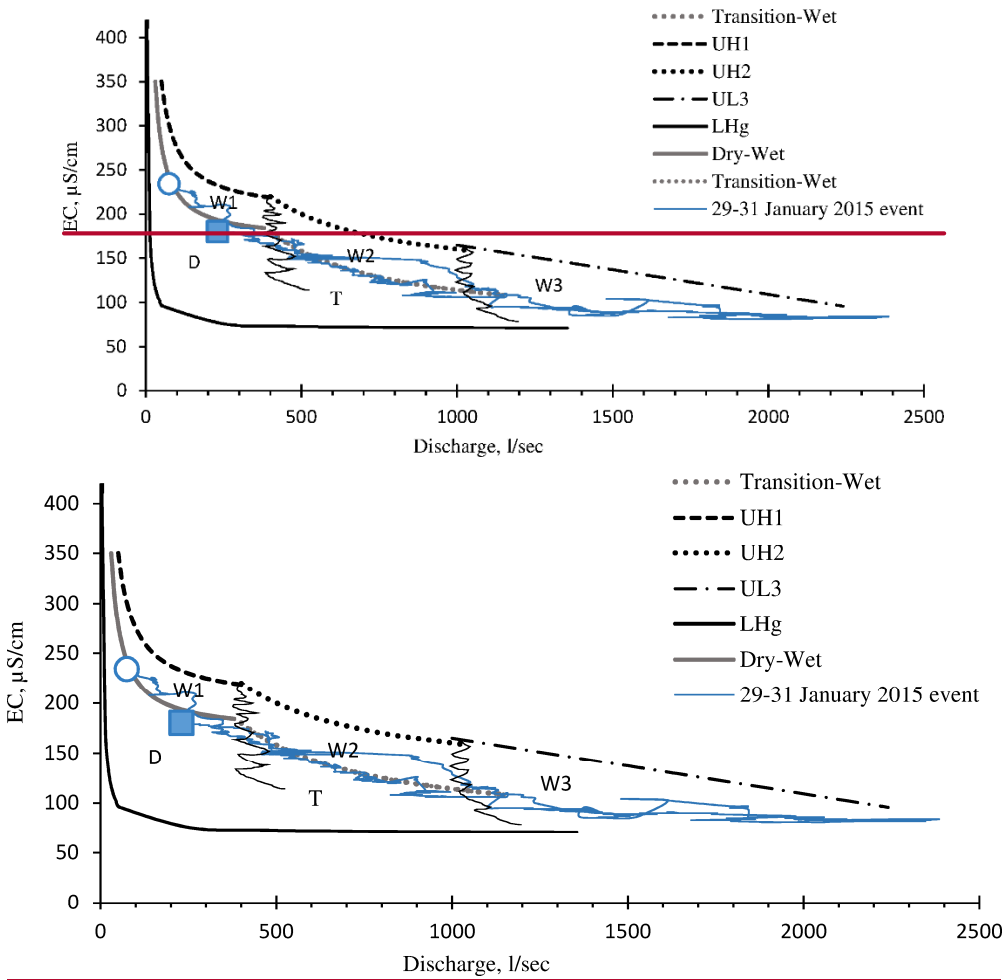
Figure 8. Delimitation of the five inner fields that define the limits of seasonal response of the catchment (modified from Cuomo and Guida, 2016, under revision) and, in blue, the hysteretic cycle of the study event, from its beginning (blue circle) to its end (blue square). Legend: UH1 and W1, upper hyperbolic curve 1 and wet area 1, respectively (typical of the Q-EC mixed value of groundwater and groundwater ridging); UH2 and W2, upper hyperbolic curve 2 and wet area 2, respectively (typical of the Q-EC mixed value of groundwater, groundwater ridging and sub-surface flow); UL3 and W3, upper linear curve and wet area 3, respectively, typical of the Q-EC mixed value of groundwater, groundwater ridging sub-surface flow and direct runoff; LHg, lower hyperbolic curve typical of the Q-EC response when direct runoff is suddenly added to the groundwater, following the heavy showers occurring during the dry period; D, dry area where the Q-EC typical of a dry event falls for which only the groundwater flow feeds the streamflow; T, transition area, where the Q-EC typical values of a dry-wet or wet-dry events fall, when the groundwater flows, groundwater ridging and the soil pipe feeds the streamflow.

Table 2:3: Hydro-chemical parameter range, distinctive for the wet (W), dry (D) and transition (T) period events. Legend: GW is for groundwater, SSF is for subsurface flow, DR is the direct runoff. (modified from Guida and Cuomo, 2016 under revision).

Field	Processes and Contributing Areas	EC_{quick} Range (mS/cm)	EC_{slow} Range	$Q_{threshold}$

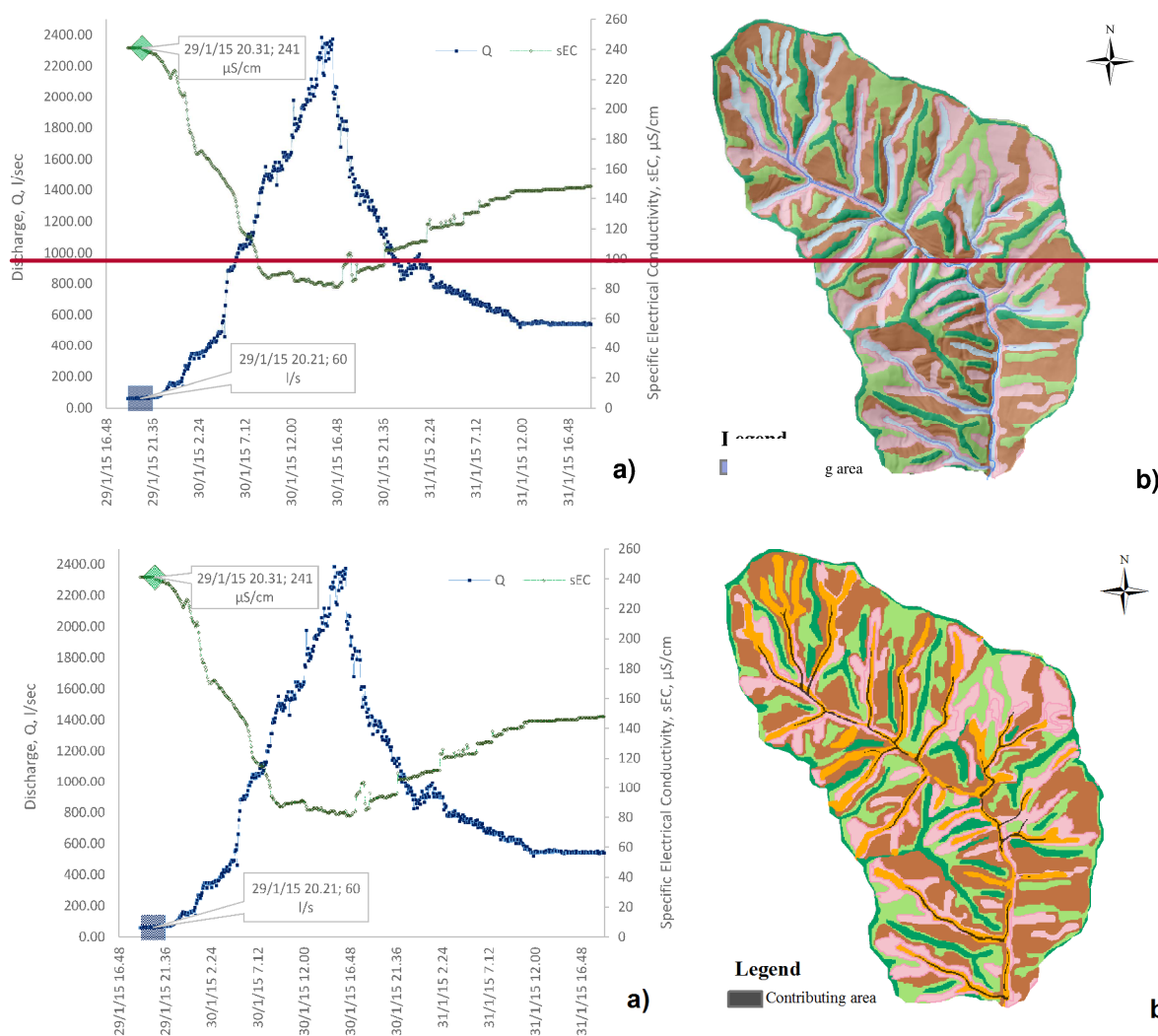|			(mS/cm)	(l/s)
W1	GW from bedrock deep and perched aquifer		250-300	30-50
	GW+GW$_{ridging}$ added from riparian corridor	200-220		400
W2	GW+GW$_{ridging}$ along the riparian corridor		200-220	
	GW+GW$_{ridging}$+SSF added from colluvial hollow	120-180		1000
W3	GW+GW$_{ridging}$+SSF		120-180	1000
	GW+GW$_{ridging}$+SSF + DR added from soil pipe	70-180		>>1000
D	GW		320-350	3-5
	GW+ GW$_{ridging}$	100-180		400
T	GW+ GW$_{ridging}$		100-180	400
	GW+ GW$_{ridging}$ + DR added from soil pipes	100-120		

By including the hysteretic cycle of the 29-31 January 2015 study event on the plot of Fig. 8, the hydro-geomorphological response can be classified as typical for a wet-period, that occurred after a short transition period during which the aquifer began to fill and groundwater ridging decreased progressively. As expected, during the event, all the runoff components were progressively activated when the Q-EC threshold values for each started. Consequently, the Contributing Areas enlarged the floodplain upslope, the riparian corridors and the zero order basins upstream, encompassing the Q-sEC value ranges listed in Table 3. These values were verified during the field survey reported in Sec. 3.1 and used for the hydro-geomorphological analyses of the next section.

4   Results

For the storm study, the variability of the contribution area was obtained by combining the hydro-chemical procedure and the object-based hydro-geomorphotype map. As a result of this analysis, Contributing Area space-time variability was obtained for the selected storm event by combining hydro-chemical procedure outcomes, the hydro-geomorphotype map and the Contributing Area scenarios.

On the right hand side of Figures 9 to 13 hydro- chemograph evolution at the five time steps discussed in Fig. 6a are illustrated, while on the left hand side of Figures 9 to 13 the progressive expanding contribution areas shown on the hydro-geomorphotype map can be seen. Specific observations are provided in the figure captions and the corresponding values for the increasing contribution area are listed on Table 4.

Figure 9 shows pre-event conditions, when only the base flow and the decreasing groundwater ridging from previous event were activated.

Figure 9. a) Pre-event hydro-chemograph conditions, just before the storm event, with Q=60 L/sl/s, filled blue square and EC=240 µS/cm , filled green diamond, b) scenario corresponding to groundwater and decreasing groundwater ridging contribution to streamflow running exclusively along the riparian corridor and main streamflow.
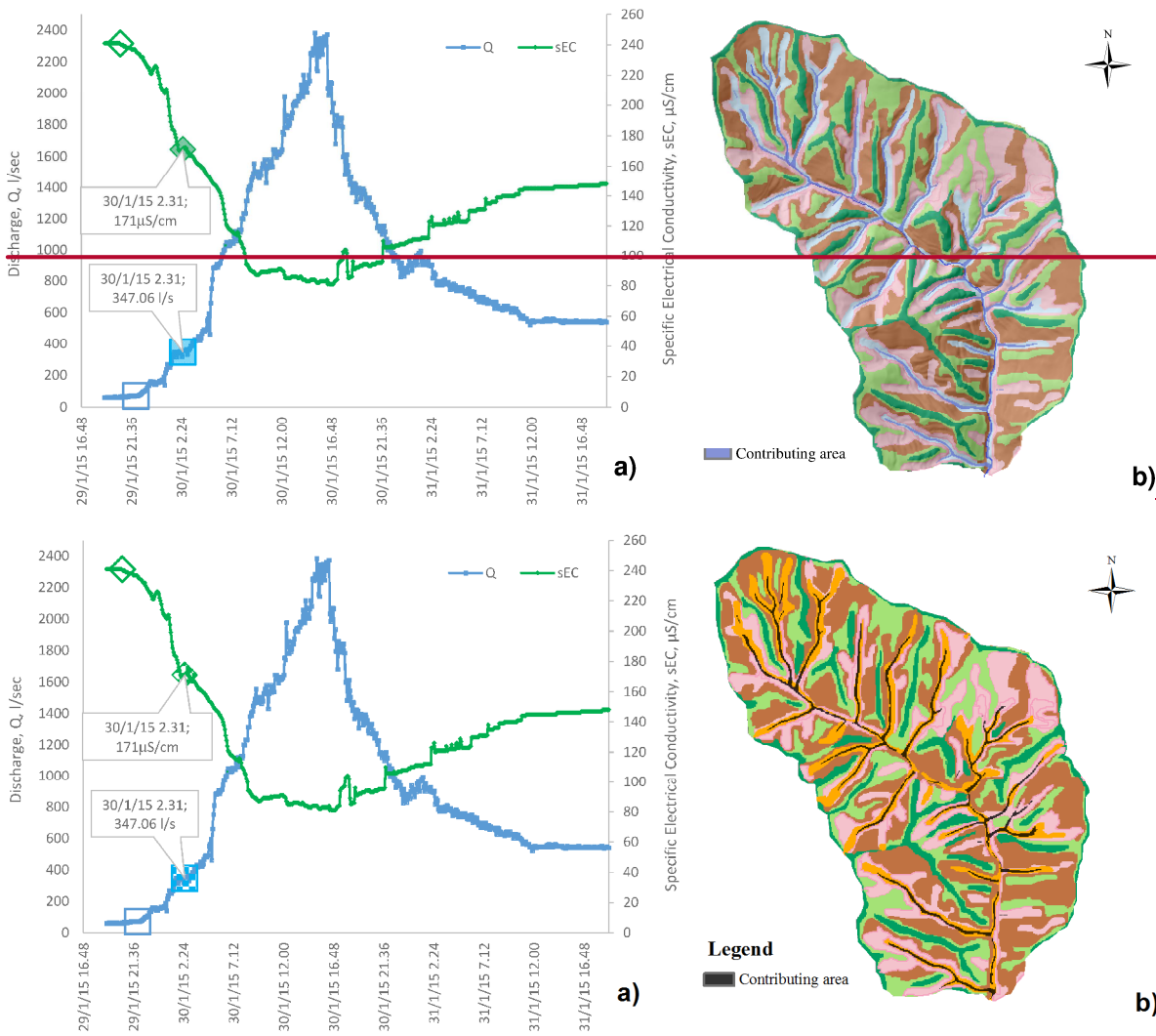
Figure 10. Initial hydro-chemograph conditions, just after the beginning of the storm event, with approximately Q=350 L/sl/s, filled blue square and approximately EC=170 µS/cm, filled green diamond, b) scenario corresponding to an increasing groundwater ridging and initial saturation excess contributions to streamflow. The first occurs along the riparian corridor, the second at the apical transient channels just downstream the colluvial hollows, respectively.
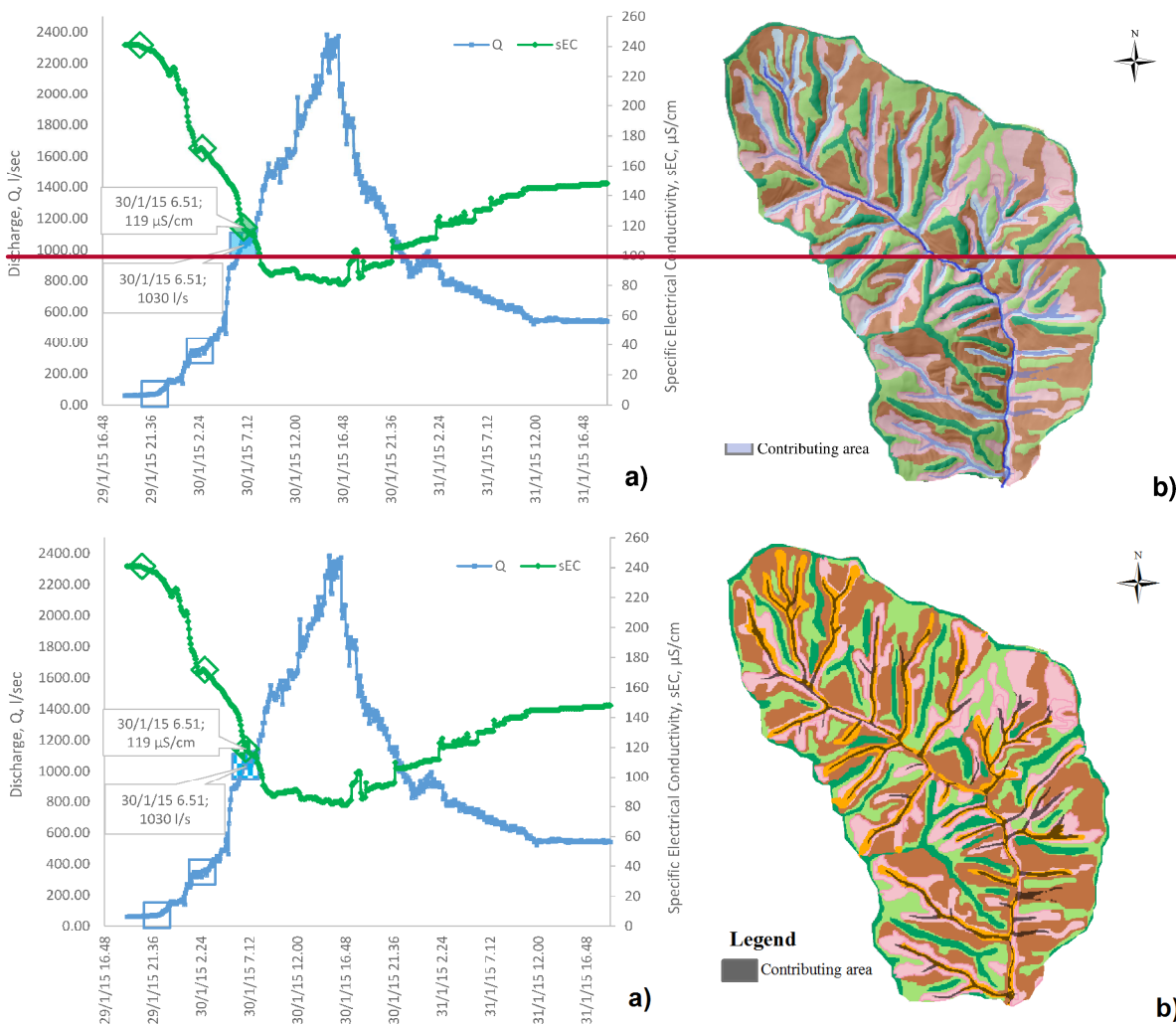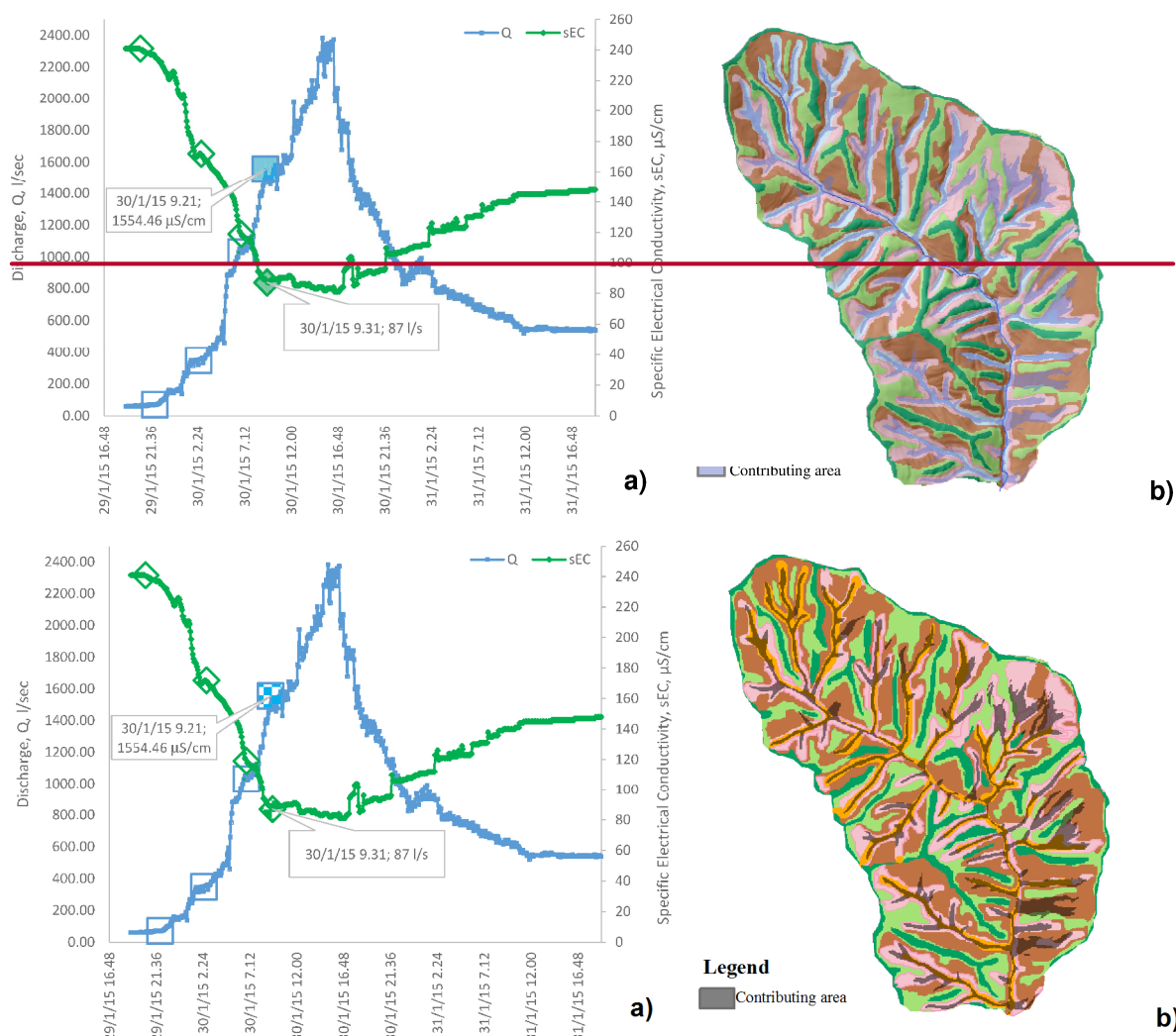
Figure 11. a) Progressive hydro-chemograph conditions, after approximately 60 mm of rainfall, with approximately Q= 1000 ~~L/s~~l/s, filled blue square and approximately EC=120 µS/cm, filled green diamond, b) scenario corresponding to a full saturation excess contributions to streamflow along the riparian corridor and at transient channels within the colluvial hollows, respectively.

5 Figure 12. Advanced hydro-chemograph conditions, after approximately 80 mm of rainfall, with approximately Q= 1550 L/sl/s, filled blue square and approximately EC=90 µS/cm, filled green diamond, b) scenario corresponding to a full saturation excess contributions to streamflow along the riparian corridor and the whole colluvial hollows, respectively.
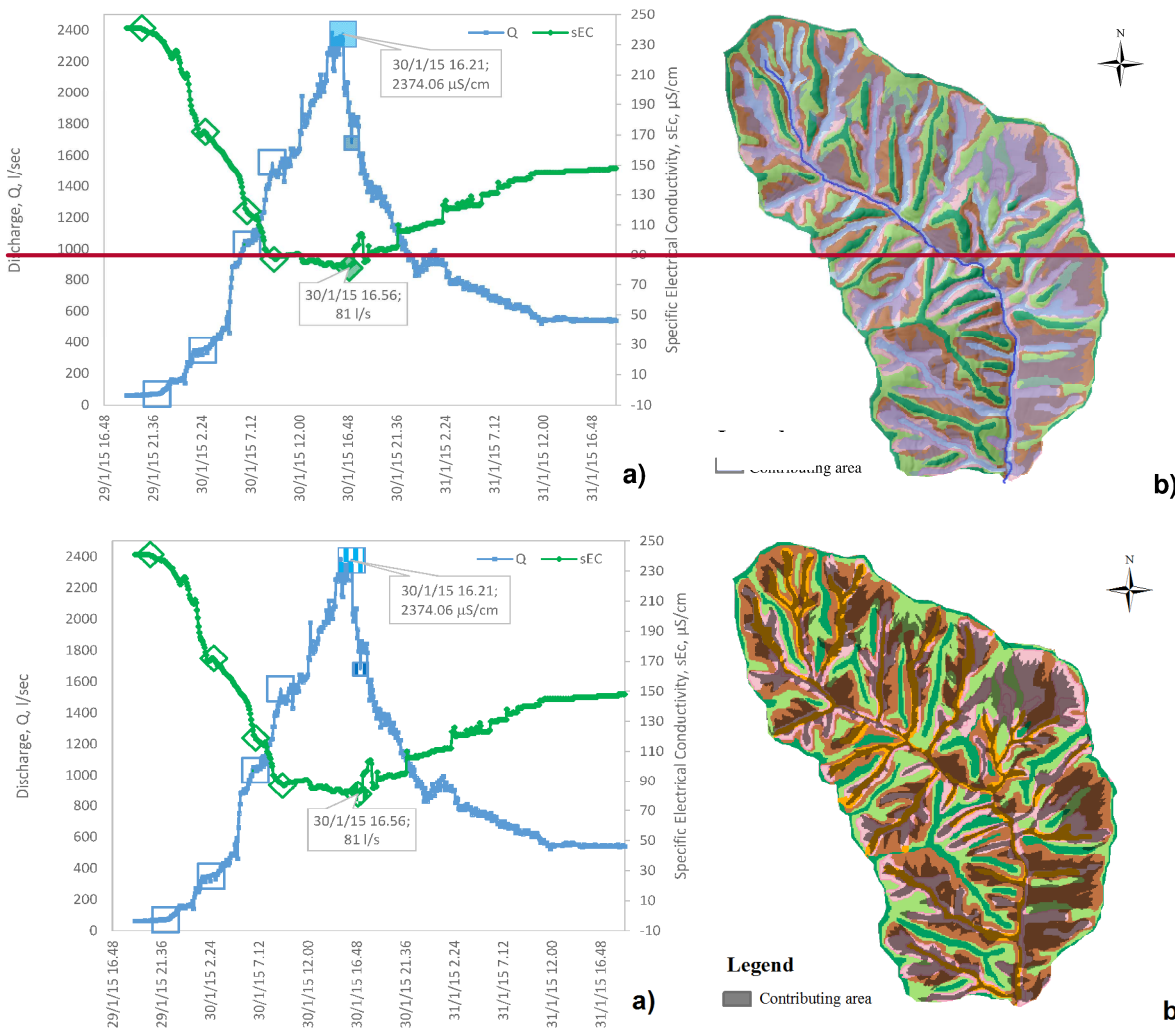
Figure 13. Final hydro-chemograph conditions, after approximately 100 mm of rainfall inducing a peak discharge approximately Q= 2400 ~~L~~l/s, filled blue square and about EC=80 µS/cm, filled green diamond, b) corresponding both to full saturation excess contributions to streamflow from the riparian corridor and colluvial hollows, as well as to macropore (soil pipe and fracture) and excess infiltration, on noses and partially on the ridges respectively.

10

Table ~~3~~4. Synoptic values of the Q-sEC scenarios and ~~C~~ontributing ~~A~~areas values for each hydro-geomorphotype. Legend: q is the specific discharge calculated respect the area of the catchment; A1 is the ratio between the Contributing Area and the hydro-geomorphotype; A2 is the ratio between the Contributing Area and the area of the catchment.

HYDRO-GEOMORPHOTYPE (HG)	SCENARIO	DISCHARGE Q (l/s)	SPECIFIC DISCHARGE q (ls⁻¹km⁻²)	CONTRIBUTING AREA, S (m²km²)	% AREA 1 (A1) (on the area of each HG)	% AREA 2 (A2) (on the total area)
Riparian corridor	1	50	16.47~~150.93~~	0.0575~~6800~~	0.143	0.018704
	2	300	98.79~~754.67~~	0.102~~102150~~	0.257	0.033638
	3	600	197.58~~1509.34~~	0.157~~157250~~	0.396	0.051783
	4	1000	329.30~~2515.56~~	0.227~~226775~~	0.570	0.074678
	5	1900	625.68~~4779.56~~	0.576~~575725~~	1.448	0.189588
Hillslope	1	50	16.47~~53.28~~	0.001~~1475~~	0.00157	0.000486
	2	300	98.79~~319.69~~	0.003~~2625~~	0.00280	0.000864
	3	600	197.58~~639.38~~	0.015~~14525~~	0.0155	0.004783
	4	1000	329.30~~1065.64~~	0.038~~37550~~	0.0400	0.012365
	5	1900	625.68~~2024.72~~	0.420~~419775~~	0.447	0.138233
Nose	1	50	16.47~~79.31~~	0.00008~~75~~	0.00012	2.47E-05
	2	300	98.79~~475.83~~	0.0002~~0200~~	0.00032	6.59E-05
	3	600	197.58~~951.66~~	0.001~~825~~	0.00131	0.000272
	4	1000	329.30~~1586.11~~	0.015~~15225~~	0.0241	0.005014
	5	1900	625.68~~3013.60~~	0.119~~118825~~	0.188	0.039129
Hollow	1	50	16.47~~71.23~~	0.007~~6975~~	0.00994	0.002297
	2	300	98.79~~427.37~~	0.015~~15100~~	0.02151	0.004972
	3	600	197.58~~854.74~~	0.050~~49900~~	0.07109	0.016432
	4	1000	329.30~~1424.56~~	0.093~~93475~~	0.13316	0.030782
	5	1900	625.68~~2706.67~~	0.450~~450075~~	0.64116	0.148211
Ridge	4	1000	329.30~~2714.87~~	0.0003~~0300~~	0.000814	9.88E-05
	5	1900	625.68~~5158.26~~	0.0055~~350~~	0.0145	0.001762

By plotting the S vs Q data from Table 3 on a normal plot we can follow the pattern of the progressive involvement of the runoff components as specific contribution areas in streamflow (Fig. 14).
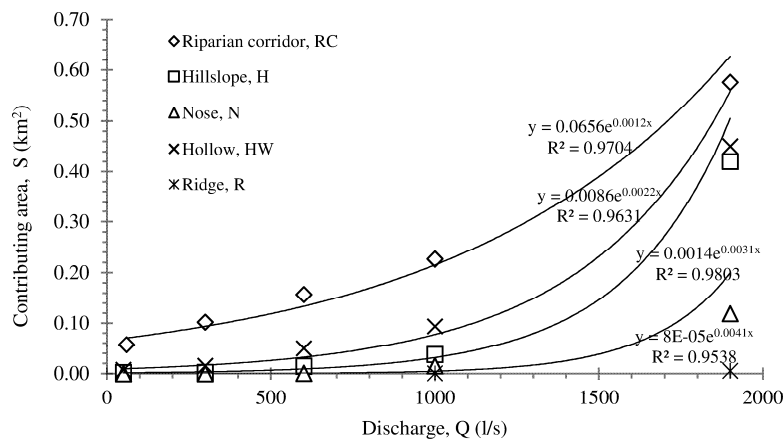

Figure 14. Plot of the Contributing Area vs Discharge from data on Table 3.

In our case, we obtained a positive exponential function for each hydro-geomorphotype curve, as shown in Fig. 14. This approach is similar to the calculations proposed by ~~Latron~~ Latron and Gallart (~~1990~~2007), but in this case the surface saturated area is calculated according to the base flow component as well as the other components connected to hydro-geomorphotypes. All the curves have a general exponential pattern (Eq. (1)):

5 $S(t)= S_0\, e^{aQ(t)}$ (1)

Where $S(t)$ is the total contribution area at instant t, S_0 the initial contribution area, e^a is a constant for a specific component considered and $Q(t)$ is the discharge at time of $S(t)$.

Equation (1) can be re-written as:

$\log S(t) = aQ(t) + \log S_0$ (2)

10 The riparian contribution trend is higher than the hollow and hillslope trends for a discharge from 50 to 1000 l/s, but the specific contribution areas from the latter progressively reach the same values of the riparian corridor for high discharge. In fact, a slight increase of the discharge from the riparian corridor was observed during the event ($a = 0.0012$). On comparing the behavior of the hollow and the hillslope, it seems that the hollow has a higher contribution area for lower discharge (from 50 to 600 l/s) than the hillslope ~~c~~Contributing ~~a~~Area (Fig.14). However, after the discharge increased, the two hydro-

15 geomorphotypes reached the same percentages as the ~~C~~contributing ~~A~~areas (~~%~~ A$_2$ in Table ~~3~~4) ~~and the two exponential curves definitively intersect for a Q> 1000 l/s (Fig.14)~~. A lower contribute originated from the nose whose ~~C~~contributing ~~A~~area is not influenced by the discharge until it reaches 1000 l/s, after which it increases rapidly ($a = 0.0041$).

Since 1970 authors have studied the relationships between the ~~C~~contributing ~~a~~Area and the baseflow discharge (Fig.15a). In fact Ambroise (1986), Myrabo (1986) and Latron (1990) found good relationships for some catchments in which the increasing

20 rate of the relative saturated area decreases with the increase of a specific discharge.

Dunne et al. (1975), observed that an increase of the saturated area leads to an increase of the discharge. More recently the same relationship was observed by Martinez-Fernandez (2005). Latron and Gallarat (2007) found a linear relationship between the specific discharge and the extent of the ~~C~~contributing ~~A~~area. The authors believe that unlike the other catchments, the linear trend could be reasonable since the saturation of the catchment considered is not conditioned by its topography.

Figure (top - part a and b):

q (ls⁻¹Km⁻²): 10, 100, 1000, 10000

◇ Riparian corridor
□ Hillslope
△ Nose
✕ Hollow
✻ Ridge

$A2 = 0.165e^{0.0005q}$
$R^2 = 0.9704$

$A2 = 0.0122e^{0.0015q}$
$R^2 = 0.9631$

$A2 = 0.0015e^{0.0029q}$
$R^2 = 0.9803$

$A2 = 0.0001e^{0.0026q}$
$R^2 = 0.9538$

% Contributing area A2 — axis: 10.000, 1.000, 0.100, 0.010, 0.001, 0.000

a) Saturated area (% of catchment area) — Dunne et al. (1975), Dunne 1978; Myrabo (1986); Ambroise 1986); Latron and Gallarat 2007); Latron 1990); Martinez-Fernandez et al. (2005)); discharge (ls⁻¹Km⁻²)

b)

Figure (bottom - part a and b):

a) Saturated area (% of catchment area) — Dunne et al. (1975), Dunne 1978; Myrabo (1986); Ambroise 1986); Latron and Gallarat 2007); Latron 1990); Martinez-Fernandez et al. (2005)); discharge (ls⁻¹Km⁻²)

q (ls⁻¹Km⁻²): 10, 100, 1000

Contributing area/catchment area (A1) — axis: 10.000, 1.000, 0.100, 0.010, 0.001, 0.000

◇ Riparian corridor
□ Hillslope
△ Nose
✕ Hollow
✻ Ridge

$y = 0.1658e^{0.0036x}$
$R^2 = 0.972$

$y = 0.0122e^{0.0067x}$
$R^2 = 0.9631$

$y = 0.0015e^{0.0094x}$
$R^2 = 0.9803$

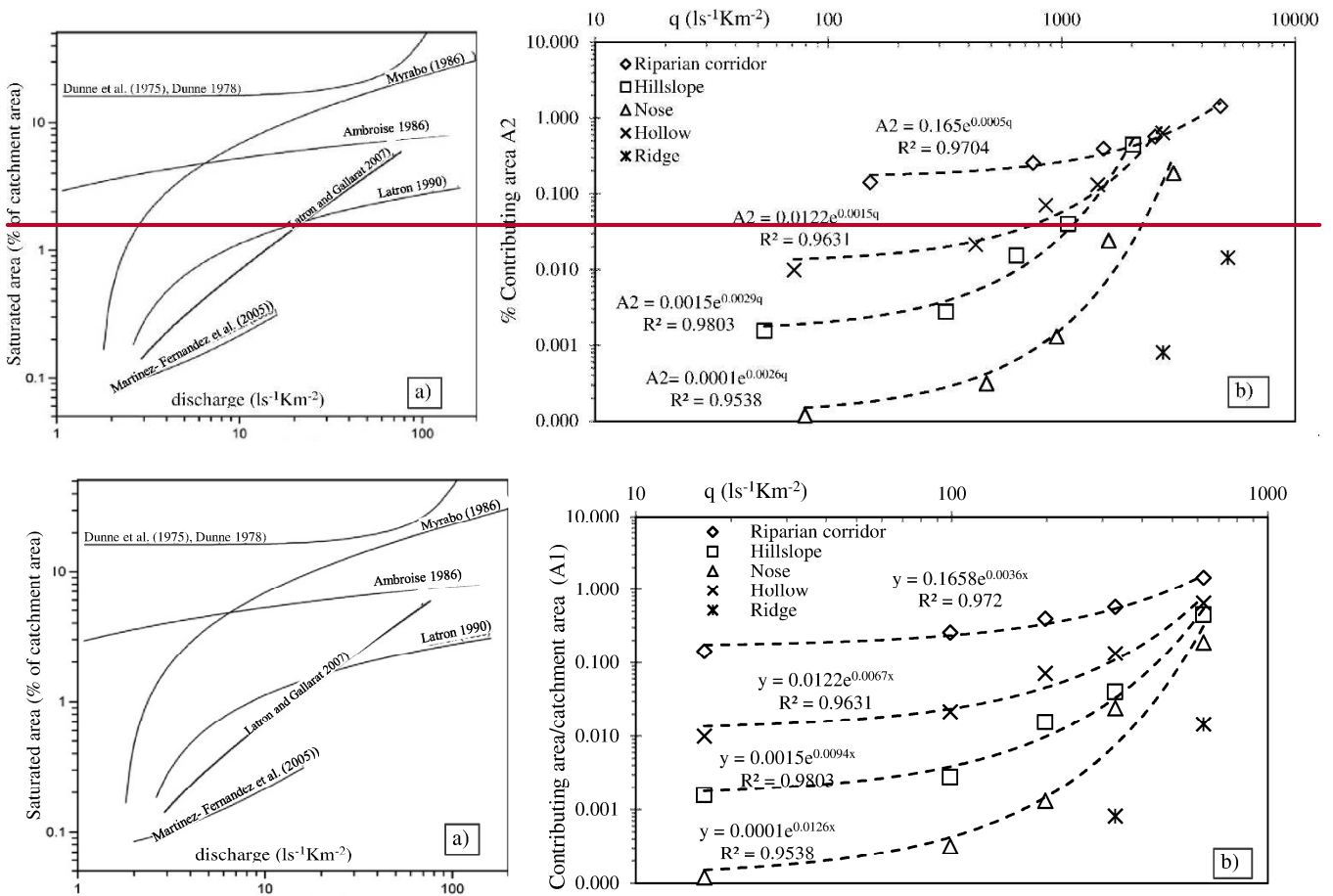$y = 0.0001e^{0.0126x}$
$R^2 = 0.9538$

b)

Figure 15. a) Relationship between the total extent of contributing saturated areas and the baseflow discharge in several small (less than 10 km²) catchments (modified from Latron and Gallarat, 2007); b) Relationship between the Ceontributing Aareas and the specific discharge for each hydro-geomorphotypes of the Ciciriello catchment.

For the Ciciriello Catchment we examined the relationships between the Percentage of the contributing areaContributing Area (%-A21 in Table 34) and the specific discharge for each hydro-geomorphotypes considered (Fig. 15b) and we believe that this trend is similar to that observed by Dunne et al. (1975).

When a low discharge occurs, the riparian corridor starts to contribute to the increasing discharge very slowly and only for a q = 344 100 l/skm² this hydro-geomorphotype widens its Ceontributing Aareas. Fig. 15 shows the increase in faster Ceontributing Aareas for hollow, hillslope and nose at a specific discharge q = 600300, 344 200 and 384 100 l/skm², respectively. In this case these q values are considered as the q threshold values for activating runoff mechanisms.

There is an evident anomaly regarding the riparian corridor as it shows a percentage of cContributing Ararea over 100%. In our opinion, this result is due to a DEM resolution and the riparian corridor must be carefully defined due to the possible overlap with other hydro-geomorphotypes, especially the hollows. In Fig. 15 an important result is observed concerning the intersection between all the curves at high q values. In our opinion, it is significant of the interaction between all the runoff mechanisms occurring in the catchment at high magnitude event before reaching the stream, as supposed by Cuomo and Guida (2016, under revision).

One of the more interesting results of this study is the experimental confirmation of the pre-event water contributions to stream flow by the rapid mobilization of the capillary fringe inducing groundwater-ridging mechanisms. Despite a number of proposed

processes and widespread acceptance, this mechanism is still poorly understood (Cloke et al., 2006). Therefore, this case study can be considered ~~to be a~~the preliminary identification, recognition and quantification of the mechanisms at catchment scale.

5 Conclusion

-According to the premises, the case study confirms the close link between geomorphometry and hydrology, since geomorphometry aims to describe land surface quantitatively and land surface is the spatial expression of the geomorphic processes acting in time and resulting in landforms generated by hydrological mechanisms, mainly in temperate and Mediterranean eco-regions. This further demonstrates how geomorphometry can usefully support hydrological analysis, by improving an interdisciplinary potential for future developments in connecting hydrology and geomorphology in data acquisition, mapping, analysis modeling and general purpose applications. This is the purpose of object-based hydro-geomorphology, based on the methods for recognizing and classifying distinctive hydro-objects within catchments, attaching ontology and semantics to significant catchment areas with distinctive hydrological behavior and response in order to allow for their objective description, holistic analysis and inter-catchment comparison.

In this perspective, firstly by means of a recursive training-target approach (Guida et al., 2015) we verified a good agreement between the expert-based geomorphological mapping and the object-based geomorphometric map~~, .obtained by a weighted profile and plane curvature sum.~~,.

-Therefore, by combining the hydro-chemical analysis and the object-based hydro-geomorphotype map, the variability of the ~~contribution~~ Contribution ~~area~~ Area during a significant storm event was spatially modeled using the log-values of the flow accumulation. In spite of its simplicity, spatial distribution of this parameters offered a good accordance with the observed Contribution Areas detected during the event by means of direct surveys and surface and groundwater discharge measurements~~this parameter provided better statistical fit with the observed contribution areas detected during the event by means of direct surveys and discharge/groundwater measurements~~. The runoff components were determined for ~~that~~the studied storm event and specific runoff discharge from each contributing hydro-geomorphotype was calculated for each time step on the hydro-chemograph.

This study is the experimental confirmation of the role and entity of pre-event water contributions to stream flow by the rapid mobilization of the capillary fringe inducing the groundwater ridging mechanism in step sloping terrains. Despite a number of proposed processes and widespread acceptance, this mechanism is still poorly understood (Cloke et al., 2006) therefore this case study can be considered as a preliminary identification, recognition and quantification of this particular mechanism at catchment scale,. According to Marcus et al. (2004), this study emphasizes the fact that field-based process studies must "*continue to form the underpinning of hydrologic application in GIS's*" and "*GIScience should not come at the expense of sacrificing field-based studies of hydrologic processes and responses*".

This is an approach that can fill the gap between simple lumped hydrological models and sophisticated hydrological distributed models based on numerous quantitative parameters and expensive data collection. This kind of interdisciplinary and integrate approach can be usefully applied to similar, rainfall-dominated, forested and no-karst catchments in the Mediterranean eco-region by using a inexpensive, parsimonious and effective methodology, as suggested by the Biosphere2 Program for water resource assessment and management. In fact, in UNESCO International Designation Areas (such as the Cilento Global ~~Geopare~~Geopark), hydro-geodiversity must be guaranteed by the Global Geopark Network ~~Mission~~mission according to the

requirements laid down by the World Heritage Cultural Landscape Management and natural and managed ecosystems (A1) must be safeguarded as established by the MAN_AND_BIOSPHERE Program.

In this perspective, geomorphometry plays a fundamental role in quantifying and objectively mapping hydro-geomorfological entities with hydrological relevance that require monitoring and modeling in production, transfer and routing flow between the different units in the catchments, as the knowledge base for progressive ecological planning on the sustainable use of water resources and best practices in land use improvements.

References

Anders, N.S., Seijmonsbergen, A.C., Bouten, W.: Segmentation optimization and stratified object-based analysis for semi-automated geomorphological mapping. Remote Sens Environ 115, 2976–2985. doi:10.1016/j.rse.2011.05.007, 2011

Ambroise, B.: Role hydrologique des surfaces saturées en eau dans le bassin du Ringelbach à Soultzeren (Hautes-Vosges), France, ''Recherches sur l'Environnement dans la Région'', Actes du 1er Colloque Scientifique des Universités du Rhin Supérieur, Université Louis Pasteur – Conseil de l'Europe, Strasbourg, France, 27–28/06/, 620-630, 1986.

Baatz, M., Schäpe, A.: Multiresolution Segmentationâ˘A´r: an optimization approach for high quality multi-scale image segmentation, in: Strobl, J., Blaschke, T., Griesebner, G., Wichmann-Verlag, H. (Eds.), Angewandte Geographische Informationsverarbeitung XII. pp. 12–23, 2000.

Babar, M.: Hydrogeomorphology, Foundamental applications and techniques, New Delhi: New India Publishing Agency, 2005.

Barling, R., Moore, I., and Grayson, R.: A Quasi-Dynamic Wetness Index for Characterizing the Spatial Distribution of Zones of Surface Saturation and Soil Water Content. Water Resourc Res., 30(4), 1029-1044, 1994.

Betson, R.: What is watershed runoff? J. Geophys. Res. , 69(8), 1541-1551, 1964.

Buchanan, B., Easton, Z., Schneider, R., and Walter, M.: Incorporating Variable Source Area Hydrology into a Spatially Distributed Direct Runoff Model, J AM WATER RESOUR AS, 48(1), 43-60. doi:10.1111/j.17521688.2011.00594.x, 2012.

Cascini, L., Cuomo, S., and Guida, D.: Typical source areas of May 1998 flow-like mass movements in the Campania region, Southern Italy.Eng Geol, 96, 107-125, 2008.

Cloke, H., Andersonb, M., McDonnellc, J., and Renaud, J.-P.: Using numerical modelling to evaluate the capillary fringe groundwater ridging hypothesis of streamflow generation, J. Hydrol., 316, 141-162, 2006.

Conacher, A. J., and Dalrymple, J. B.: The nine unit landsurface model: An approach to pedogeomorphic research, Geoderma, 18, 1-154, 1977.

Cuomo, A.: The contribute of the Hydro-Geomorphology in the evaluation of the flood discharge in the Campania region, Phd thesis, University of Salerno, Fisciano, Italy, 2012.

Cuomo, A., and Guida, D.: Discharge-electrical conductivity relationship in the Ciciriello Torrent, a reference catchment of the Cilento, Vallo Diano and Alburni European Geopark (Southern Italy), Rendiconti on line Società Geologica Italiana, 28, 36-40, 2013.

Cuomo, A., and Guida, D.: Using hydro-chemograph analyses to reveal runoff generation processes in a mediterranean
5   catchment, Hydrol. Process., accepted for publication, doi: 10.1002/hyp.10935under revision HYP 16 0037, 2016.

Cuomo, A., Guida, D., Palmieri, V., and Rossi, R.: Hydro-Geomorphotype: A New Object-Based Unit in Hydro-Geomorphological Analysis and Modelling. IAG/AIG International Workshop on "Objective Geomorphological Representation Models:Breaking through a New Geomorphological Mapping Frontier, Abstract book, University of Salerno, 15-19 october, 37-40, 2012.

10 Dragut, L., Blaschke, T.: Automated classification of landform elements using object-based image analysis. Geomorphology 81, 330–344. doi:10.1016/j.geomorph.2006.04.013, 2006.

Dragut, L., Csillik, O., Eisank, C., Tiede, D.: Automated parameterisation for multi-scale image segmentation on multiple layers. ISPRS J Photogramm 88, 119– 127. doi:http://dx.doi.org/10.1016/j.isprsjprs.2013.11.018, 2014.

Dragut, L., Minár, J., Csillik, O., Evans, I.S. Land-surface segmentation to delineate elementary forms from Digital elevation
15 Models, in: Geomophometry 2013. pp.2–5, 2013.

Dramis, F., Guida, D., and Cestari, A.: Nature and Aims of geomorphological mapping, In M. Smith, P. Paron, and J. S. Griffiths, Geomorphological mapping: Methods and applications, Elsevier, Developments in Earth Surface Processes,15, 2011.

Dunne, T., and Black, R.: Partial Area Contributions to Storm Runoff in a Small New England Watershed, Water Resourc
20 Res., 6, 1296-1311, 1970.

Dunne, T., and L. Leopold: Water in Environmental Planning. New York: W.H. Freeman and Co., New York City, 1978.

Dunne, T., Moore, T. R., and Taylor, C. H.: Recognition and prediction of runoff-producing zones in humid regions. Hydrological Sciences Bulletin, 20(3), 305-327, 1975.

Easton, Z., Fuka, D., Walter, M., Cowan, D., Schneiderman, E., and Steenhuis, T.: Re-Conceptualizing the Soil and Water
25 Assessment Tool (SWAT) Model to Predict Runoff from Variable Source Areas. J. drol, 348, 279-291, 2008.

Easton, Z., Fuka, D., White, E., Collick, A., Ashagre, B., and McCartney, M.: A Multi Basin SWAT Model Analysis of Runoff and Sedimentation in the Blue Nile, Ethiopia, Hydrol Earth Syst Sc, 14, 1827-1841. doi: 10.5194/hess-14-1827-2010, 2010.

Easton, Z., Gerard-Marchant, P., Walter, M., Petrovic, A., and Steenhuis, T. : Hydrologic Assessment of a Suburban Variable Source Watershed in the Northeast United States, Water Resourc Res., 43:W03413. doi:10.1029/2006WR005076, 2007

30 Goerl, R. F., Kobiyama, M., and dos Santos, I. : Hydrogeomorphology: principles, concepts, processes and applications, Revista Brasileira de Geomorfologia, 12, 2, 2012.

Eisank, C., Smith, M., Hillier, J.: Assessment of multiresolution segmentation for delimiting drumlins in digital elevation models. Geomorphology 214, 452–464. doi:10.1016/j.geomorph.2014.02.028, 2014.

Guida, D. and Cuomo, A.: Using discharge-electrical conductivity relationship in a Mediterranean catchment: the T. Ciciriello
35 in the Cilento, Vallo Diano and Alburni European Geopark (Southern Italy).Eng Geol for Society and Territory, Torino, Springer International Publishing 3, 201-205, 2014.

Guida, D., Cestari, A., Cuomo, A., Dramis, F., Palmieri, V., Paron, P., and Siervo, V.: The geomorphological informative mapping system of Salerno University: an overview, Proceedings of the IAG/AIG International Workshop on "Objective

Geomorphological Representation Models: Breaking through a New Geomorphological Mapping Frontier, University of Salerno, Fisciano (Italy), 71-72, 2012.

Guida, D., Cuomo, A., Cestari, A., Dramis, F., Palmieri, V., and Siervo, V.:The Salerno University Geomorphological Informative Mapping System: the Licosa polygentic case study (Cilento European Geopark, southern Italy), In J. Jasiewicz, Z. Zwolinski, H. Mitasova, and T. Hengl (Eds), Geomorphometry for Geosciences, Adam Mickiewicz University in Poznan-Institute of Geoecology and Geoinformation, International Society for Geomorphometry, 53-56 2015.

Hengl, T.: Finding the right pixel size. Computers & Geosciences 32, 1283–1298. doi:10.1016/j.cageo.2005.11.008, 2006.

Hennrich, K., Schmidt, J., and Dikau, R.: Regionalization of geomorphometric parameters in hydrologic modelling using GIS, Regionalization in Hydrology. Diekkruger, B.; Kirkby, M.; Schroder, U. (eds.), IAHS Publication 254, Proceedings of the Conference on Regionalization in Hydrology at Braunschweig, March 1997, International Association of Hydrological Sciences: Wallingford, 181-191, 1999.

Hewlett, J. D.: Soil moisture as a source of base flow from steep mountain watersheds, U. S. Forest Scrv. Southeast, Forest Expt. Sta. Paper, 192, 11, 1961.

Huang, C. and Laflen, J.: Seepage and Soil Erosion for a Clay Loam Soil, Soil Sci Soc Am J , 60(2), 408-416, 1996.

Klaus, J., and McDonnell, J. J.: Review paper: Hydrograph separation using stable isotopes: Review and evaluation, J. hydrol, 505, 47-64, 2013.

Kwaad, F.: Summer and Winter Regimes of Runoff Generation and Soil Erosion on Cultivated Loess Soils (The Netherlands), Earth Surf Processes, 16, 653-662, 1991.

Ladouche, B., Probst, A., Viville, D., Idir, S., Baqué, D., Loubet, M., . . . Bariac, T.: Hydrograph separation using isotopic, chemical and hydrological approaches (strengbach catchment, France), J. Hydrol., 242(3-4), 255-274, 2001.

Latron, J.: Caracte´risation ge´omorphologique et hydrologique du bassin versant versant du Strengbach (Aubure), Memoire de Maɪtrise, UFR de Géographie, CEREG, Université Louis Pasteur, Strasbourg I, 1990.

Latron, J., and Gallart, F.: Seasonal dynamics of runoff-contributing areas in a small mediterranean research catchment (Vallcebre, Eastern Pyrenees), J Hydrol., 335, 194-206, 2007.

Longobardi, A., Guida, D., Cuomo, A., and Villani, P.: Chemical streamflow analysis as a support for hydrograph filtering in small size watersheds: the Ciciriello experimental catchment (Cilento, Vallo di Diano and Alburni European and Global Geopark). In J. G. Ceron Breton, J. Quartieri, M. Guida, D. Guida, and C. Guarnaccvia (Eds), WSEAS, (p. 96-102). Vietri (SA), Italy, 2014.

Lyon, S., Walter, Gerard-Marchant, V., and Steenhuis, T.: Using a Topographic Index to Distribute Variable Source Area Runoff Predicted with the SCS Curve-Number Equation, Hydrol. Process., 18, 2757-2771, 2004.

Marcus, A. W., Aspinall, R. J., and Marston, R. A.: Geographic information systems and surface hydrology in mountains, In M. P. Bishop and J. F. Shroder Jr, Geographic information science and mountain geomorphology,. Chilchester, UK: Springer-Praxis, 344-370, 2004.

Martɪnez Fernandez, J., Ceballos Barbancho, A., Herna´ndez Santana, V., Casado Ledesma, S., and Mora´n Tejeda, C.:Procesos hidrolo´gicos en una cuenca forestada del Sistema Central: Cuenca experimental de Rinconada. Cuadernos de Investigacion Geografica 31, 7–25, 2005.

Moore, I., Burch, G., and Mackenzie, D.: Topographic Effects on the Distribution of Surface Soil Water and the Location of Ephemeral Gullies. Transaction ASAE, 31(4), 1098-1107, 1988.

Myrabo, S.: Runoff studies in a small catchment. Nord. Hydrol., 17, 335-346, 1986.

29

National Research Council: New strategies for America's watrshed. Wasshinghton, DC, New York: National academy Press, 1999.

Okunishi, K.: Hydrogeomorphological interactions: A review of approach and strategy, Trans Jpn Geomorph Union, 12, 99-16, 1991.

5   Okunishi, K.:Concept and methodology of hydrogeomorphology, Trans Jpn Geomorph Union, 15A, 5-18, 1994.

Peckham, S. D.: Geomorphometry and spatial hydrologic modelling. In T. Hengl, and H. J. Reuter, Geomorphometry: concets, software, applications, Amsterdam : Elsevier, 579-602, 2009.

Pionke, H., Gburek, W., Sharpley, A., and Schnabel, R.: Flow and Nutrient Export Patterns for an Agricultural Hill Land Watershed, Water Resourc. Res., 32(6), 1795-1804, 1996.

10   Sidle RC, O. Y.: Hydrogeomorphology: overview of an emerging science, Hydrol. Process., 18, 597-602, 2004.

Sidle, R. C., Tsuboyama, Y., Noguchi, S., Hosoda, I., Fujieda, m., and Shimizu, T.: Stormflow generation in steep forested headwaters: a linked hydrogeomorphic paradigm, Hydrol. Process., 14, 369-385, 2000.

van Asselen, S., Seijmonsbergen, A.C.: Expert-driven semi-automated geomorphological mapping for a mountainous area using a laser DTM. Geomorphology 78, 309–320. doi:10.1016/j.geomorph.2006.01.037, 2006

15

Vander Kwaak, J., and Loague, K.: Hydrologic-Response Simulations for the R-5 Catchment with a Comprehensive Physics-Based Model, Water Resourc. Res., 37(4), 999-1013, 2001.

White, E., Easton, Z., Fuka, D., Collick, A., Adgo, E., Mc-Cartney, M., . . . T.S, .. S.: Development and Application of a Physically Based Landscape Water Balance in the SWAT Model, Hydrol. Process., 25, 915-925. doi:10.1002/hyp.7876, 2011.

20   Zollweg, J., Gburek, W., Pionke, and Sharpley, A.: GIS-Based Delineation of Source Areas of Phosphorus Within Agricultural Watersheds of the Northeastern USA. Proceedings of the IAHS Symposium on Modeling and Management of Sustainable Basin-Scale, Colorado: 10-14 July, Boulder, 31-39, 1995.