



HAL
open science

Hydrogeomorphologic atlas of the Duyes valley

Christian Depraetere

► **To cite this version:**

| Christian Depraetere. Hydrogeomorphologic atlas of the Duyes valley. 2023. <hal-04427157>

HAL Id: hal-04427157

<https://hal.science/hal-04427157v1>

Preprint submitted on 30 Jan 2024

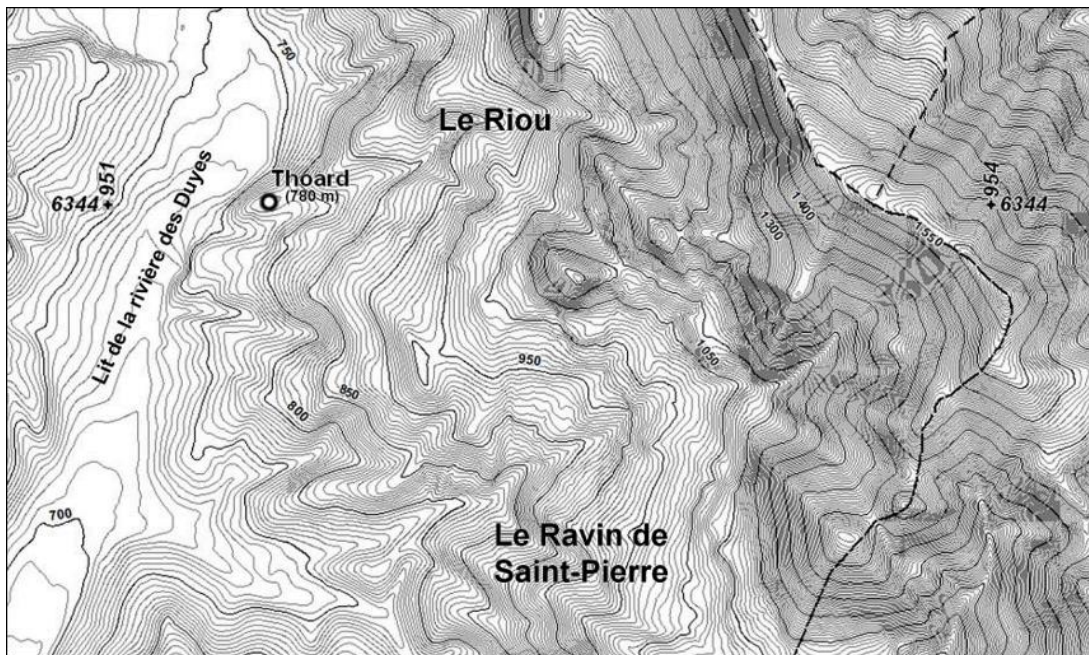
HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons CC0 1.0 - Universal - International License

Hydrogeomorphologic atlas of the Duyes valley



Christian Depraetere

Institut de Recherche pour le Développement



Montpellier, France, Version June 2023

PREAMBULE

“Reading landscape” through eyes... and computers:

“Reading landscape” is a key activity for natural scientists especially for geomorphologists as quoted by professor Jiun-Chuan Lin in his book “Geomorphometry” (reference [16] and **Figure 1**). It can be done during field work but also through our computer screen as most of us do it nowadays.

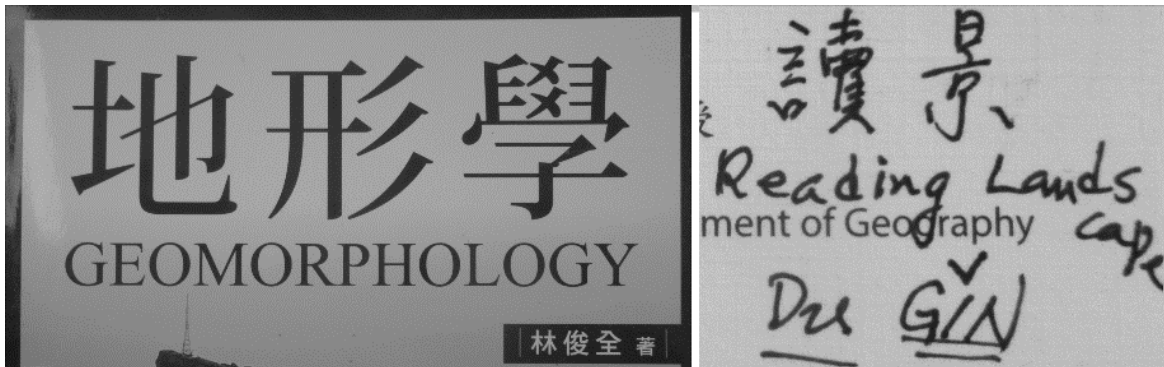


Figure 1 : the book of professor Lin-Chuan Lin [16] and the concept of “reading landscape”

The aim of this document is to synergize the process of reading landscape during the field trip in the valley des Duyes in June 2023 (**Photo 1**) with usual works on our screens.



Photo 1 : « Reading landscape » tutorial for kids on the Duyes valley from Thoard’s spur (August 2006)

The supervisors of the field trip from 17 to 21 June 2023 are Professor Jiun-Chuan Lin of the National Taiwan University (NTU), Professor Benoît Defontaine of the University Gustave Eiffel (Paris) and Dr Christian Depaetere of the Institut de Recherche pour le Développement (IRD, Montpellier), in collaboration with the Géoparc UNESCO de Haute Provence and the town council of Thoard.

The **Table 1** summarize the GIS layer maps used in this atlas

GIS layers from DTM RGE-Alt-SEAD	Couches SIG dérivées du MNT RGE-Alt-SEAD	In Chinese	In German	Unit	Layer extension	Maps	Figures
DTM resolution $\mu=10m$	resolution $\mu=10m$?	?	Meters	DTM	2	1, 4, 5, 11 and 12
Shading	Estompage	?	?	NW illumination	SHA	4	
Slope gradients	Pentes	?	?	% or °	SLG	3, 5, 7 and 8	1
Slope aspects	Orientations	?	?	°	SLA	6	
South facing slopes	Adret/ubac	?	?	South orientation (From SLA)		6	
Plan convexities	Convexités horizontales	?	Horizontal Krümmung	$^{\circ}/2\mu$	PLC	9	7
Profile convexities	Convexités verticales	?	Vertical Krümmung	$^{\circ}/2\mu$	PRC	10	
Across-slope convexities	Convexités transversales	?	?	$^{\circ}/2\mu$	ASC	11	
Mean curvatures	Courbures moyennes	?	?		MC	12	
Mean quadratique curvatures	Courbure moyennes quadratiques	?	?		MQC	13	
Drainage network (D8)	Modèle de drainage (D8)	?	?	Directional codes 1 to 8	DD8	14	13 and 14
Distance to outlet	Distances à l'exutoire	?	?	km	DIO	16	3
Length of drainage lines	Longueurs des drains	?	?	km	DRL	17	
Upstream area	Surfaces à l'amont des drains	?	?	km ²	DRA	18	
Multidirectional drainage (DRAMP)	Drainage multidirectionnel (DRAMP)	?	?	percolation from upstream	DMP	20	13 and 14
LOG(DRAMP)	LOG(DRAMP)	?	?	percolation from upstream	LOG	21	
Catchment basins	Bassins versants	?	?	Codes	CB	1	
River network	Réseau de rivière	?	?	Threshold from DRA		26	
Sub catchment basins	Sous-bassins versant	?	?	Pfaffstetter/Bocquillon codes	SCB	22	6
Massifs	Massifs	?	?	Codes level 0 to 9	MAS	23 and 24	8 and 9

Table 1 : the GIS layers derived from the RGE-ALTI-SEAD DEM at 10 metres resolution

The terminology in **Table 2** needs to be completed with [30].

Terminology in English	Terminologie French	Chinese	German	Comments			
Relief	Relief (Formes d'ensemble)*	?	Relief (Gross formen)				
hillshape, moulding ?	Modélé (formes de détail)*	?	Klein Formen				
Roughness	Rugosité	?	?	Roughness versus "mountainness"?			
"Mountainness" ?	"Montuosité"?	?	?				
Massives	Massif (montagneux)	...	Gebirgsmassen				
Shuttle	Navette	?	?				
Thrust sheet	Nappe de charriage	?	?				
Solifluction	Solifluxion	?	?				
Alluvial fan	Cône alluvial	?	?				
Hillock, knoll	Monticule	?	Wörth, Holm, Brink				
Interflue	Interfluve	?	Riedel				
Ravine, gulch, clough, gully	Ravin	?	Wasserriss				
Crest line	Ligne de faite (de crête)	?	Firstlinie, Trauje, Scheitel				

Table 2 : terminology related to hydrogeomorphology

* *Formes d'ensemble (Relief) résultant des déformations de l'écorce terrestre, formes de détail (Modélé) du travail de l'érosion* (Baulig, 1957, page 10, [30]).
Translation: "Relief resulting from deformations of the earth's crust, moulding (or Hillshape?) from the work of erosion."

The references are noted as [1], [2] and so on.

The appendices 1 to 7 give more details about few results presented in the atlas.

“The waters subjected to follow at first the relief of an uneven ground destroyed little has little, the irregularities of the slope... Here, they gnawed; there they exhausted... The result of all these actions was to create a new curve, which is better suited than the primitive profile of the ground to the flow of water.” (Surell, 1841)

Introduction

The Duyes valley is defined as the catchment from the confluence with the Bléone river.

Few words about about hydromorphology from DTM:

A Digital terrain Model (DTM) is a scalar field of elevations; the gradient of a scalar field is a vector field¹ that could be assimilated in the case of topographical surfaces as the gradient of slopes and also to surface flows directions. The gradient and the aspects of slopes are the two components of the gradient vectors that are the most commonly use to analyse landforms from DTM [25]. It is worth noting that the slope gradient should also be considered as scalar field whose the vector field refers to “gradients of gradient” and therefore as curvatures (Refers to the second derivative of the land surface) of the original elevation scalar fields. Several softwares have been developed for DTM geomorphological processing since 1982 ([27] and [28])².

The RGE-ALTI DTM of the IGN (Institut Géographique National):

This DTM covers the entire French metropolitan and most of its overseas territories at a resolution of 1 meter and a centimetric precision for the elevation. For hydrological applications in this document, this metric DTM has been resampled at 10 meters with the SEAD method (*Sous Echantillonnage ADaptatif*) [6] and defined as RGE-ALTI-SEAD-10m with elevation in decimetres³.

The catchment basin of the Duyes river:

The *Map 1* computed from the RGE-ALTI-SEAD-10m DTM shows the main characteristics of this catchment. The valley covers 124.1 km² and is made of three main parts (**Map 2**):

- The head of the valley includes the sub catchments upstream of the confluence of the Duyes and its major affluent, the Ravin de Chevalet (744 m). It collects all the runoff from the most mountainous and rugged part of the valley;
- The right bank sloping down gently from the Crête de Vaumuse down to the main river bed of the Duyes;
- The left bank is narrower and bumpier with several steep torrents flowing directly into the Duyes.

The longest streams⁴ (28 km) flows from the Barre de Géruen (1862m) and Montagne de Mélan (1719m) down to the outlet of the Duyes (482m) at the confluence with the Bléone river. Notice that watersheds can be extraction automatically from the outlets of catchment basin⁵.

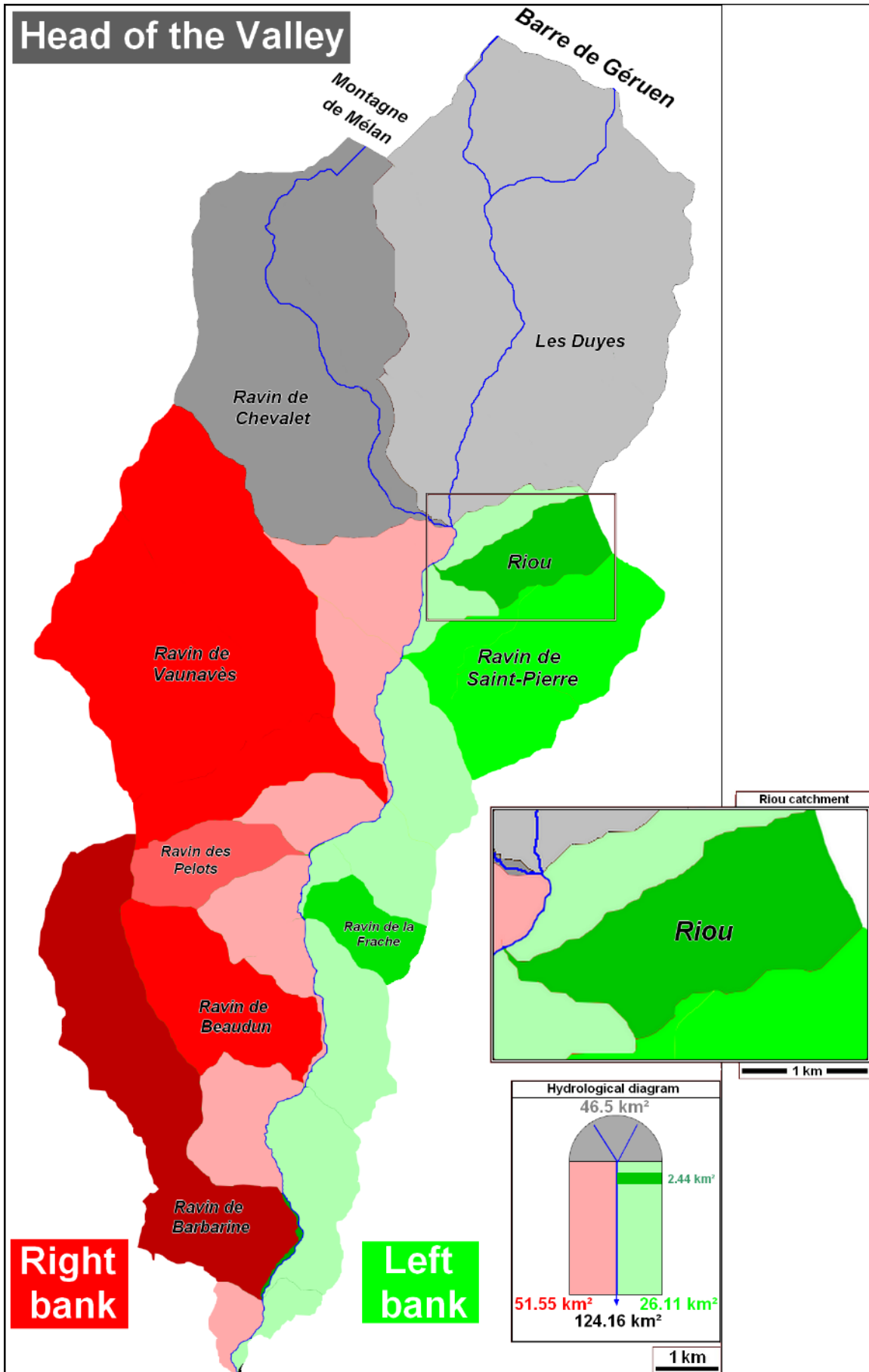
¹ A scalar field is a one-dimensional set of objects with no orientation (i.e. elevations). A vector field, on the other hand, is a two-dimensional entity with a magnitude and a direction (i.e. slope gradient and aspect). At its turn, a component of the vector field (i.e. slope gradients) can be taken as scalar field with a specific vector field (i.e. curvature or “roughness” of the topography).

² Most of the results presented in this document come from DEMIURGE [8].

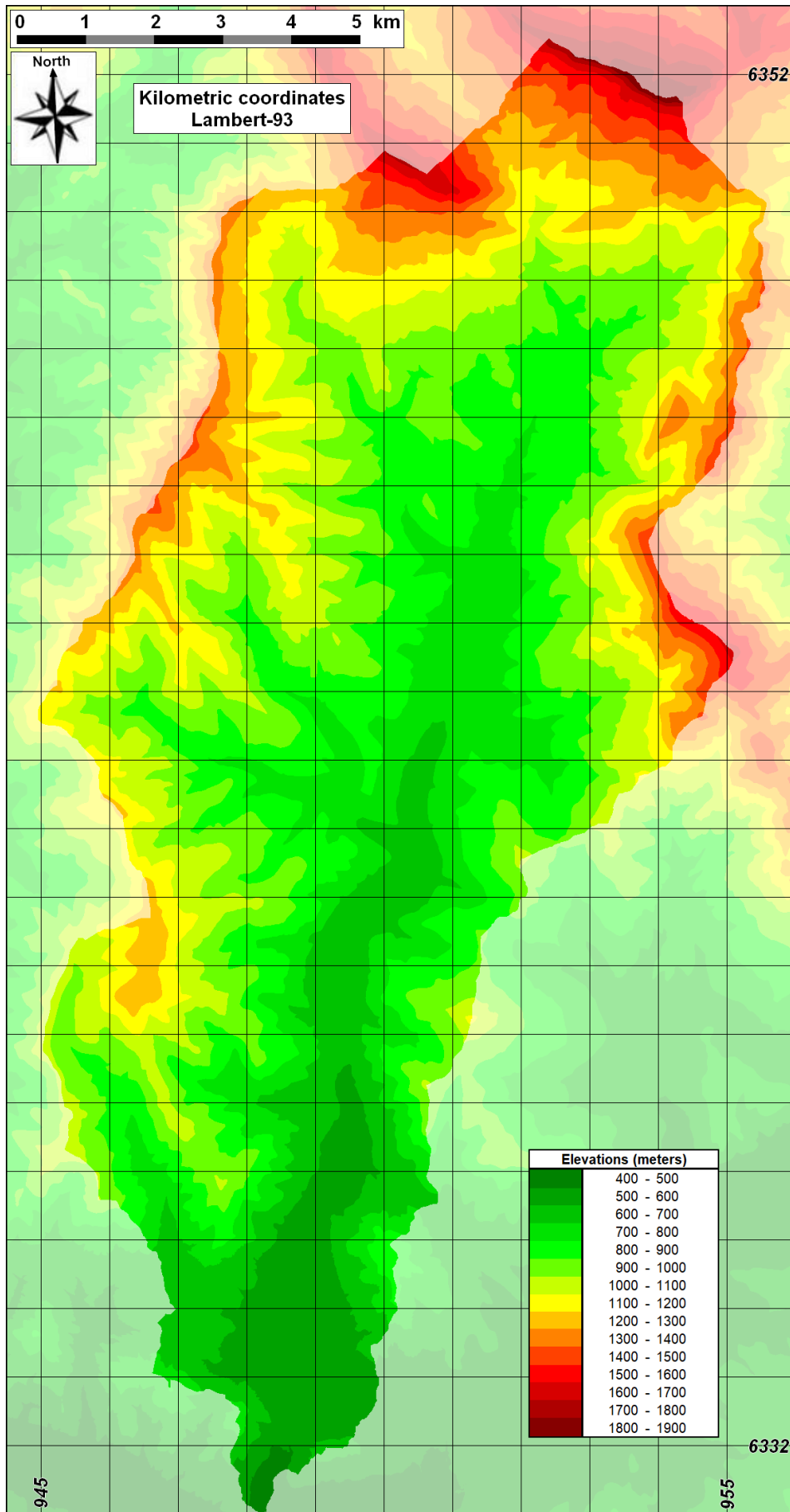
³ Available for download on <https://geoservices.ign.fr/rgealti>

⁴ The length of stream (in that case talweg treated as a « river ») depends of the DTM/DEM resolution (Cf. Mandelbrot).

⁵ See example catchment basins tessellation from shorelines outlets on Formosa in [appendix 9](#).



Map 1 : main hydrological parts of the Duyes catchment basin (Delineated from RGE-Alti-SEAD-10m).



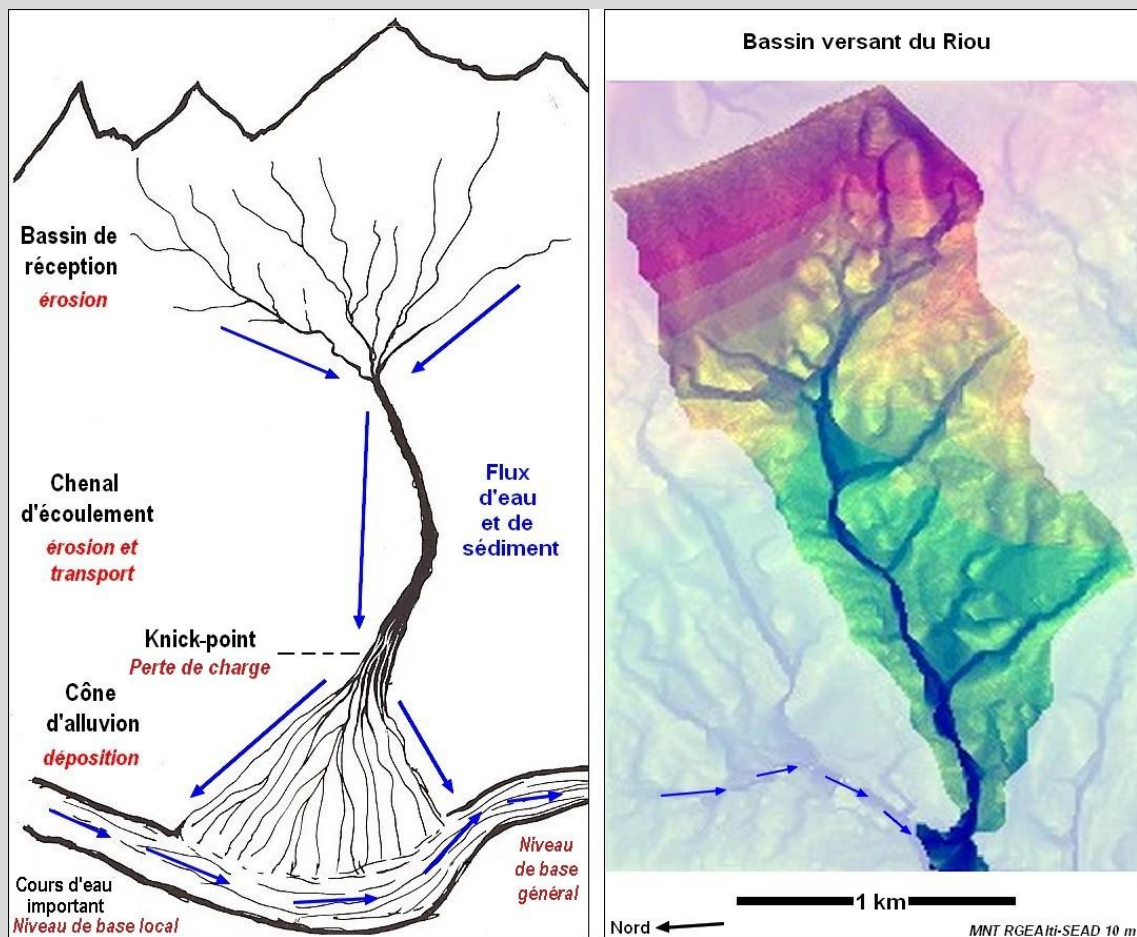
Map 2 : topography of the Duyes catchment basin (From RGE-Alti-SEAD-10m)

Few words on ...
The sub catchment basin of the Riou as a prototype of torrential valley

This torrent is right bank affluent of the main Duyes river and the catchment covers 2.44 km² including and a large alluvial fan at the bottom. This valley is a prototype of alpine elementary basin and exemplified fluvial erosion and lesson of the torrents in the context of Mediterranean mountains [7]. The torrents are natural laboratories for the study the dynamic of hydrogeomorphological processes. The torrent makes it possible to pose most of the problems relating to fluvial erosion and to grasp some of the mechanisms of the work of the rivers: problem of the assumption of responsibility of the materials which erosion provides, of the modalities of the transport of these materials and their deposit [9].

Like the Riou Bourdou (Southern Alps), the Riou of Thoard is a typical torrential valley. Both are still very active torrent with spasmodic floods despite the progressive reforestation since the end of the XIX^e century. Both "Riou" are divided into three parts :

- The reception basin, which constitutes the upper course;
- The flow channel, which corresponds to the middle course;
- The alluvial cone, or lower zone.

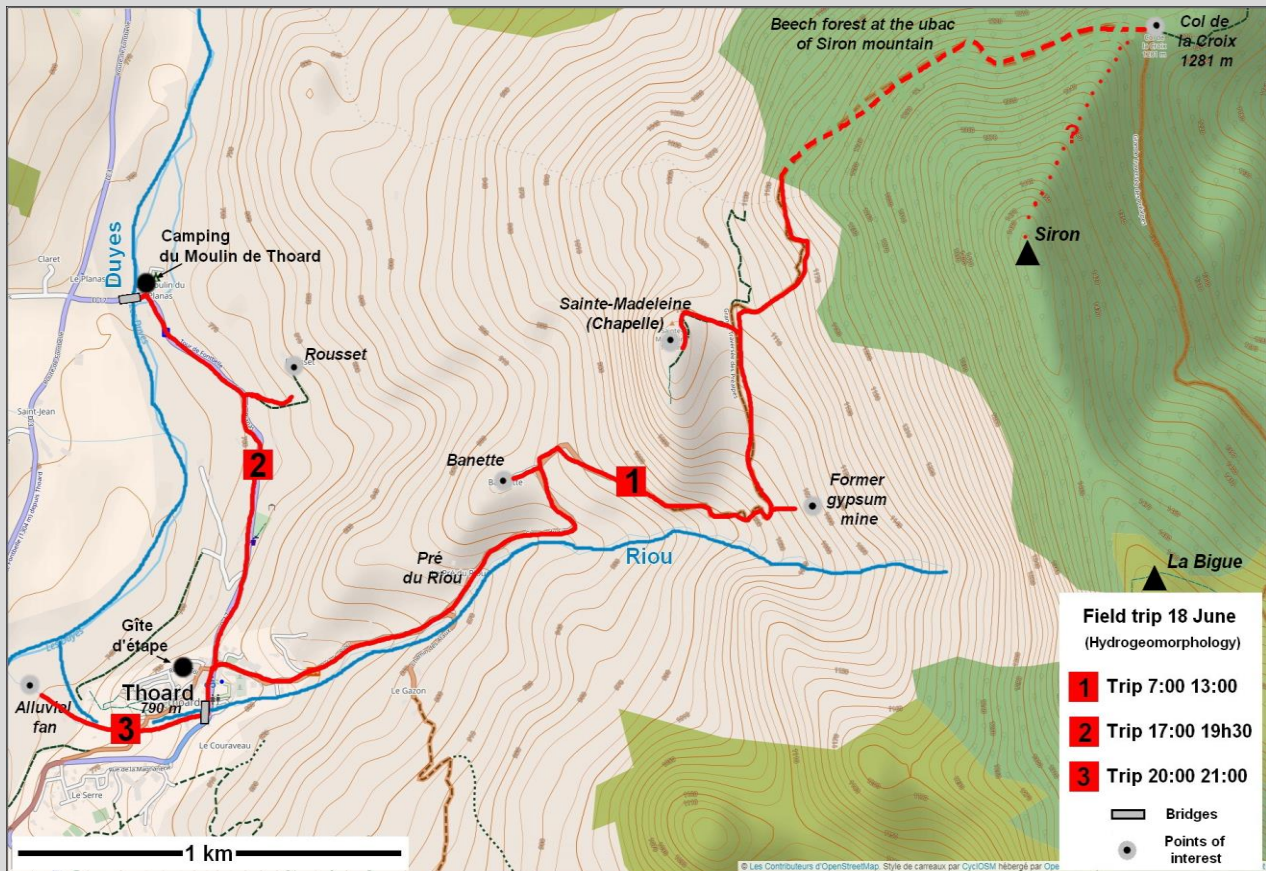


The Riou valley a prototype of torrential valley in Southern Alps.

Thus, the torrential basin of the Riou appears as a sort of diabolo, with the central part corresponding to the flow channel between the upper basin and the alluvial fan, both of which are dilated, but the catchment basin, or flow channel, can be short and narrow (More details in appendix 1). Flash floods occurred in the past and at present. This hazard is major risk for the village particularly its bridges and houses downstream in the alluvial fan (**Cf. appendix 2 about flash flooding**).

Few words on ... the hydrogeomorphological field trip, 18 June 2023

The trip will start (1) by a transect from the spur of Thoard village up to the top of the hill of the Chapelle Sainte-Madeleine (A geological “Shuttle” before the crest of Siron/La Bigue) and the limit of the beech forest on the “*ubac*” (North facing slope), including few stops at Pré du Riou, La Banette and the former gypsum mine. In the afternoon (2), another transect from the Thoard village down to the Moulin de Thoard shows various landforms (Ancient solifluxions at the farm of Rousset, vertical cross-section of colluvial deposits). From the alluvial terrace flanking the stony river bed of the Duyes (Camping du Moulin de Thoard), the ongoing incision and scouring of the riverbed is destabilising the banks and undermining one of the bridge piers. In the evening (3), a short walk from the village Bridge down to the alluvial fan of the Riou will illustrate the hydrological and depositional processes at the knick point between the steep talweg of the Riou torrent and the sub-horizontal river bed of the Duyes.



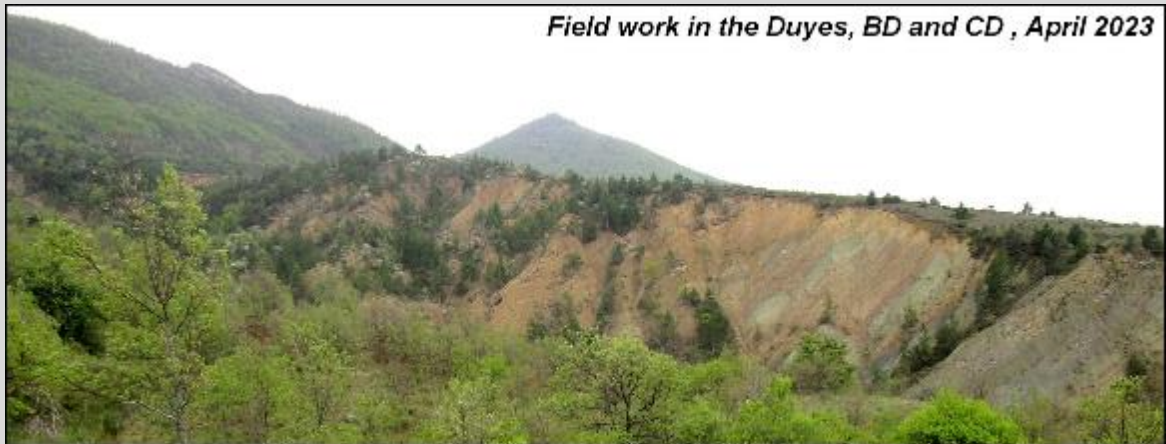
Map from Géoportail IGN (<https://www.geoportail.gouv.fr/>)



Size of the culvert under the Thoard bridge

Few words on ...
the geological field trip, 19 June 2023

Cf. provisional program of B. Deffontaines. To be completed...



Geomorphometric data and maps computed from the DTM:

The most commonly used information derived from the DTM relates to slopes and aspects, which are two specific components of the topographic first derivative. Composite map of slopes (Map 3) and shading (**Map 4**) overlaid with other layers of information such as catchment basin are useful to observe the general setting of landforms as exemplified in Map 5. There are also other measurements derived from aspects like south facing slopes (Map 6).

The maps of slope gradients in percentage (**Map 7**) and degree (**Map 8**) are key information to define various landforms such as riverbeds, alluvial fans, piedmont, scree slopes and cliffs related to hydrogeomorphological processes or to the geological structure.

As we will see, a set of more in-depth information and landform depictions can be measured such as curvatures, convexities, catchment and sub-catchments basins, talweg and river networks with their hydrographic characteristics such as length and distance to the outlets, and also hydrological proxies of surface and subsurface flow patterns. It build up a multilayer hydrogeomorphometric database relevant for many GIS applications in hazard mapping and modelling.



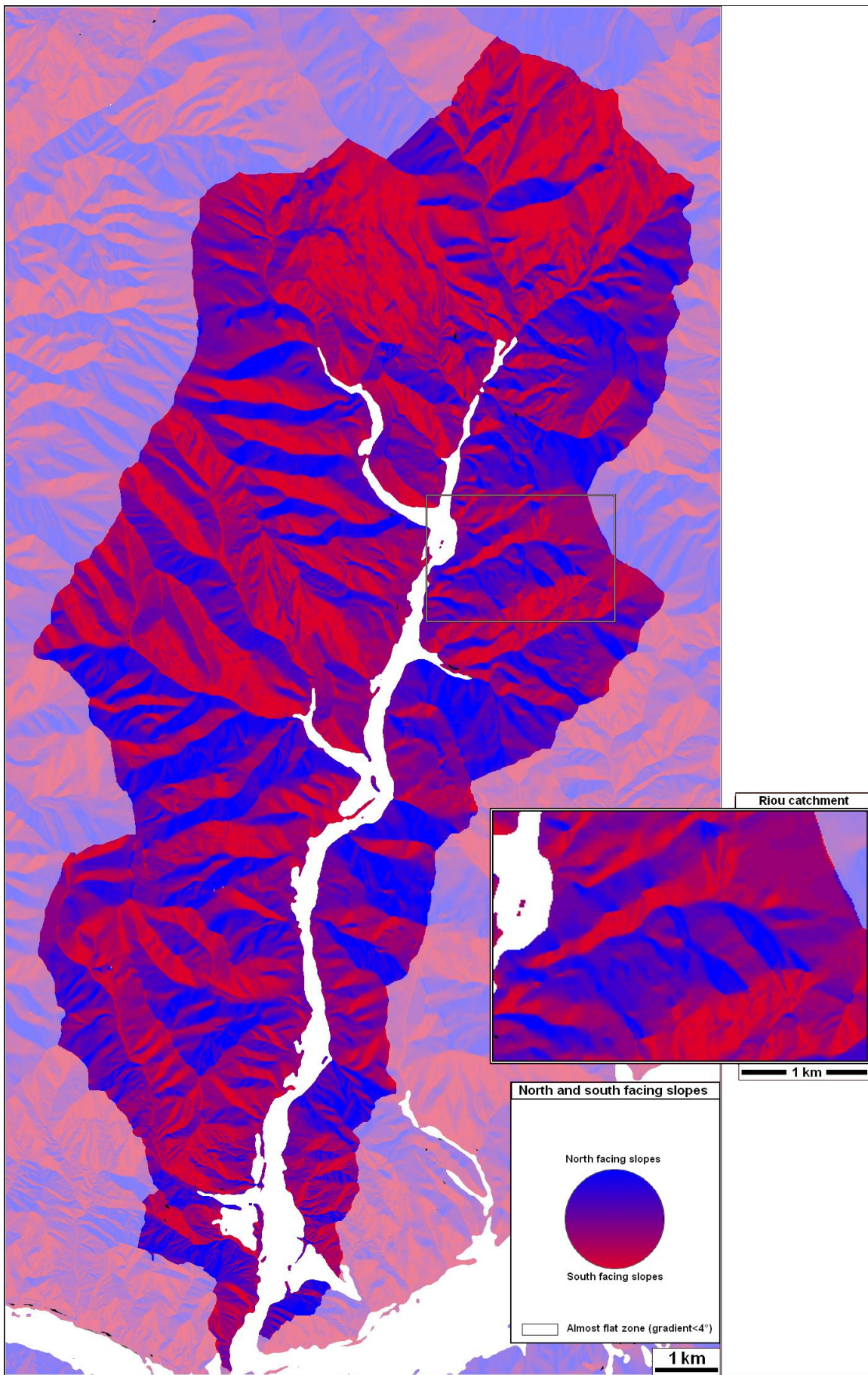
Map 3 : gray scale of slope gradients



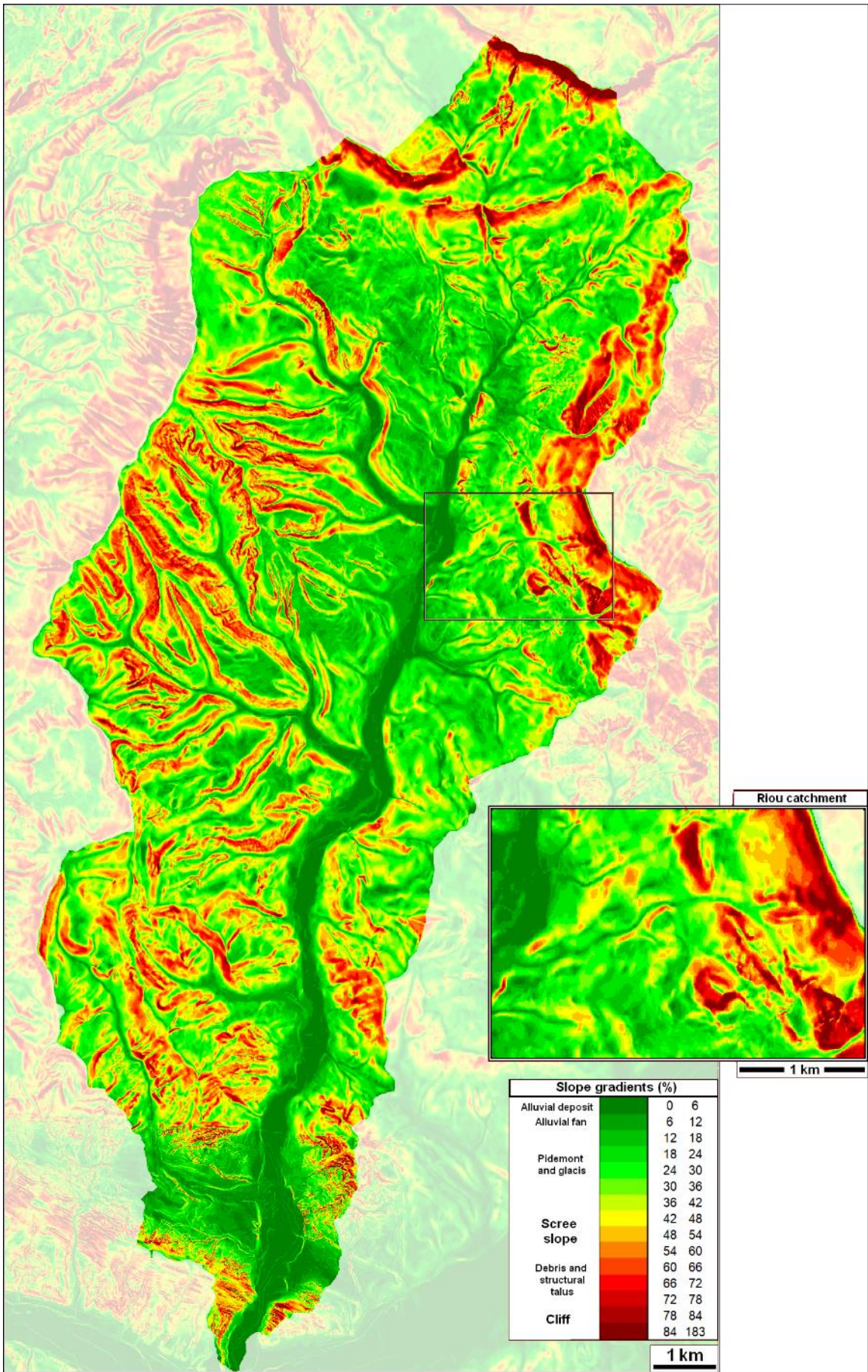
Map 4 : shading



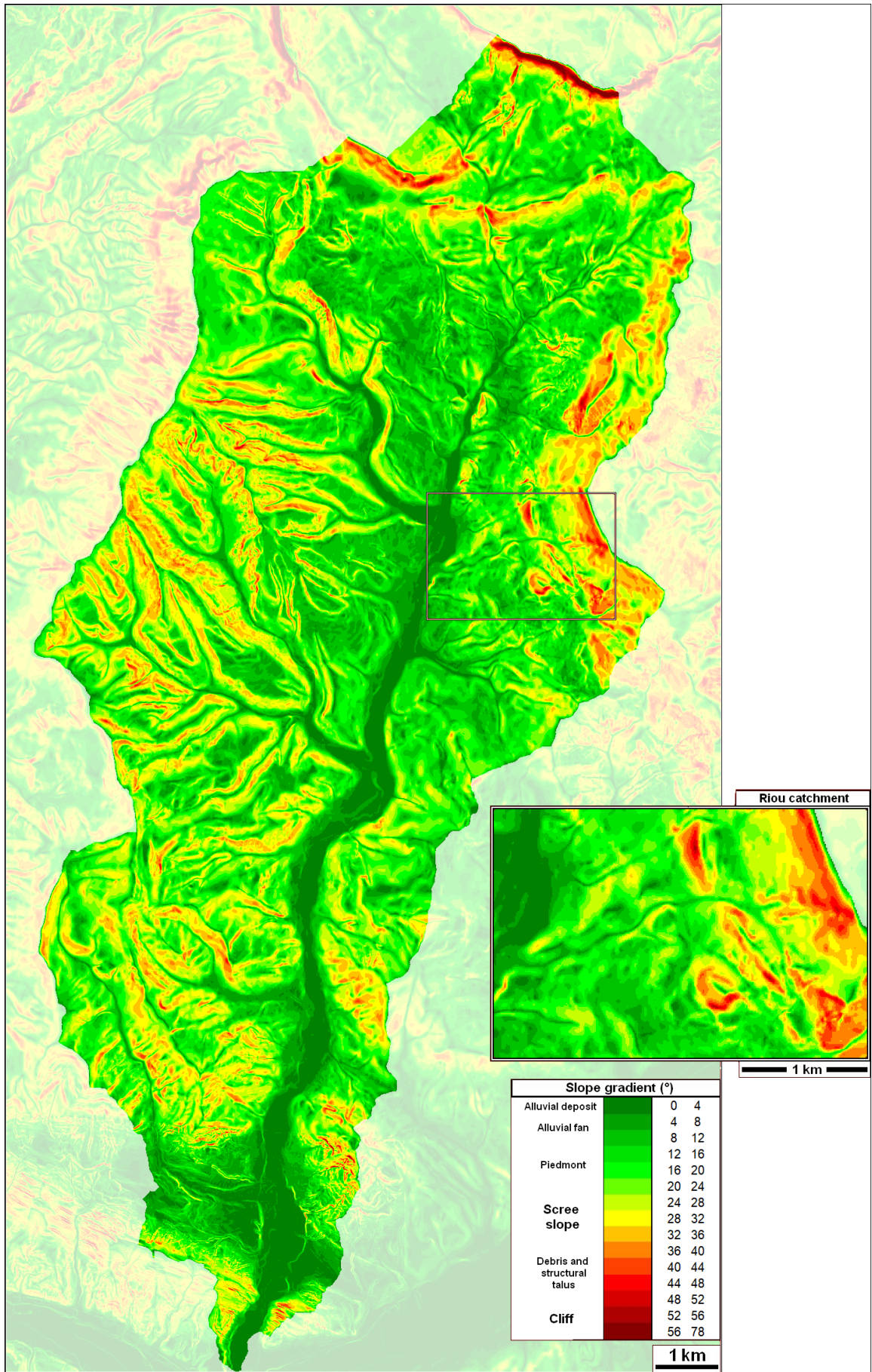
Map 5 : composite map of slope gradient and shading.



Map 6 : north and south facing slopes (ubac et adret)



Map 7 : slope gradients in percentage (%)



Map 8 : slope gradients in degree (°)

The frequencies diagram of elevation on **Figure 2A** shows that 75 % of the Duyes valley is within the elevation range 700 to 1150 m corresponding to sub alpine Mediterranean climate. From the scatter plot (**Figure 2B**) of elevations (X axis) and slope gradients (Y axis), the average gradients in percentage (%) and degrees (°)⁶ can be computed as shown on **Figure 2B**. It allows an altitudinal zoning of averaged gradients (S_a in %):

- < 720 m (S_a 1 to 28% (18°)): the lower part of the valley related to the widening of the alluvial river bed of the Duyes;
- 720-1140 m (S_a 28 to 40%): the main part of the Duyes valley and the foothills of the surrounding main ridges (Vaumuse, Siron/La Bigue, Montagne de Mélan, Geruen);
- 1140-1415 m (S_a 40 to 42% (20°)): piedmonts;
- 1415-1680 m (S_a 42 to 83% (40°)): glacis;
- 1680-1880 m (S_a 83 to 180 % (60°)): cliffs of Geruen and Montagne de Mélan (**Photo 2**).

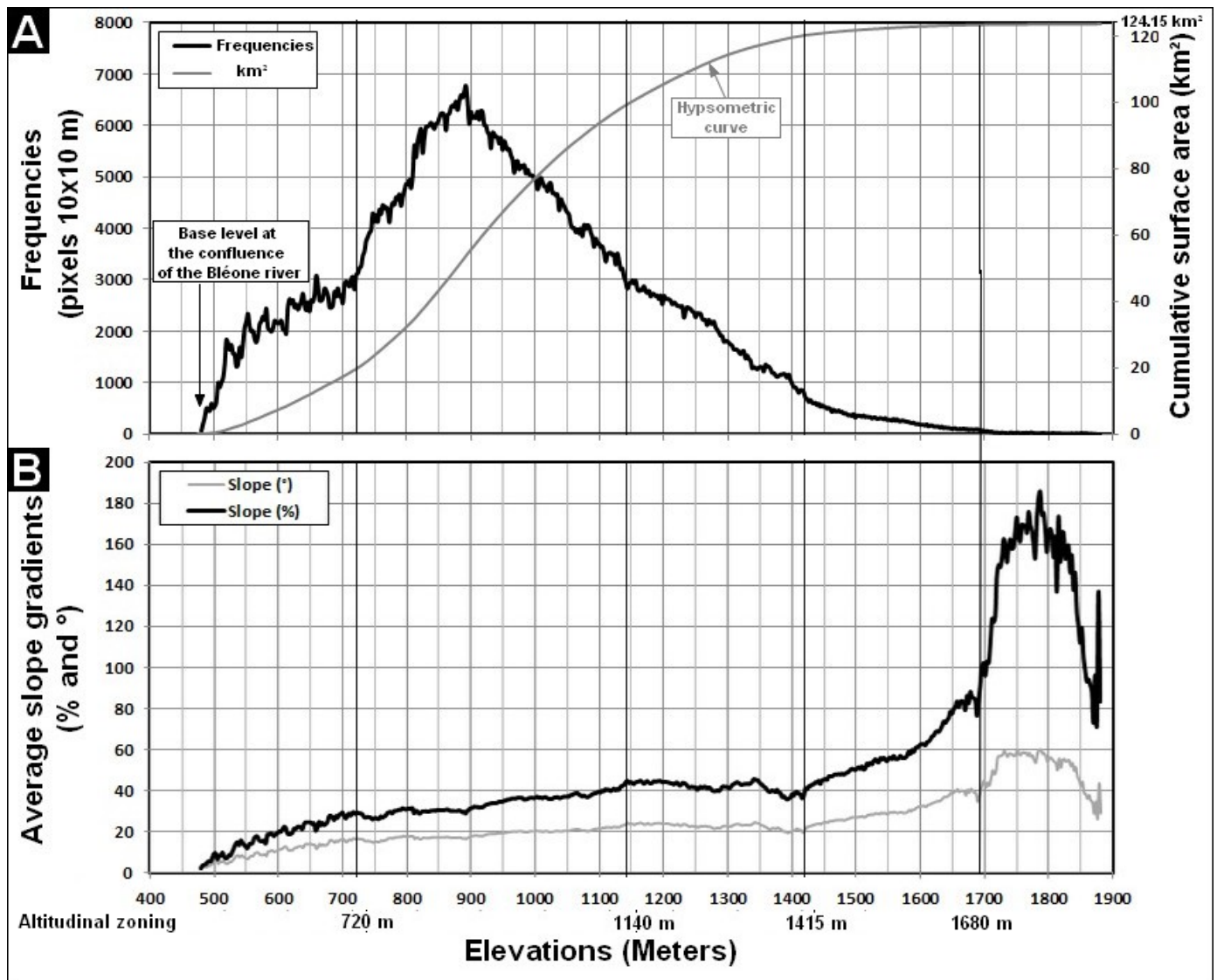


Figure 2 : combination of elevations and slope gradients on the Duyes catchment
 A./ Frequencies of elevation, local base level and hypsometric curve
 B./ Average slope gradients (% and °) according to elevation as computed from the scatter plot.

⁶ The use of percentage (%) or degrees (°) units are more or less appropriate according to the steepness. Percentages are more commonly used for shallow slopes and vice-versa for degrees. For this reason, geomorphologists use more frequently percentages while geologists express slope and inclination (dip) of geological layers in degrees.



Photo 2 : the Montagne de Mélan (Left) and Geruen (Center)
as viewed from the *bibliothèque municipale* of Thoard

Landform convexities:

Various components of the second derivative of the land surface can be compute from DTM, each of them referring to specific topographical lines of local landforms ([12] | 13]):

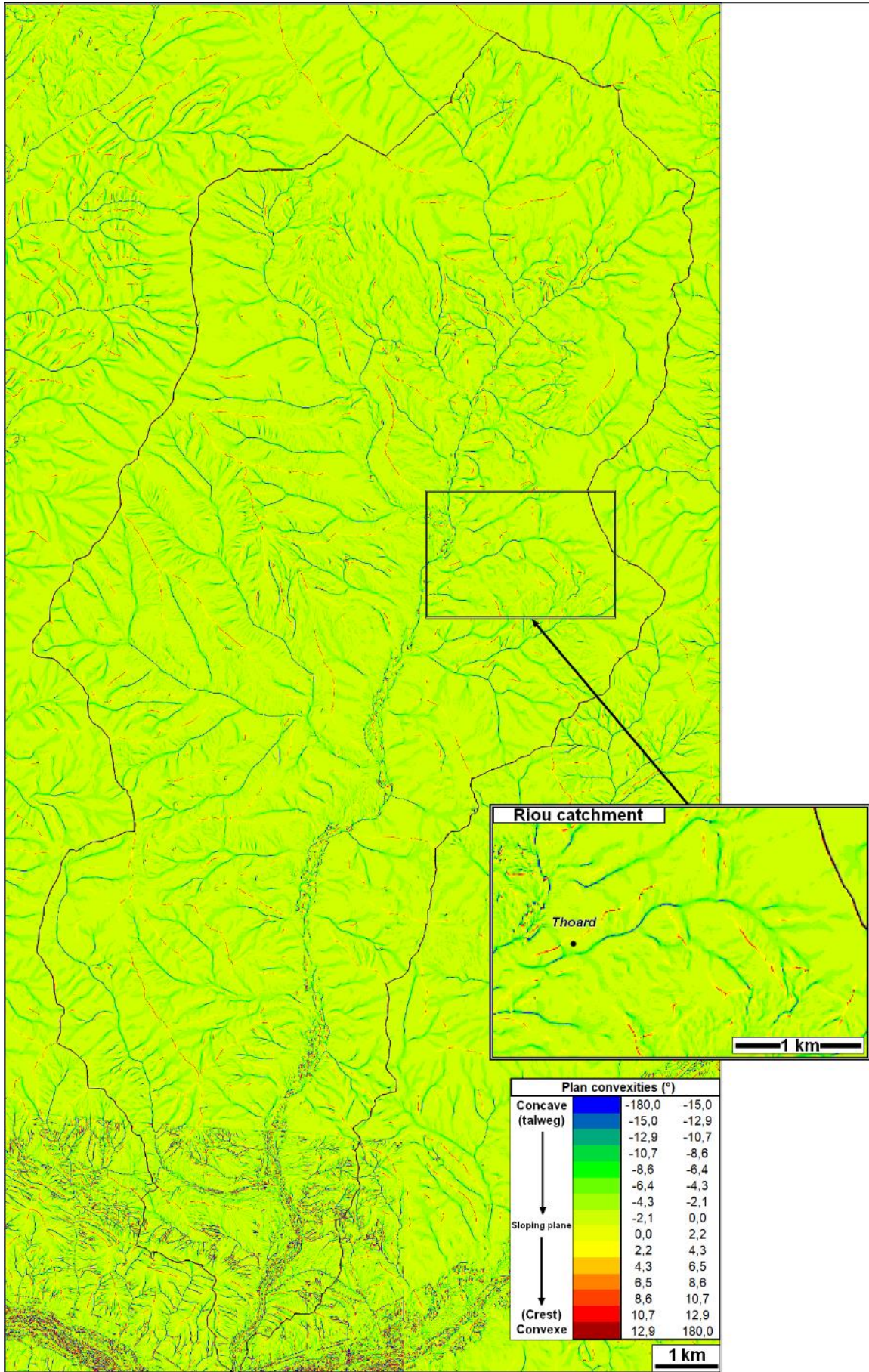
- Plan convexity (PLC) as shape of the contour line (**Map 9**): when the convex part of contour is orientated downstream ($PLC >> 0$), surface flows will be divergent as they are perpendicular to contours; then, there will be a downhill dispersal of flow. Conversely, if the convex part of contour is orientated upstream ($PLC << 0$), a downstream concentration of surface flow will occurs. In the case the contour is straight ($PLC \approx 0$), flow lines tends to be parallel with no significant dispersal or concentration. With PLC, crests, watershed (water divide), talweg and large river bed (Braided channels, alluvial benches and deposits) can be identified;

- Profile convexity (PRC) as shape of the steepest descent line (**Map 10**): when the slope gradient is increasing downstream ($PRC >> 0$), the hillslope is convex with an acceleration of runoff speed. On the other end, the speed of surface flow will tend to decrease on a concave hillslope ($PRC << 0$) due to a diminution of slope downstream. On a regular slope, so to say an incline plan, there is neither acceleration nor deceleration of runoff ($PRC \approx 0$). PRC compare to PLC are more acute to locate landforms associated with lithological features and depict the convexo-concave shape of hillslopes beside the talweg and river;

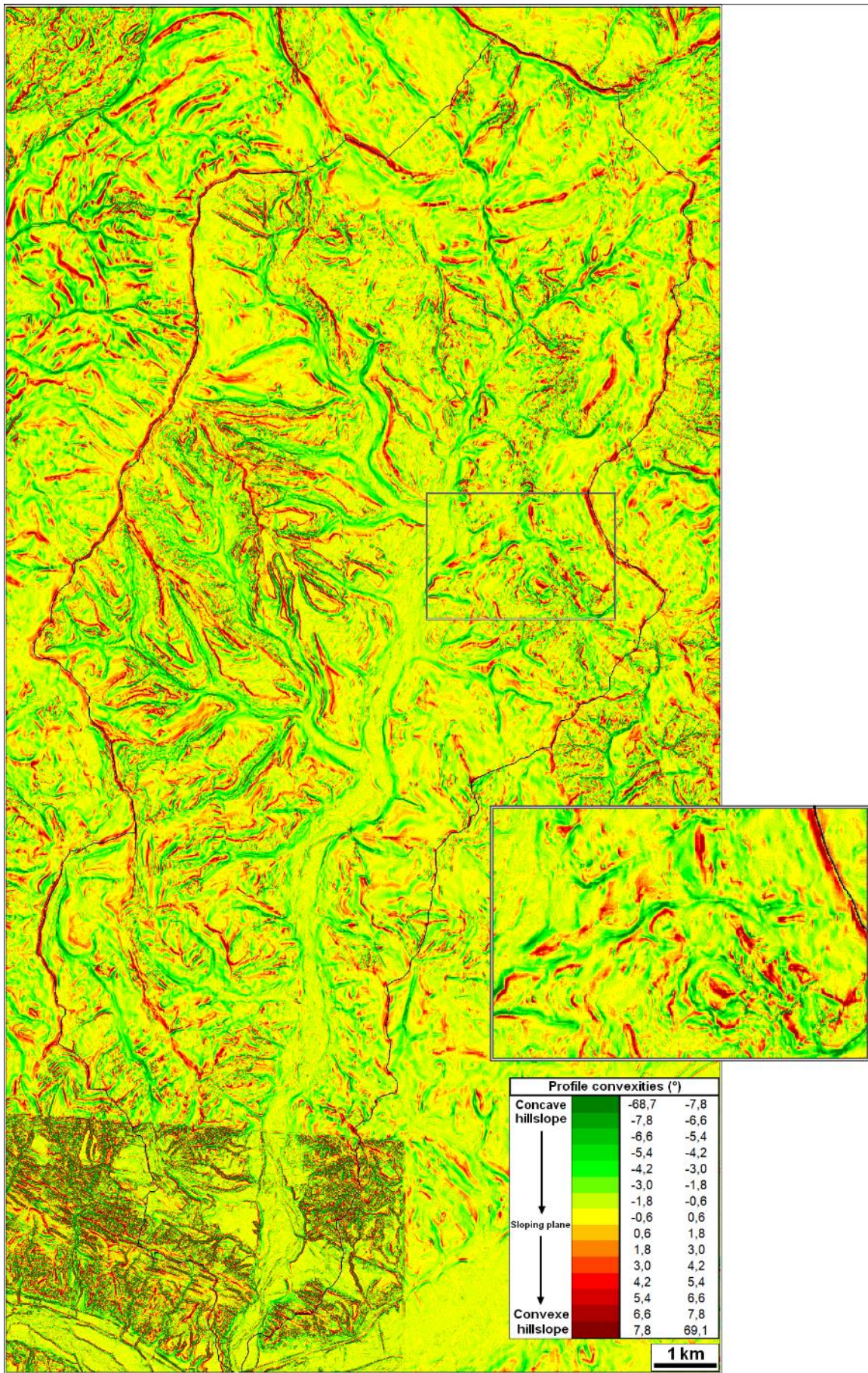
- Transverse (alias across-slope) convexity (TRC) (**Map 11**): this convexity refers to the line perpendicular to the main downstream direction.

-

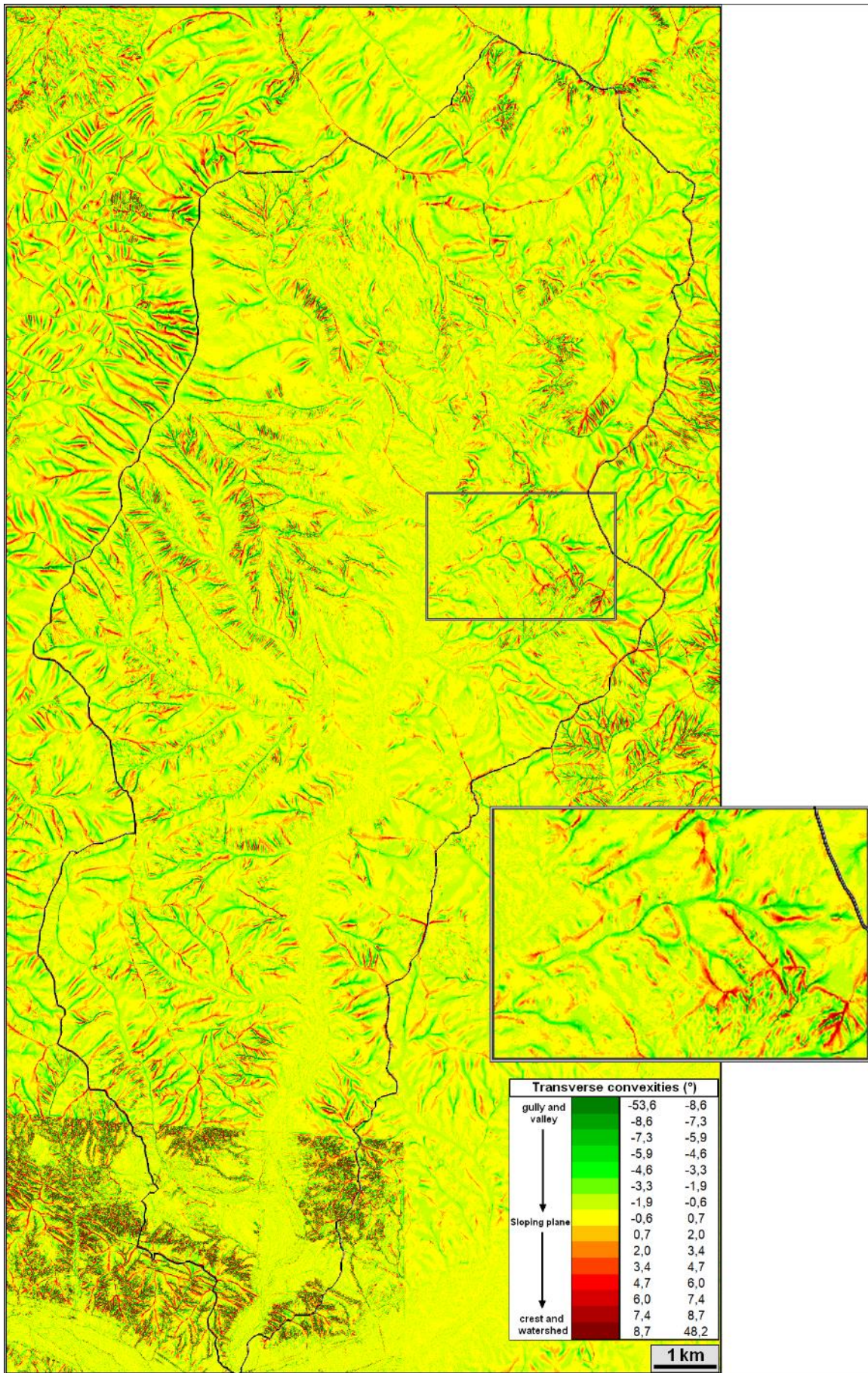
- [To be discuss with Ian Evans, Serge Riazonoff \(DEMIX\) and others in Romania in July.](#)



Map 9 : plan convexities (convexités horizontales)



Map 10 : profile convexities (convexités verticales)



Map 11: transverse convexities (convexités transversales)

Landform curvatures :

Compared to convexities, the curvatures (**Map 12**) do not refer to specific geometrical lines like contours, steepest descent lines or across-slope transects, cf. **Map 9, Map 10 and Map 11**). Instead, they measure the overall properties of local topographic curviness, so to say “roughness”. Thus, it is more difficult to interpret them in geomorphological terms compared to convexities but reflect the local bumpiness of landform (The French term “modelé” would be appropriate in that case).

On **Map 13**, the mean quadratic curvature is a synthetic measure of the landform “roughness”. A flat surface has a value of 0, while crest lines and embedded river beds have high values. Notice that this measure is very sensitive to the source of DTM as shown in the SW corner of the map.

“Roughness” : To be discuss with Ian Evans, Serge Riazonoff (DEMIX) and others in Romania in July.

Excerpt from Depraetere C. & Deffontaines B. and Riazonoff S, (2023):

“Resampling and hydro-geomorphometrical processing of dense Lidar/DEM: Relationships between landforms and hydrological processes in a Mediterranean peri-alpine catchment basin”.

To be published in the Proceeding of the Geomorphometry 2023 conference, Iasi, Romania, 8-11 July 2023.

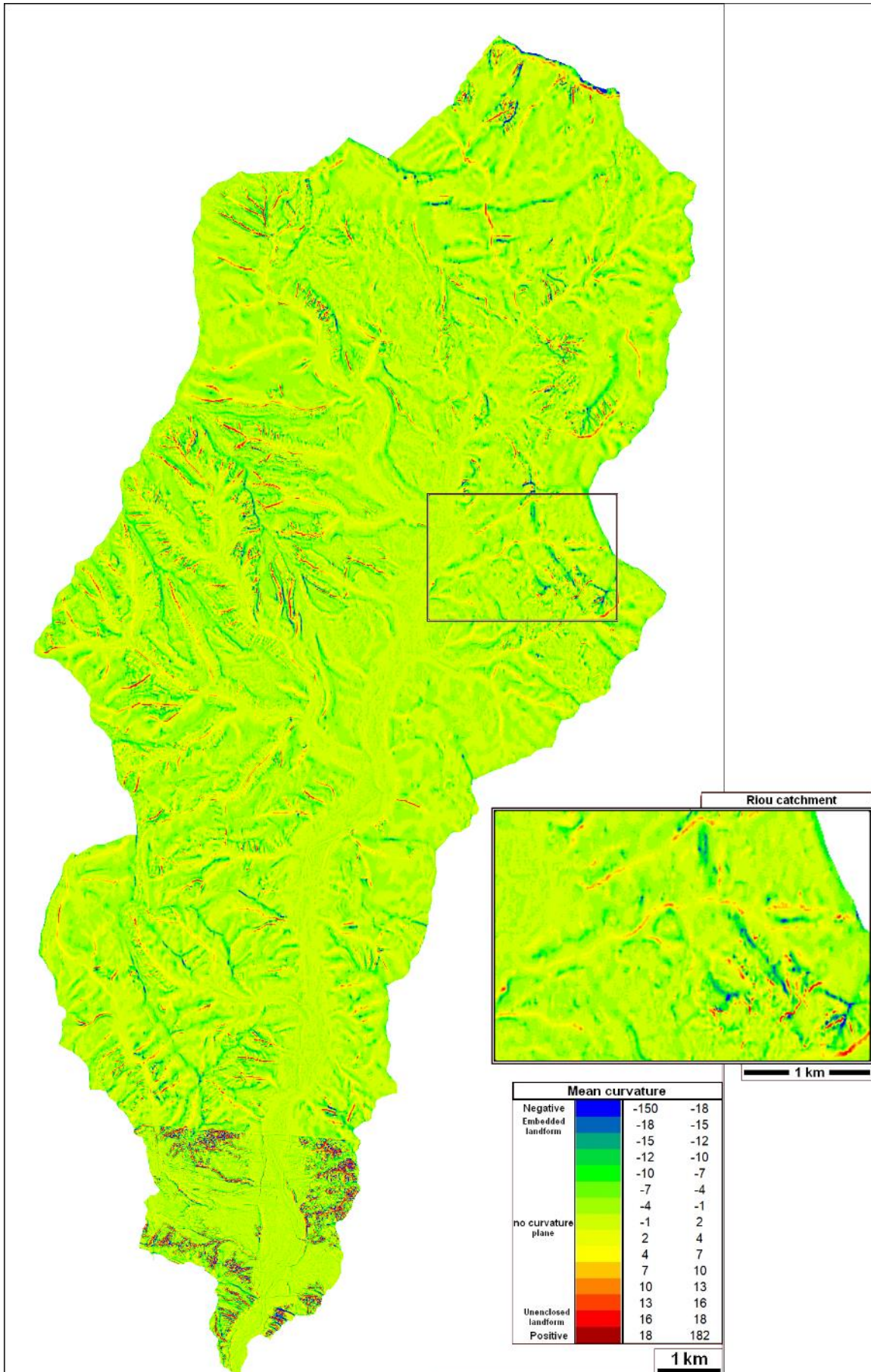
Abstract: DEM are largely used for hydrological modeling since the late seventies; most of ad hoc GIS toolboxes offer surface flowpaths algorithms suitable for hectometric and decametric resolutions. Nevertheless, the availability of finer and more accurate metric DEM unfold new perspectives both for surface water flows modeling but even more for sub-surface percolation simulation usually closely related to specific and identifiable landforms. The Lidar/DEM RGE-Alti of the IGN/france at 1 meter resolution covers entire France and some of its overseas territories; All over Europe, the forthcoming Copernicus DEM EEA-10 of the ESA at 10 meters would be soon available.

We present a DEM under sampling method from dense to coarser resolution specifically suitable for hydrological applications (SEAD method, Depraetere 2013 pp. 22-26). From the RGE-Alti 1m; this allows comparing the effect of the SEAD at 5, 10 (so to say "pseudo DEM EEA-10") and 25 meters resolution on sub-surface percolation patterns with the DRAMP algorithm (Depraetere 2013 pp. 56-61) which is a simplified variant of the Topographic Wetness Index (TWI, Beven et al., 1979, 1983).

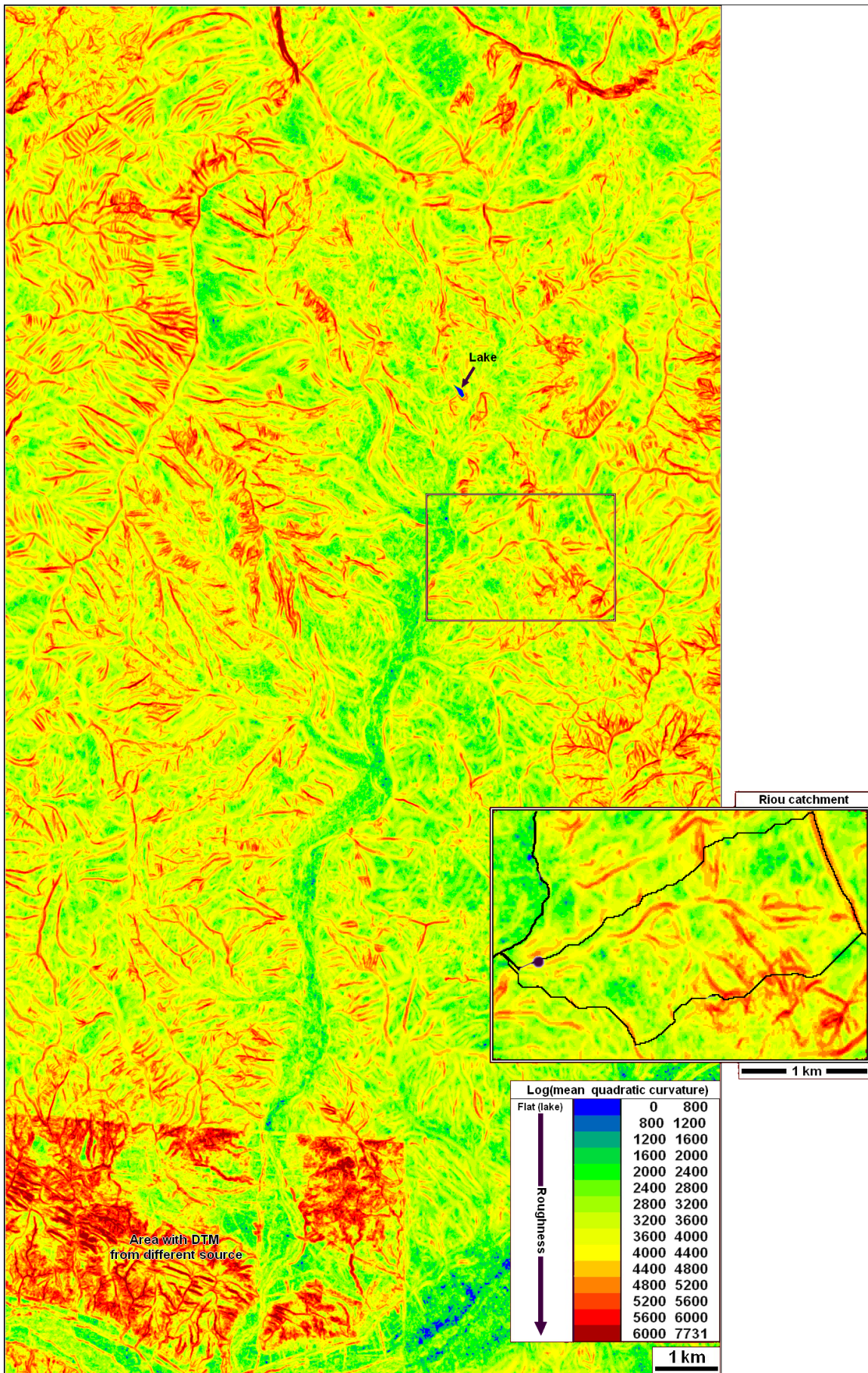
The data, methods and results are tested on the catchment basin of the Vallée des Duyes (150 km²) in Haute Provence; the morpho-tectonic context is thrust sheets made of folded and faulted layers of gypsum, limestone and shale combined with more or less indurate puddingstone and breccia on hillslopes. This catchment offers a large palette of structural formations associated with hydrodynamic landforms such as glacis, upstream reception basins, gullies, alluvial fans, fluvial terraces, stony river beds, etc.; It is representative of Mediterranean sedimentary peri-alpine regions.

Generally speaking in the scientific literature, the two terms "roughness" and "ruggedness" tend to be elusive while processing DEM at various resolutions in different morpho-structural and climatic contexts. To disentangle the two terms for the sake of geomorphometry, roughness should only relate to the landforms setting (alias Modelé [French] or Kleinformen Gestalt [German]) while ruggedness should utterly refer to the relief pattern/spacing of the land surface per se (Alias Gestaltung/Medellierung, Großformen). Both roughness and ruggedness can be quantify with appropriate geostatistical methods and compare with the resulting catchment basin, thalweg network and surface and sub-surface flowpaths extracted from DEM.

Keywords: Dense Lidar/DEM, under sampling of DEM, hydrogeomorphometry, sub-surface flowpaths, semi automatic geomorphological mapping.



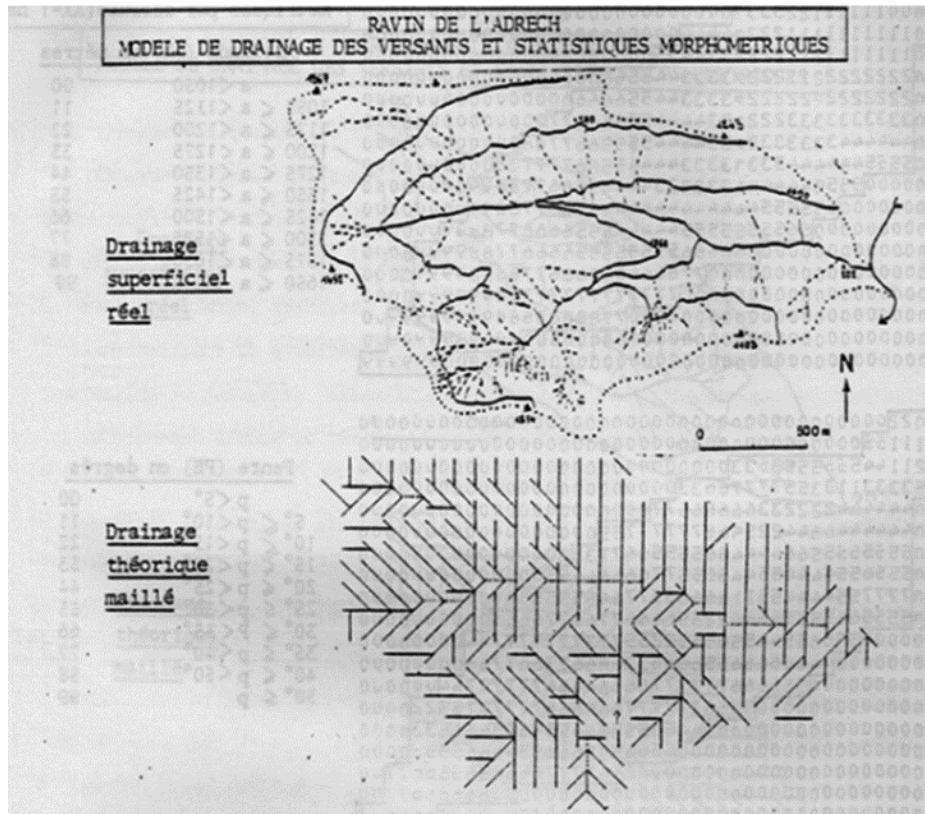
Map 12 : Mean curvature (Courbure moyenne)



Map 13 : log of mean quadratic curvature (Courbure moyenne quadratique))

Surface flow paths:

The method D8 is using the steepest descent to define monodirectional surface flow or “drainage network” in 8 directions ([3][14]). The integration of all elementary flow directions defines a “drainage model” of the topographical surface as for instance on a map from 1981 on the Adrech catchment basin (Map 14) with specific geological landform (Cf. the “velodrome” and Lame de Facibelle on Photo 3), . This simple method of flow routing is widely used in Hydrology since the early 80th to depict a transfert function on catchment basins down to their outlet.



Map 14 : monodirectionnel drainage on the Adrech catchment basin (From [3])

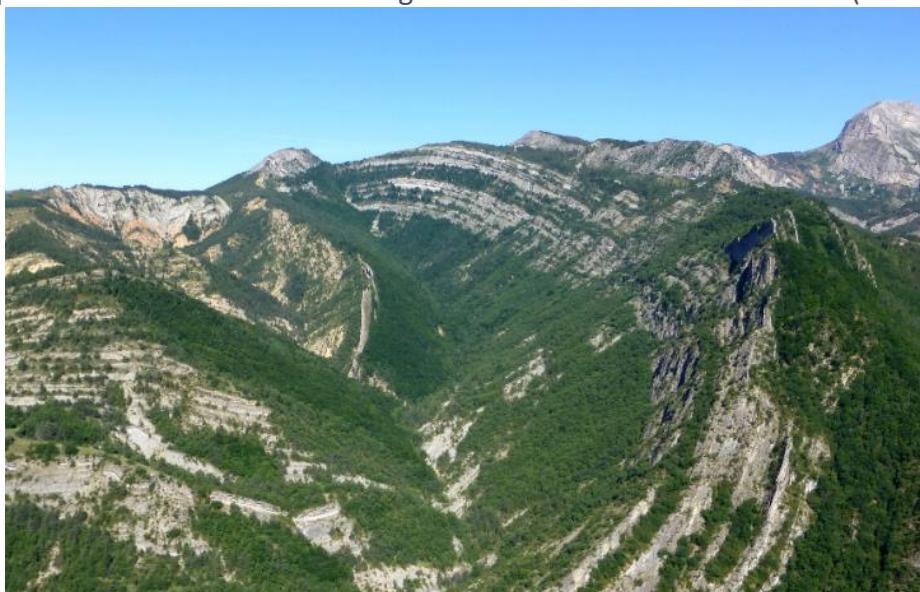
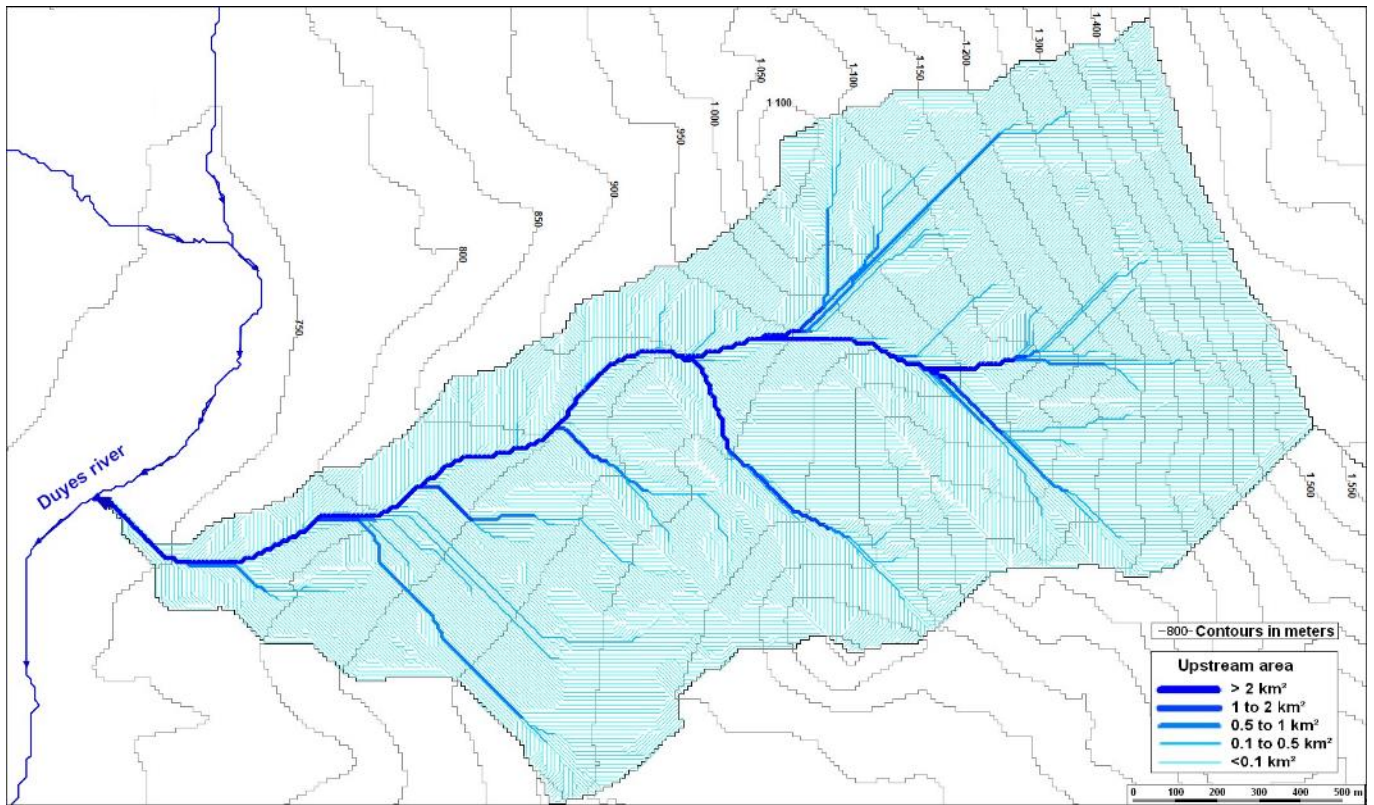


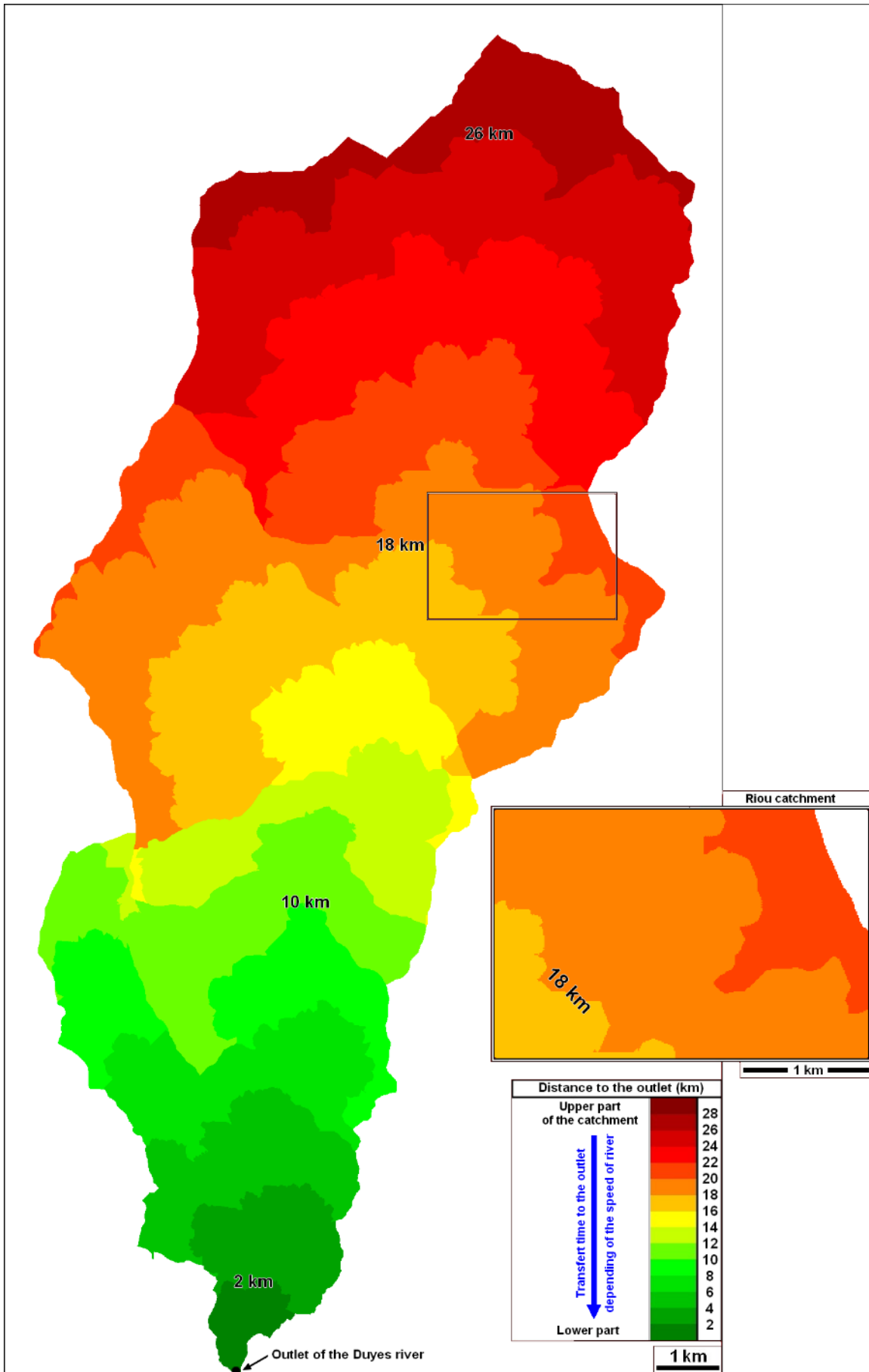
Photo 3 : view of the Adrech Valley from the village of Esclangon, Haute Provence (Photo Géoparc UNESCO Haute Provence)

The **Map 15** shows the detail of the drainage hierarchy on the Riou catchment; the main direction of surface flow according to the steepest descent flow is known for each patch of 10x10 metres (resolution of the RGE-Alti DTM).



Map 15 : detail of the D8 drainage pattern on the Riou catchment basin

The geometric distance to the outlet is one of the hydrographic geometry calculated from the D8 method (Map 16). It is worthwhile to keep in mind that this distance depends of the resolution of the DTM. Therefore, the results have some statistical value but they could not be taken as a physical representation of stream flows length from the sources. In this case with this DTM the longest drainage lines are 28 km long with their springs on the bare de Geruen and Montagne de Mélan. As statistical proxies, the distances to the outlet are used to make scatter plots of catchment long profil by combining them with elevation as illustrated on the Duyes (**Figure 3A**) and the riou (**Figure 3B**).



Map 16 : distances to the outlet in km.

These long profiles derived directly from the scatter plot of elevations (Y axis) versus distances to the outlet (X axis) shows that the slope gradient river bed of the Duyes main collector is steady at about 1.5 % up to 20 km upstream from its outlet (**Figure 3A**). The contrast in gradient between the right and left bank tributaries of the Duyes valley is striking, for instance between the Riou on the left bank and the Barbarine river on the right bank. The downstream part of the Riou is steeper with 9% slope gradient proving that there is a knick point from 9 to 1.5% at the confluence with the Duyes and explain the large alluvial fan of the Riou coalescent with the stony main river bed of the valley (**Figure 3B**).

These long profiles of catchment basins and rivers (more precisely talweg) are a standard scatter plot by-products from DTM.

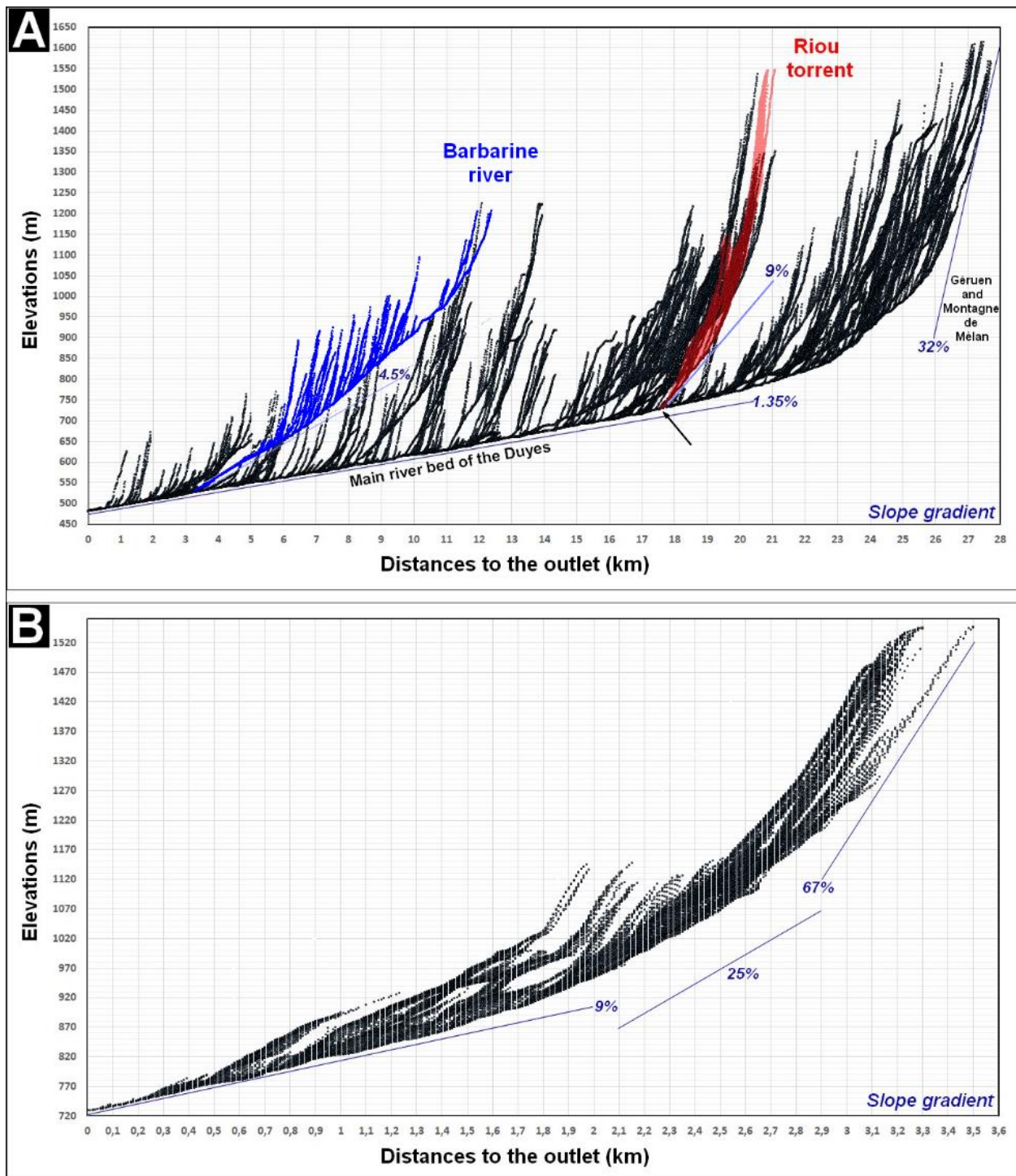


Figure 3 : long profile of catchment basins from distance to the outlet
A./ The Duyes catchment B./ The Riou catchment.

Another common by-product is the hypsometric integral either for mountains or catchments. For a given altitudinal magnitude, the potential energy of the topography within a catchment basin in relation to the base level can be expressed as an hypsometric integral ([29]) corresponding to cumulative frequencies from the minimum elevation (base level) to the highest point (Usually on the water divide at the head of the catchment). The **Figure 4** corresponds to the standardized hypsometric curve (SHC) of the Duyes and the Riou catchments.

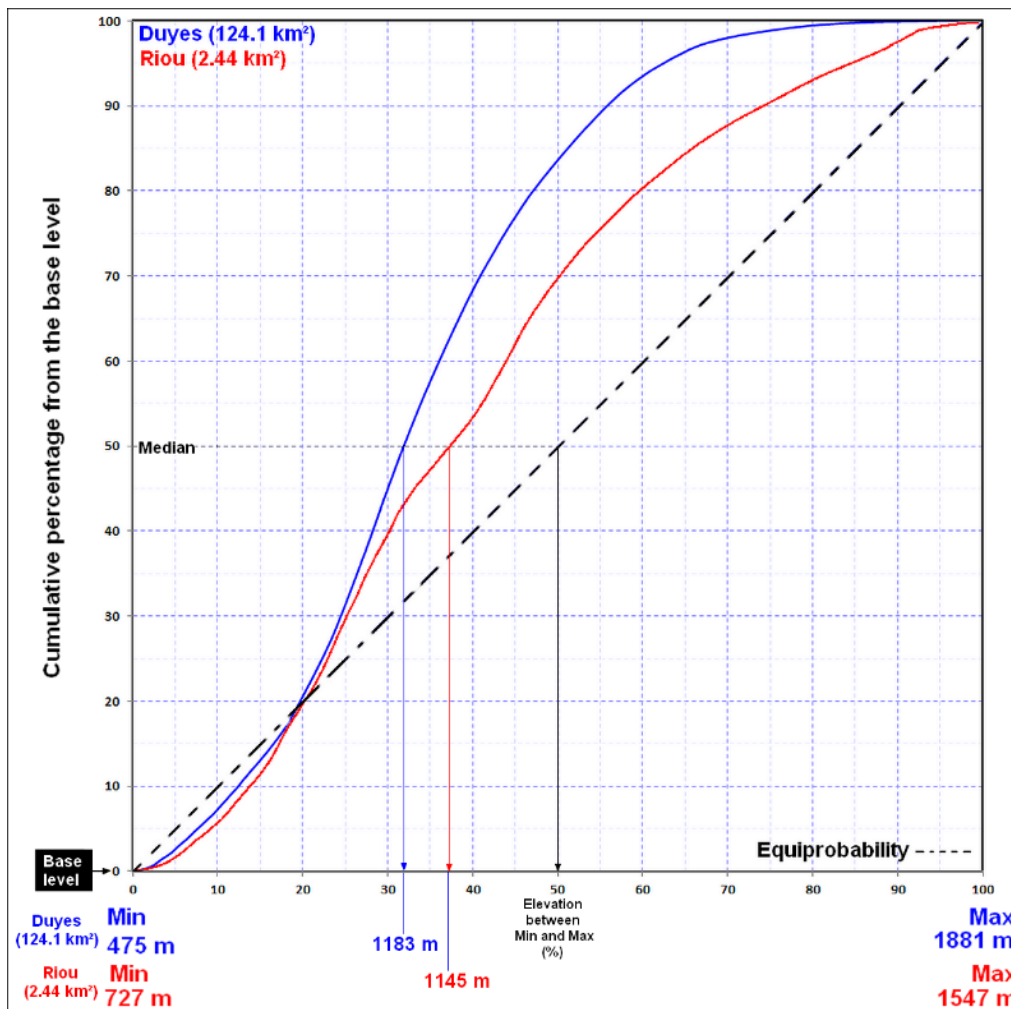


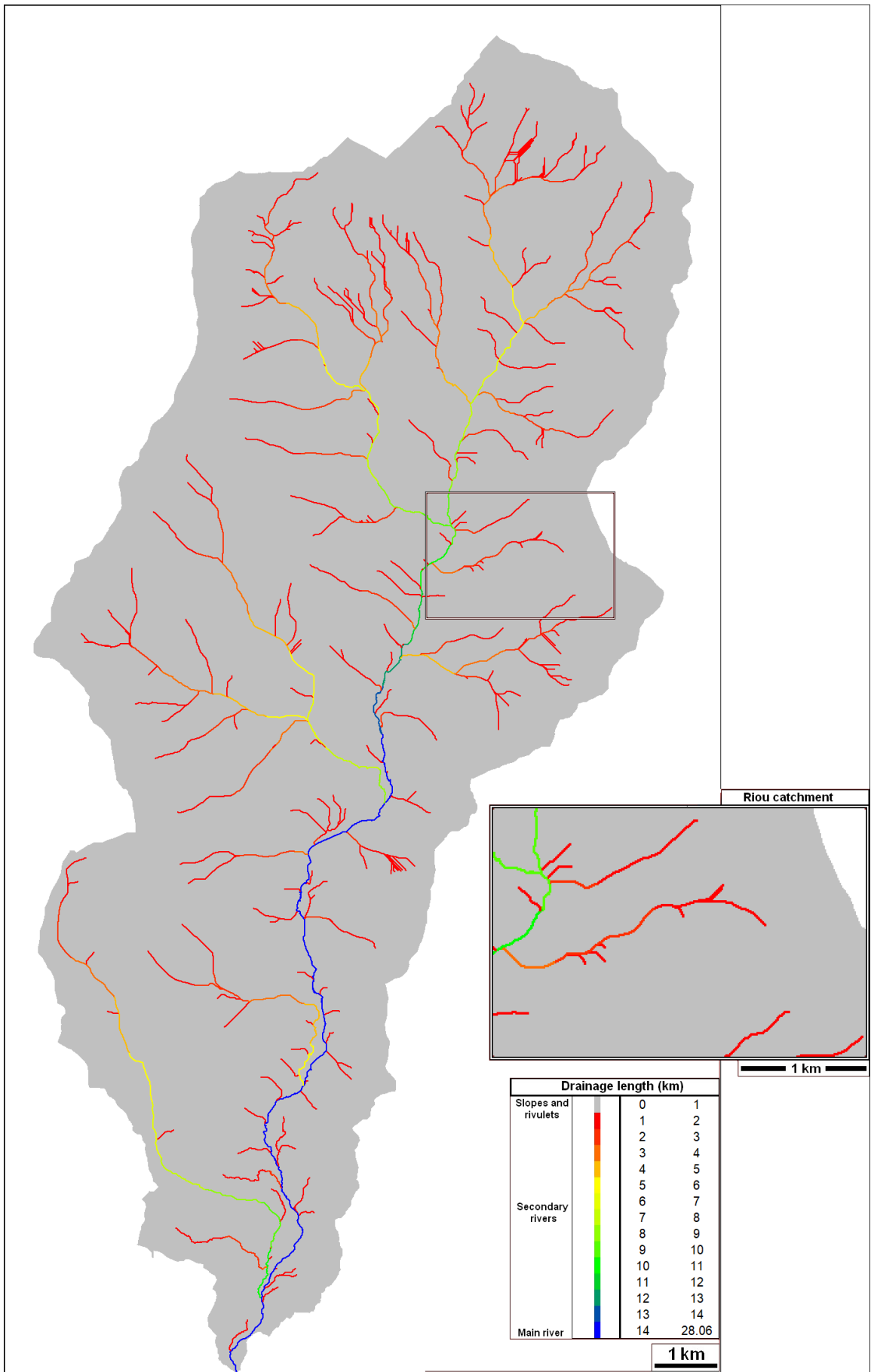
Figure 4 : the standardized hypsometric curve for the Duyes and the Riou catchments compared to the equiprobability line (All elevations have the same frequency).

Their SHC could be compared to the case of a theoretical surface presenting an “equiprobability” of elevations (i.e. a rectangular tilted plane with regular slope along the long axis) with a straight line SHC as shown on **Figure 4**. The surface below the SHC corresponds to the volume above the base level and gives an estimation of the potential energy of land mass but also of runoff flowing on surface after a rain.

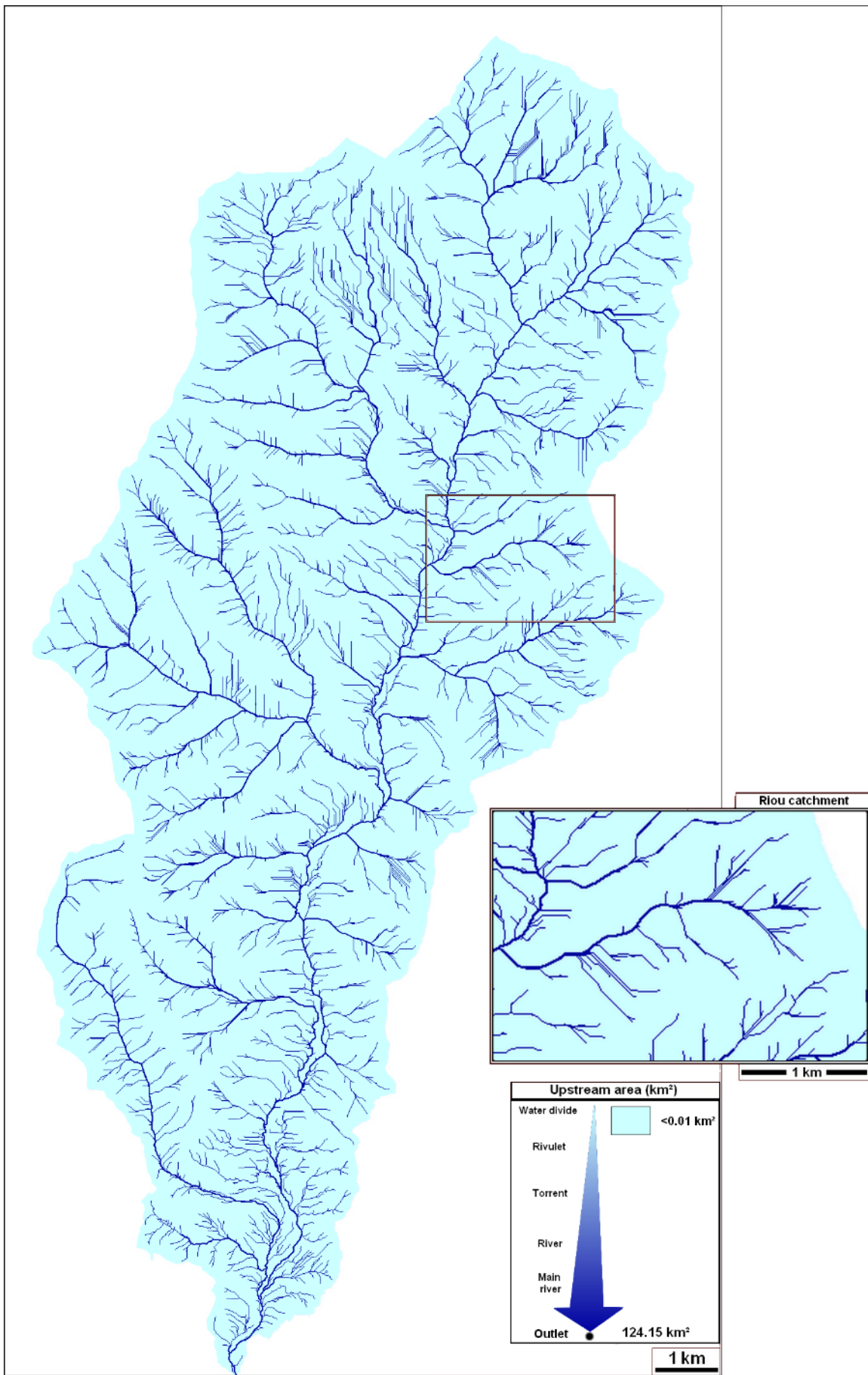
Taking the equiprobability theoretical case as a calibration reference for the integral (SHC=1), a value higher than 1 corresponds to a surface with higher frequencies of low elevations compared to high elevation (a concave landform) and vice-versa the SHC when the value is inferior to 1. The Duyes (SHC=1.33) and the Riou (SHC=1.19) catchment present higher values than the equiprobability case (SHC=1). This reflects the concave shape of both long profiles and quantifies the fact that the Duyes valley is more embedded than the Riou valley as illustrated on **Figure 3A and B**. It was formerly used by geomorphologists to compare the adaptation of geological erosion surfaces to their base level (Davisian theory of landform evolution).

The classification according to length of drainage line of **Map 17** looks like a “river” network. Strictly speaking, it refers to the length of talweg which is topographic features while the “hydrological length” of rivers depends of the amount of stream flow: during flooding the length of the river axis is shorter than during low water. In practice, there are often confusion between the “blue lines” defined as rivers on the map and talwegs as collectors water coming from upstream.

The surface of the upstream catchment is an important measurement to define a threshold for hydrographic network for mapping purpose on the map because the minimal hypothesis is that larger the upstream area (or drained surface) higher the probability to have river flow (**Map 18**). A threshold T corresponding to a minimum upstream area empirically selected is often used to define sub catchments river sections and confluence as exemplified later (cf. $T > 2\text{km}^2$ **Map 22**).

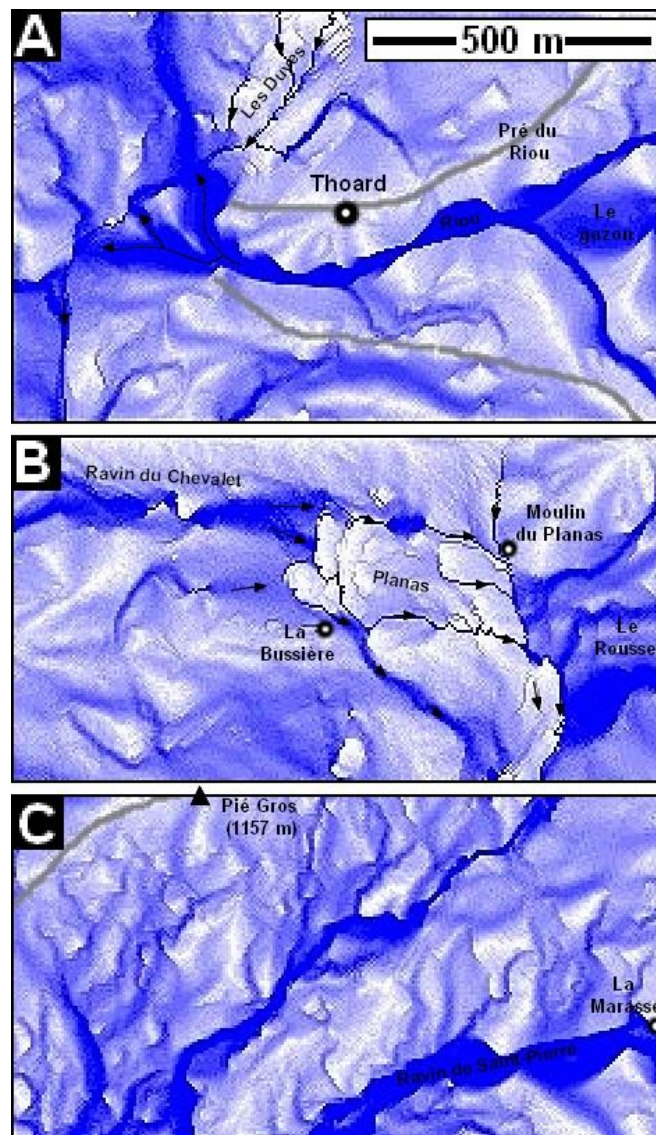


Map 17 : lengths of drainage in km (Alias length of river)



Sub-surface flow paths :

The method DRAMP⁷ as a variant of the Topographic Wetness Index (TWI, [1] [2] [17]) appears to be more suitable for hydrogeomorphological mapping of multidirectional flow paths and routing (cf. **appendix 6**) as shown on **Map 19** and **Map 20** compared to **Map 18** with the so called usual “blue lines” of monodirectional steepest descent network. Instead of the genuine TWI mapping, it must be considered as an index of potential sub surface flow (ISSF). For mapping and modelling reason, it is better to take the logarithmic value of ISSF that depict more accurately the details of potential percolation on hillslope and not only in the canyon, valley and river beds **Map 21**. On this map, there are various patterns of Log(ISSF) that could relate to specific geomorphologic landforms (i.e. alluvial fans, scree slopes, braided channels in river bed ...) and process (i.e. solifluction, sheet flow, gullyng, ...).



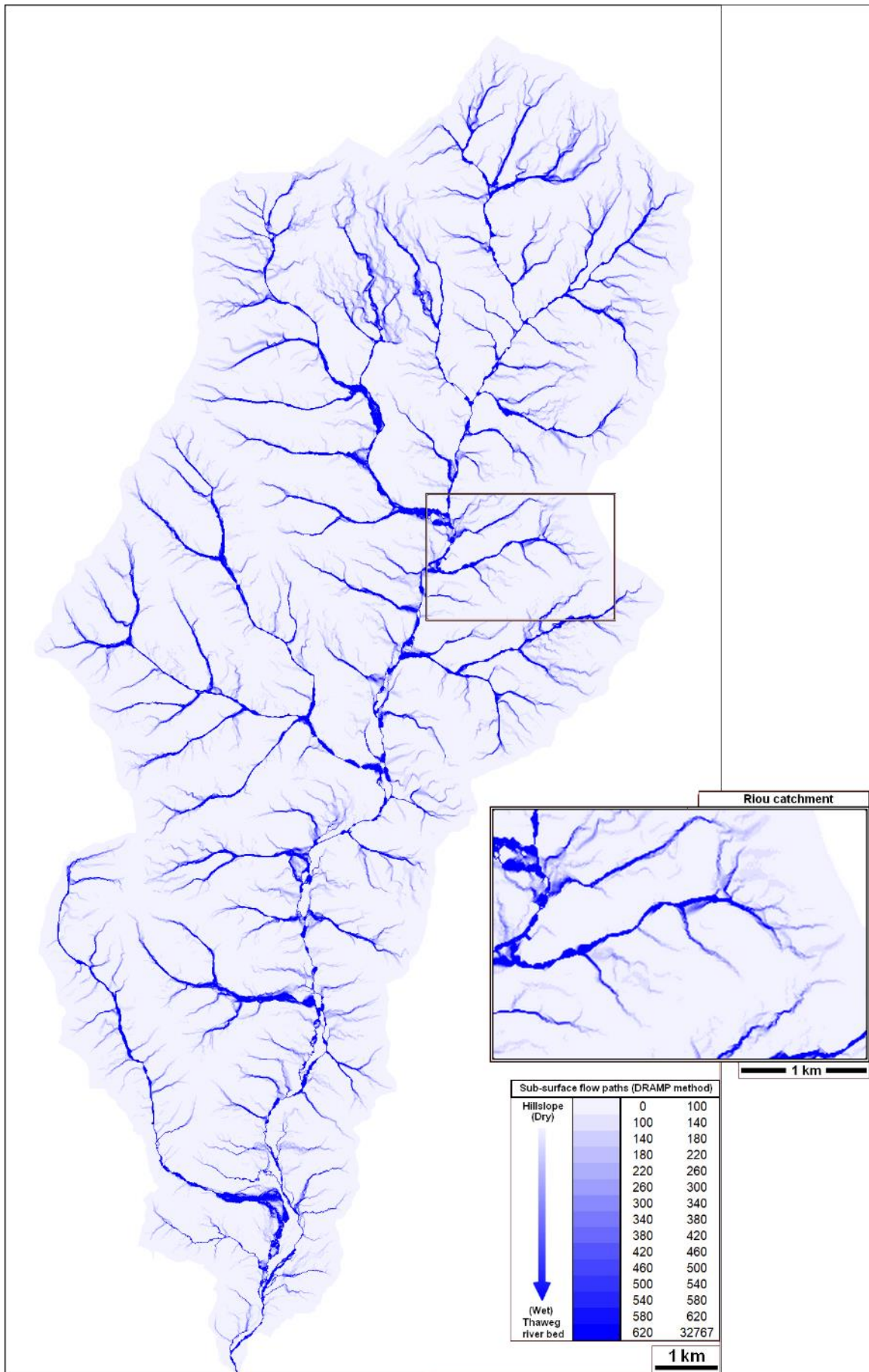
Map 19 : Examples of various Log(ISSF) flow patterns.

A./ Downstream section of the Riou with divergent flow on its alluvial fan.

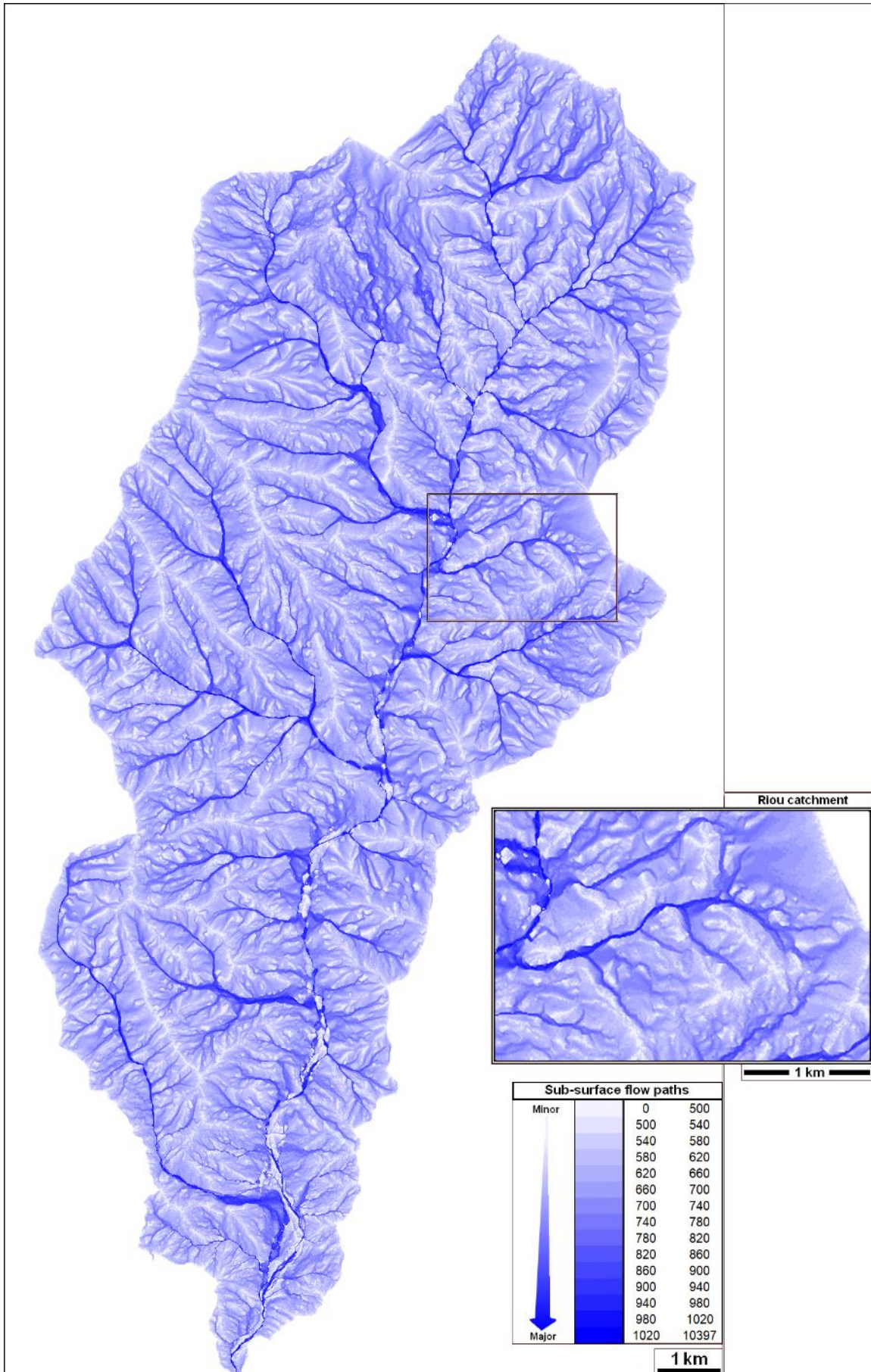
B./ Alluvial plane at the mouth of the Ravin du Chevalet.

C./ Hypodermic percolations in braid on a slope of the Ravin de Saint-Pierre.

⁷ DRAInage Multidirectionnel Probabiliste.



Map 20 : sub-surface flow paths (Method DRAMP)



Map 21 : sub-surface flow paths with Log(DRAMP) (see Map 20).

Automatic extraction of sub-catchments:

The automatic extraction of sub catchments is based on the labyrinth algorithm applied to a hierarchical river network ([4][20])⁸. On top of the automatic extraction of asset of catchment associated with rivers, the Pfafstetter-Bocquillon coding is associated automatically to river branches and sub-catchments providing an overall hierarchical and topological pattern for flow routing on the entire catchment basin via a topological coding system (Figure 5).

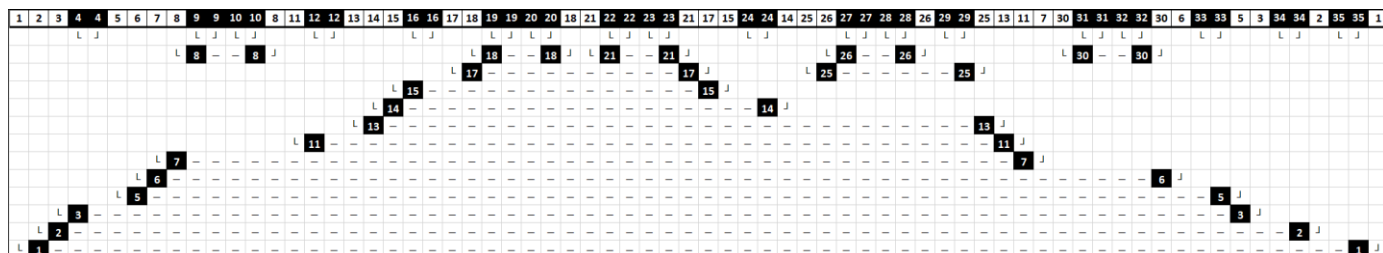


Figure 5 : extended topological PB coding for the Duyes catchment basin related to Map 22.

On **Map 18**, the primary river network defining the “labyrinth” is extracted from the DTM for upstream area > 2 km² as shown on **Map 22**. This topological coding is commonly used for distributed hydrological modelling on a set of sub-catchments and rivers ([6]). On the other hand, other usual hierarchical stream ordering methods like Horton-Strahler and Shreve as implemented in GIS toolboxes have limited relevance for hydrological modelling *per se*.

⁸ Cf. also https://en.wikipedia.org/wiki/Pfafstetter_Coding_System

Pattern of « massifs » (massives?) tessellation:

The steepest descent defines drainage line downward to the outlet as shown previously and various hydrographic features. What about “steepest ascent”? Intuition would lead us to believe that all we have to do is reverse the maximum descent, which is incorrect complex topography, as the Rasemann’s diagram in **Figure 6** shows. As we will see, the actual steepest descent lines correspond to the steepest descent applied to the “anti-relief” and convergence of these “inverted” lines correspond to crest line and water divide.

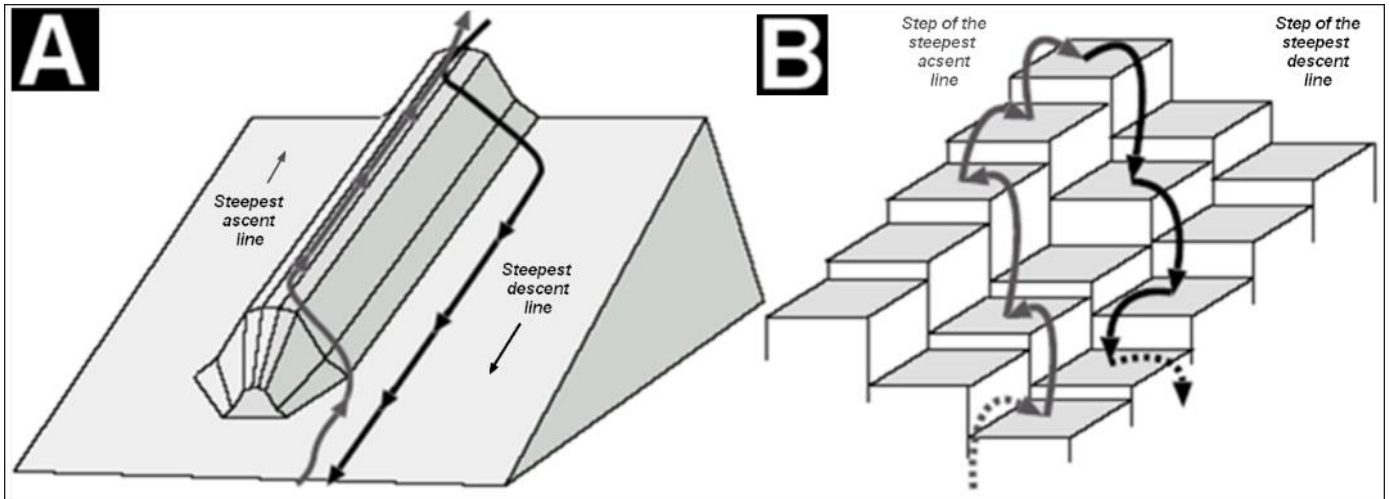


Figure 6 : influence of plan curvature on the course of a slope line. Slope lines derived up and down the slope take different courses when plan curvature occurs (from [21] [19]).

A “massif” (Massive?) is define as all the steepest ascent lines converging toward the same summit (Massifs of level 0 or “elementary massifs” (**Figure 7**). A stepwise merging via saddle points from elementary massifs delineates large and larger massifs of 1 to 5 (**Figure 7**, levels 1 to 5). The steepest ascent lines are computed alike the steepest descent (D8) but applied to the inverted elevations, that is to say that the DTM is turned upside down, low point becomes high point and vice-versa ([5][6][19][31]).

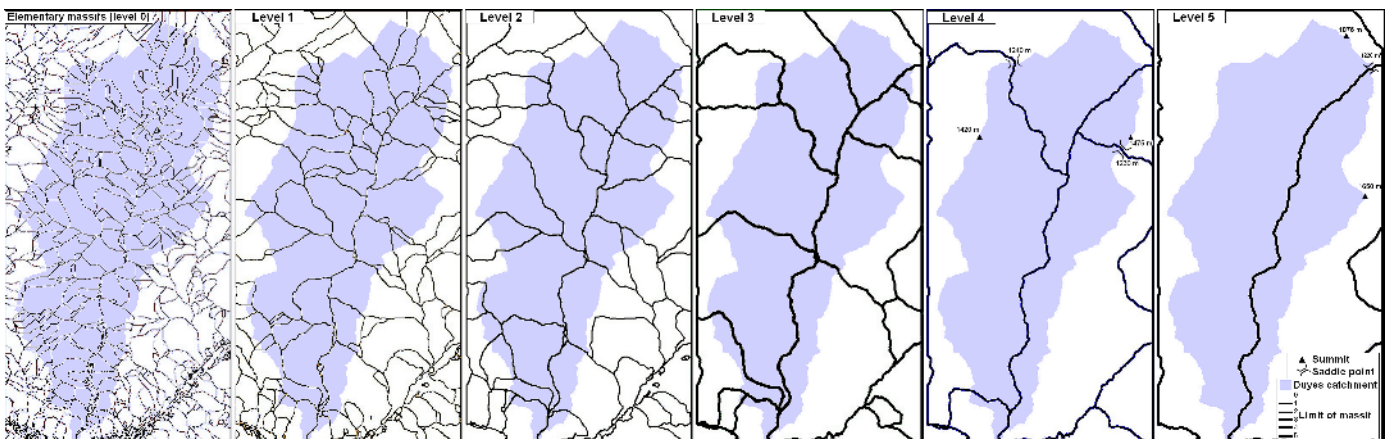


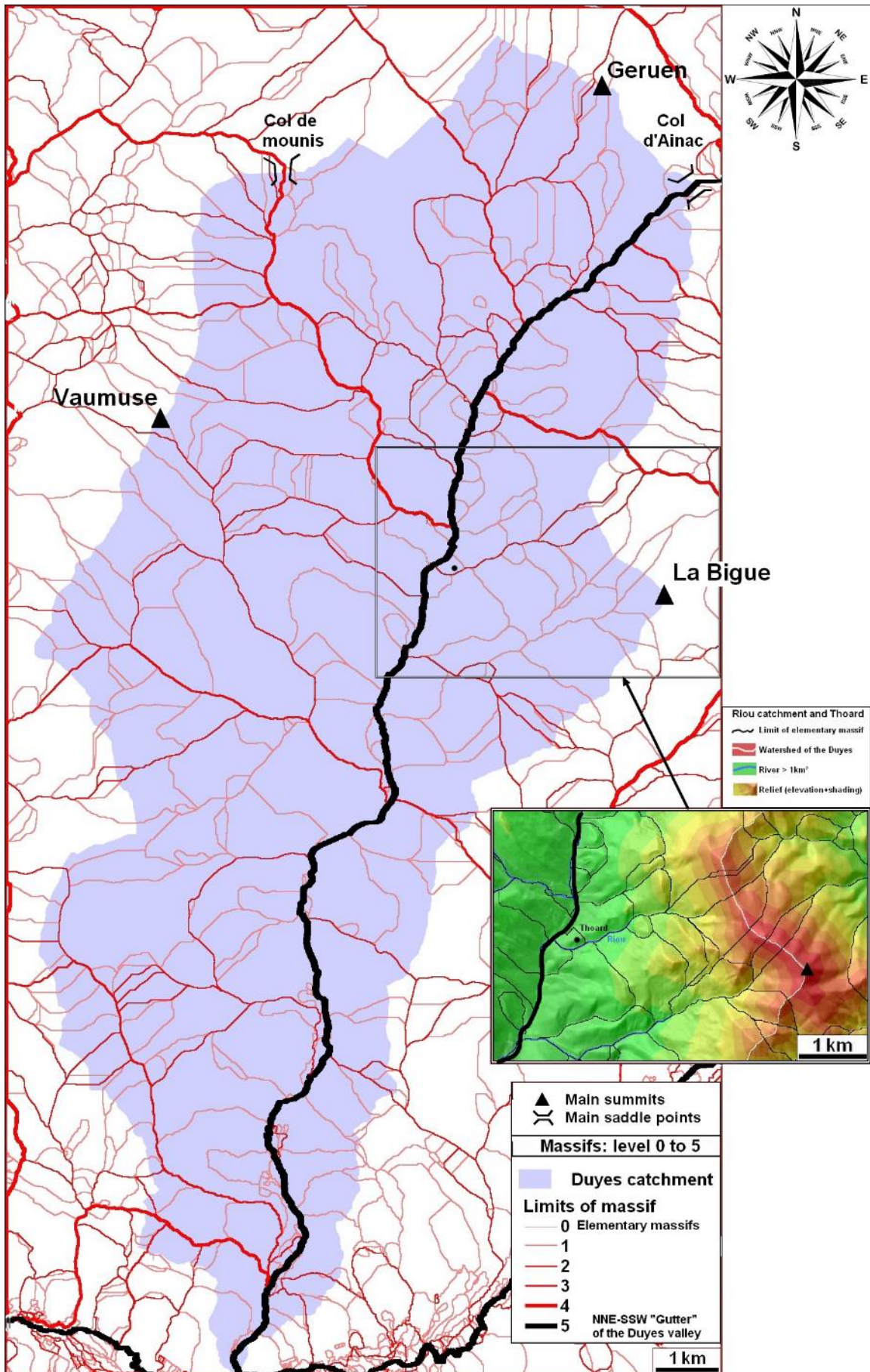
Figure 7 : maps of massif from level 0 to level 5

The limits of massif correspond to the talweg lines or lines of minimum elevation passing through the saddle points. At the highest level, in that case level 5 the partition of topographical massif reflects the major divide; on **Figure 7**, the limit of the two major mountain ranges (alias “massif”) comes along the talweg of the Duyes up to a saddle point (1220m) located between the two major summits of Geruen (1676m) and La Bigue (1650 m).

The massif tessellation of the topographical surface could be consider as the dual catchment partition of the land surface; the first focus on steepest ascent lines going to local maximum (summit) and delineate the mountain range divides between massif (“anti water divide”) while the second define steepest descent lines flowing to outlets and confluences and delimit water divide per se. All the saddle points are located at the intersection between “anti water divides” and water divides as shown on few examples along the watershed of the Duyes river (Level 4 and 5 of **Figure 7**).

The combination of all levels of massif depicts a hierarchical set of embedded landforms paving the interfluves (**Map 23**). This partitioning of the land surface reflects the geological structure including faultings and foldings, on top of geomorphological features.⁹ It is worth noting that the major divide at level 5 could be consider as the main “gutter” of the Duyes valley between the eastern trust sheet of La Bigue’s massif and the western massifs of Geruen and Vaumuse. The direction of this “gutter” is NNE to SSW while the limits of level 3 and 4 secondary massifs tend to be perpendicular to this axis.

⁹ Cf. Examples in various morpho structural contexts in the Balkanic region [5] , Martnique [6], Crete and Cyprus islands [19].



Map 23 : pattern of massifs from level 0 (elementary massifs) to level 5 including the mains massifs of Geruen, Vaumuse and La Bigue.

The areas of elementary massif range from less than one hectares mostly along the gutter (Alluvial benches in the main river beds) up to several square kilometres on the foothill surrounding the Barre de Geruen and Montagne de Mélan (**Figure 8A**). The diagram of frequencies is bimodal with two pics between 1 and 3 hectares and another in the range 0.6 to 1 km² (**Figure 8B**). Conversely, there are very few massif patches of 5 hectares. These two modes of patchiness for the massifs depend of several factors such as the the geological formations, the drainage density, the steepness of hillsides and the past and present geomorphological processes.

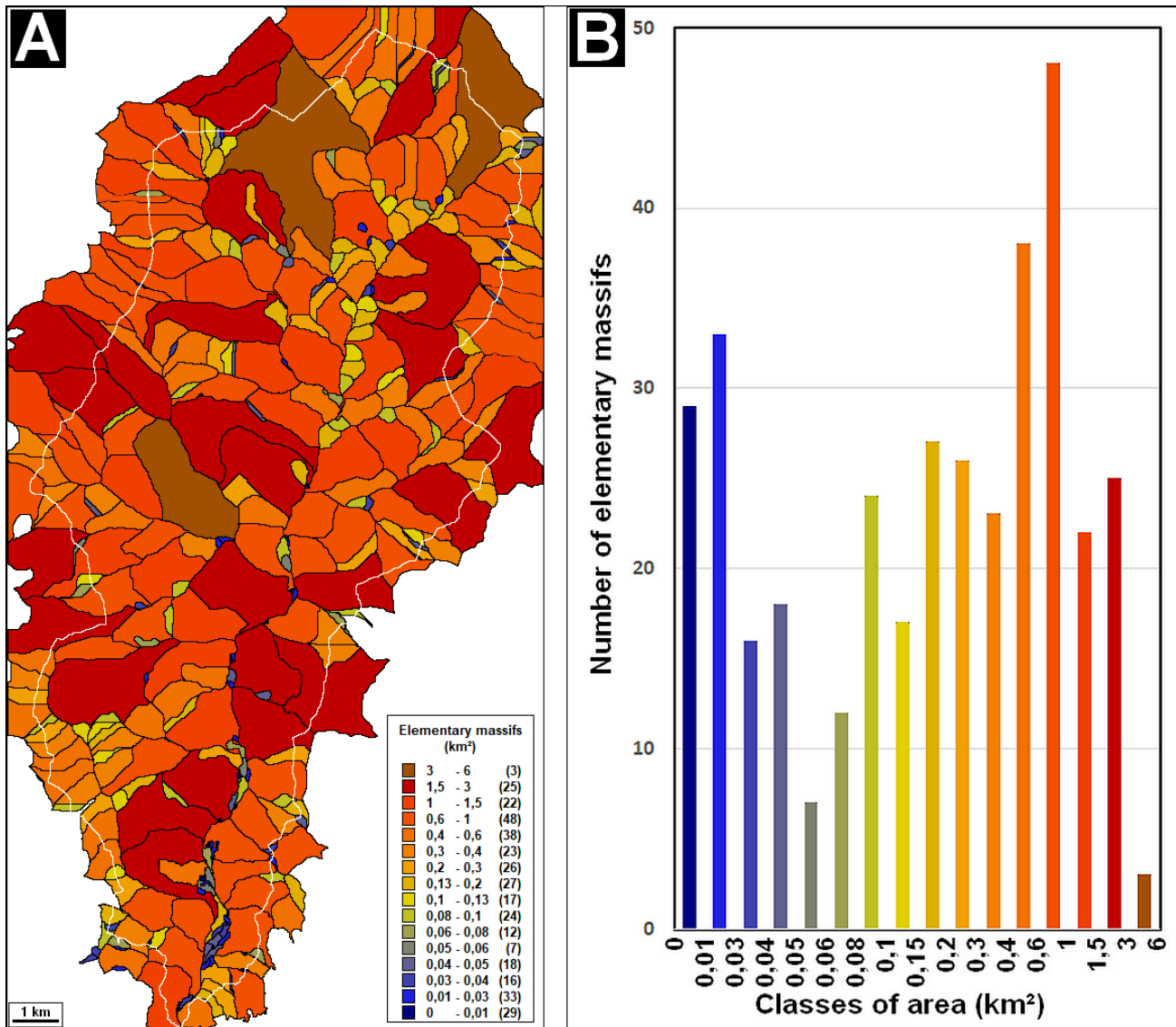
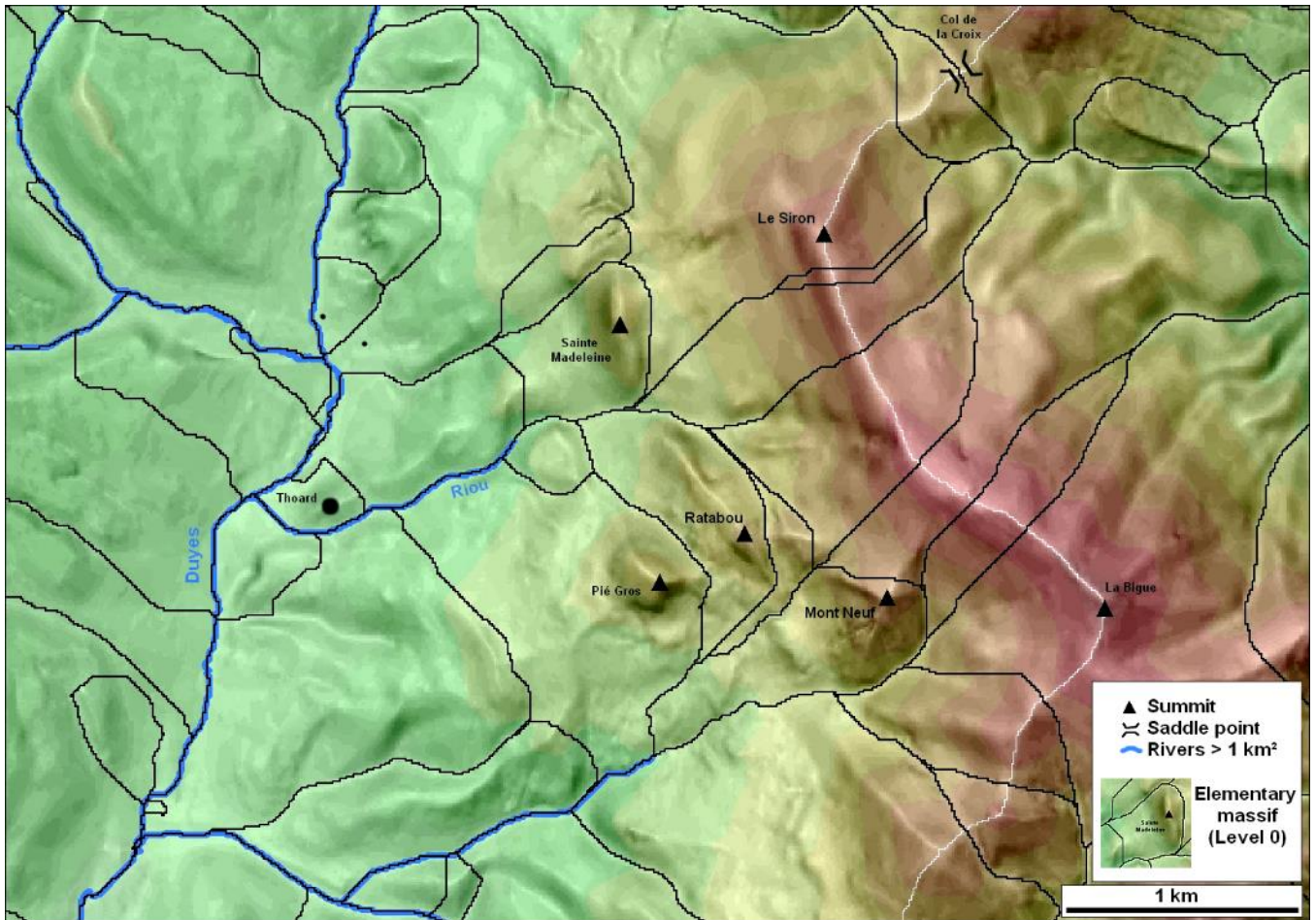


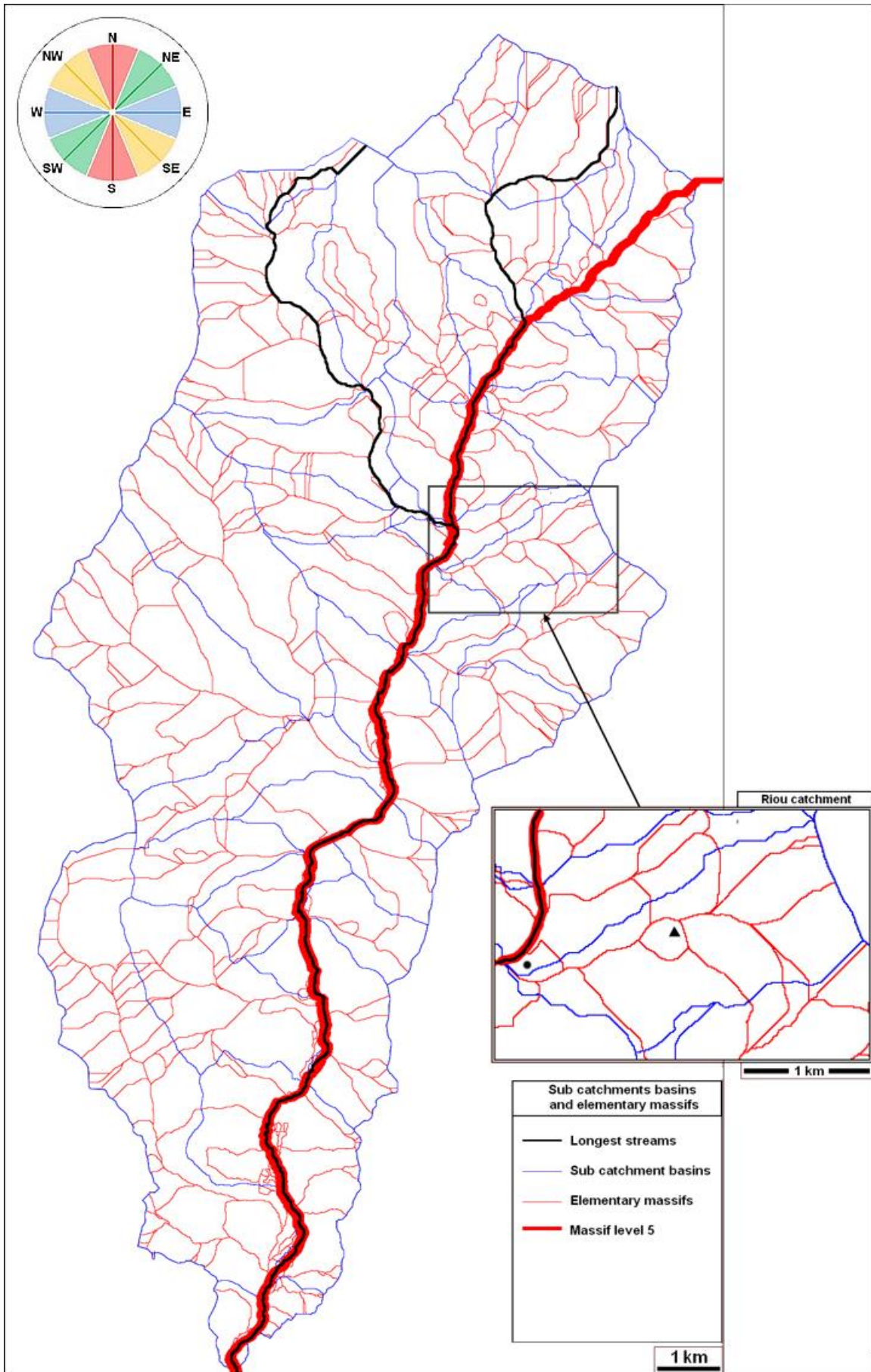
Figure 8 : Area of elementary massifs (Level 0)
 A./ Map of Massifs entirely or partly in the Duyes catchment.
 B./Diagram of frequencies of massif areas (km²)

The **Map 24** shows that the village of Thoard stands on an elementary massif related to a spur perched over the main gutter of the Duyes valley. There are also several well-defined elementary massifs on the piedmont of the major Siron/La Bigue crest line corresponding to the watershed with the Galabre valley on the East: Saint-Madeleine which is the most prominent one, Ratabou, Pié Gros, Mont Neuf and few lesser and lower massifs. There correspond to shuttles (“*Navettes*”, personal communication BD) before the crest line of the thrust sheet as shown on the geologic and tectonic 3Dview of **Figure 9**.



Map 24 : the elementary massifs at the East of Thoard and nearby the Riou catchment.

The combination of all levels of massif depicts a hierarchical set of embedded landforms paving the interfluves. This “puzzle” of land surface elements results from geological structure including faultings and foldings, but also from geomorphological as well as hydrological processes. The puzzle is even more intricate when the limits of sub-catchment, as defined in **Map 22**, are overlapped on those of elementary massifs (**Map 25**). the combination of both sub-catchments and elementary massifs delineates new elements of the topographical surfaces corresponding to hillside associated to the left or right banks of rivers or torrents with a specific massif: for instance the village of Thoard is located on the hillside corresponding to the right bank of the Riou torrent within the massif related to the spur.



Map 25 : combination of sub catchments (Map 22) and elementary massifs (Map 23).

The directional variograms¹⁰ give general insights on the amplitude of topography according to 4 directional axes and is additional to the previous processing of massifs (**Figure 10**). The ranges (correlation length) is about 4 km along the West-East (WE) axis and 5 km on the SE-NW axis ; this reflect the average width of the valley on both east and west sides of the NNE-SSW Duyes gutter.

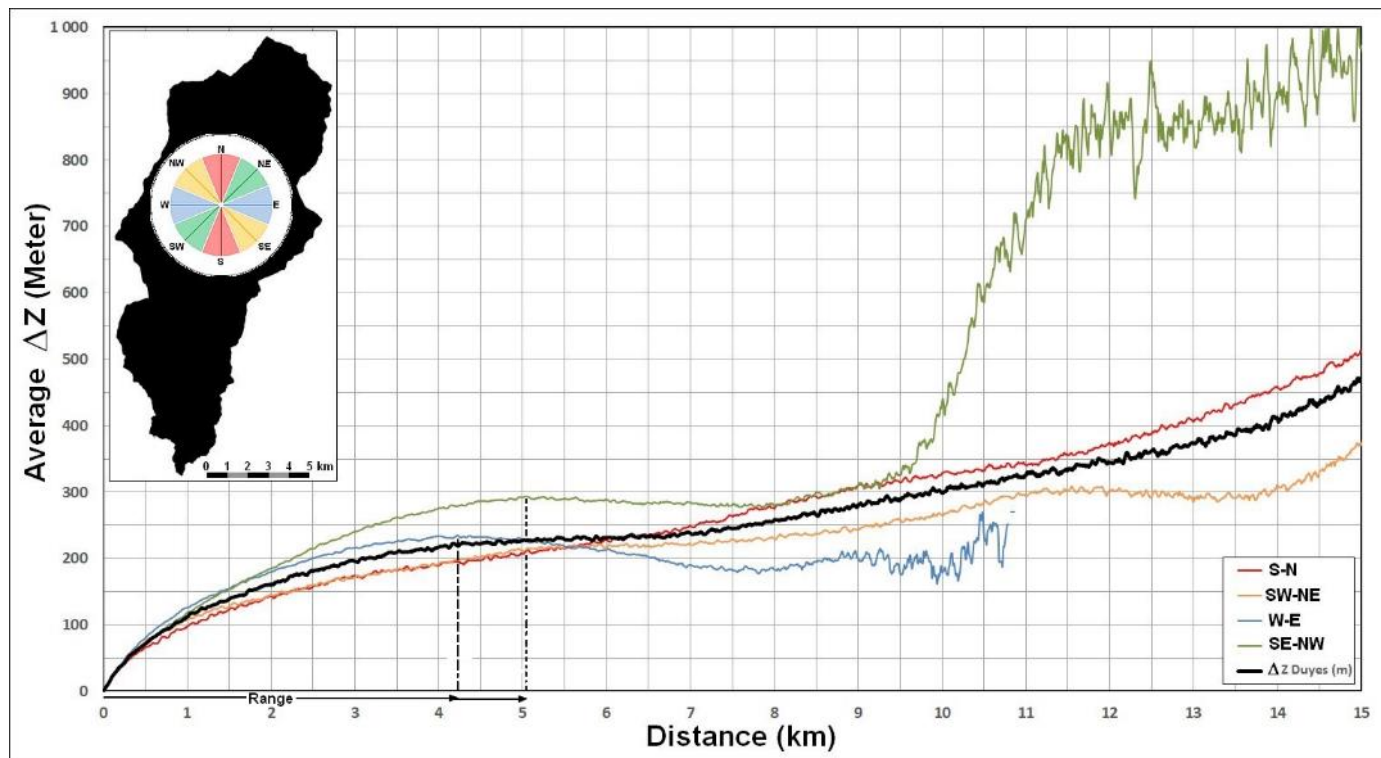


Figure 10 : directional variograms of elevations on the Duyes catchment.

As simplified 3D views, the **Figure 11** illustrates the scatter plot of the catchment on the four axis used for the directional variograms plotted in **Figure 10**. The EW view in **Figure 11D** gives a transverse landform picturing of across the Duyes catchment. Conversely, the SN view in **Figure 11B** correspond more or less to the long profile of the valley as illustrated in the previous Figure 3A.

¹⁰ Cf. the same method applied on Taiwan with SRTM DEM in Appendix 9

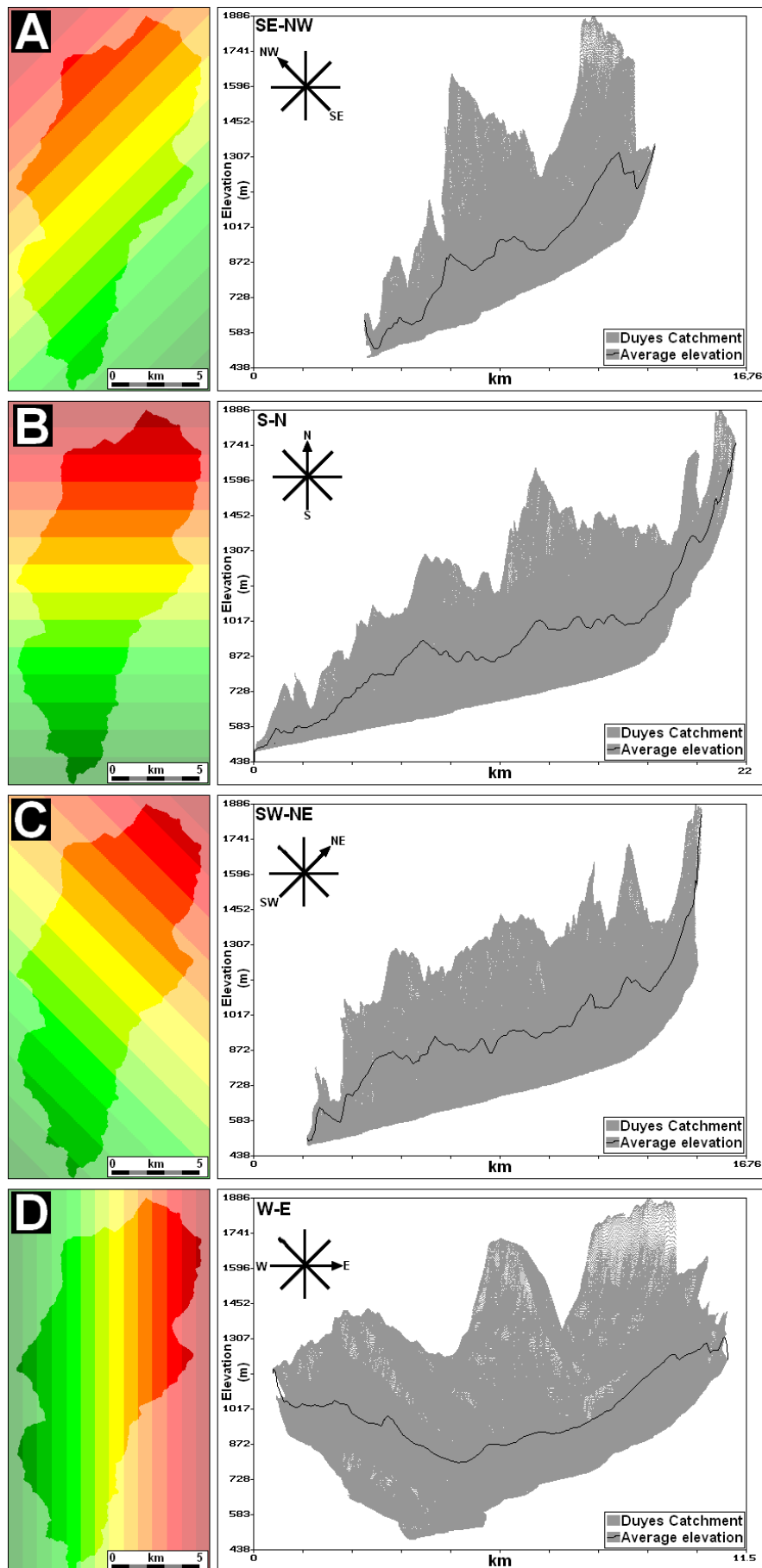


Figure 11 : scatter plot of the Duyes catchment elevations along the four directional axis SE-NW (A), S-N (B), SW-NE (C) and W-E (D)

Conclusions:

This set of hydrogeomorphometrical layers computed from the DTM provides insights on various characteristics of landforms and their intricate relationships with geomorphological and geomorphological processes that shaped them. It also appears to be a useful tool for geomorphological and hazard mapping such as floods along the rivers and torrents, landslides on slopes, sheet and gully erosion, rock falls and collapses from the cliff. Those maps could also contributed to a better “reading” and understanding of landscapes during fieldworks.

It is worth mentioning that some processing in the context of the Duyes valley and probably the French Southern Alps are truly useful with a DTM resolution of less than 25 meters and a vertical accuracy of about one decimetre as tested on the Riou Catchment (**Figure 12**). For instance, the alluvial fan of the Riou torrent is clearly depicted at 5 and even 10 meters resolution (**Figure 12A' and B'**) but the pattern of multidirectional drainage becomes fuzzy at 25 meters resolution (**Figure 12C'**).

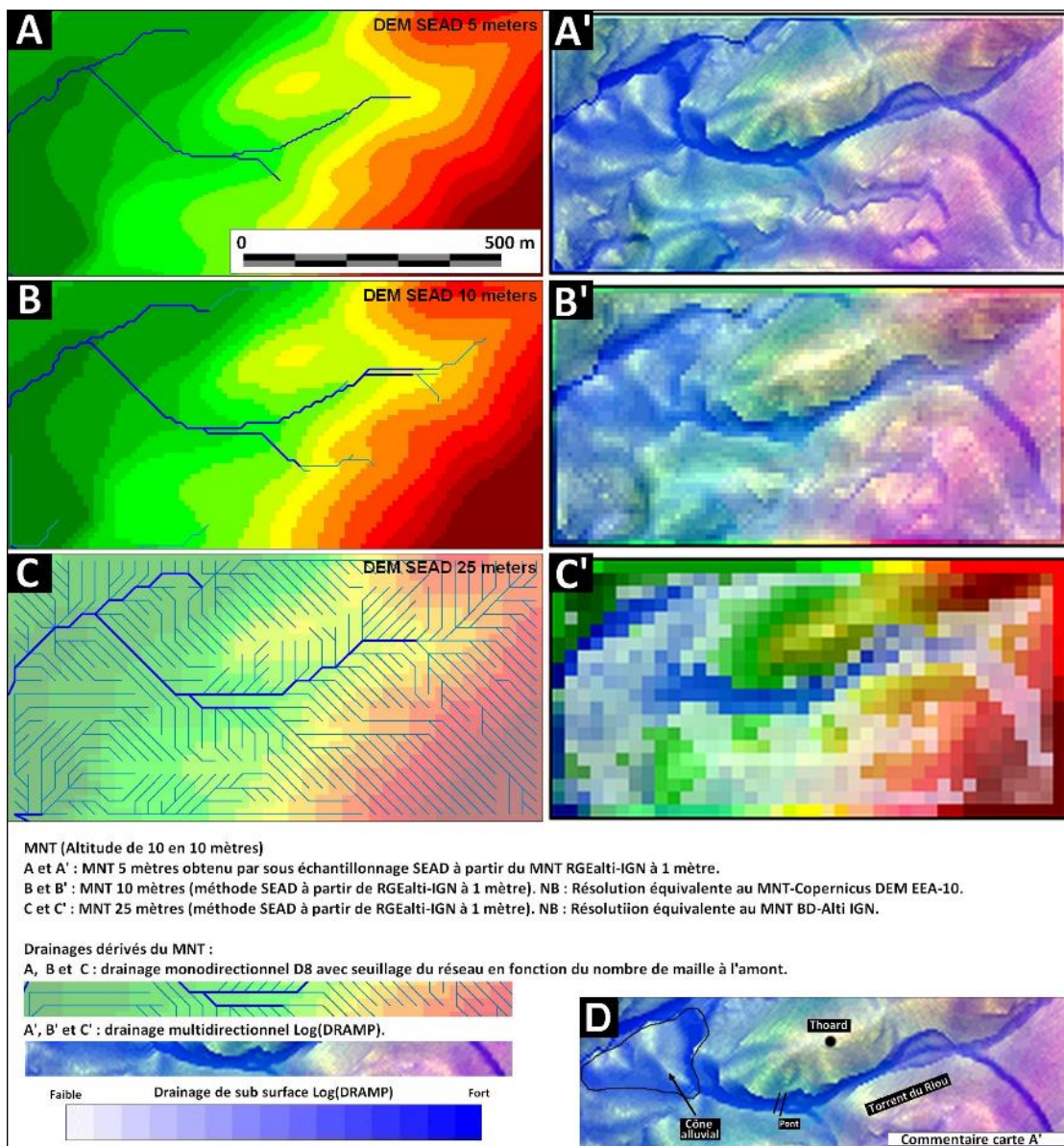


Figure 12 : mono (A, B and C) and multidirectional drainage (A', B' and C') patterns according to the DTM resolution (5 meters in A and A', 10 meters for B and B', 25 meters for C and C') on the Riou Catchment. (Depraetere, Deffontaines and Riazanoff, 2023)

APPENDIXES

Appendix 1: potential energy of moving water and flash floods

Appendix 2: about "Fluvial erosion: the lesson of the torrents"

Appendix 3: technical report after the damage due to the flood of 2019

Appendix 4: water issues are simple but capricious: "too much, not enough, too dirty"

Appendix 5: chronicles of floods and landslides in the Duyes in 1774

Appendix 6: multidirectional versus monodirectional drainage from DTM

Appendix 7: geomorphological hydrograph of the Riou Catchment

Appendix 1: potential energy of moving water and flash floods

From:

Gautier Y. (1998), Inondations. In Dictionnaire des sciences de la Terre : Continents, océans, atmosphère.
Albin Michel en coédition avec Encyclopædia Universalis, Septembre 1998, 922 pages.
(Translation in English from French partly with Deepl)

"The damage caused by flash floods is mainly due to the potential energy of moving water. One litre of water weighs one kilogram, which may not sound much, but it's the same as saying that one cubic metre of water weighs one tonne. 55 millimetres of water over 1 square kilometre, travelling 300 metres downhill, have a potential energy equivalent to that released by the Hiroshima bomb (1.4×10^{14} joules). Anything that reduces the concentration time of water and its infiltration (slope, impermeability of the land, lack of vegetation, etc.) accelerates the mobility of water and its destructive potential. What's more, the materials carried away by moving water add to its power. So it's hardly surprising that after a rainstorm, suddenly unleashed water can sweep away vehicles, houses, bridges... like chaff." (Gautier 1998, p 3 83).

Appendix 2: about "Fluvial erosion: the lesson of the torrents"

Translated from French :

Max Derruau, Précis de Géomorphologie, 1965. Masson & Cie, Paris, 415 pages, excerpt pages-60-63
(Translation in English from the French version partly with Deepl)

"The term erosion can have two meanings, a broad and a narrow one: a narrow one, which identifies erosion and digging, a broad one, which means digging as a result of the digging, i.e. digging + transport of the removed materials + accumulation of these materials.

The visible mark of erosion in the broad sense is the "hillshape".

The torrents are watercourses with spasmodic regime, with strong slope and which work in materials easy to scour. It is therefore abusive to call the Rhone a torrent, since, although its slope is steep, its regime is the most regular of the four major French rivers. On the other hand, the Manival, near Grenoble, and the Riou Bourdou, a tributary of the Ubaye (Southern Alps), are typical torrents. The first one is less active than in the past; there are even extinct torrents, vestiges of a more humid or spasmodic ancient climate and no longer functioning today. On the other hand, the Riou Bourdou is a perfectly active torrent.

***The torrents are natural laboratories for the study of fluvial erosion;** they meet, indeed, all the conditions for this erosion to be maximal since they dig brutally, all the more so as the materials of their basin are scourable; and they transport and deposit in proportion to their digging capacity. The torrents are particularly well known by the work that Surell devoted to them in 1841 and which became classic. The dangers that they constitute as well for the pastures as for the inhabited sites are rightly famous.*

A "complete" torrent is divided into three parts:

- the reception basin, which constitutes the upper course ;
- the flow channel, which corresponds to the middle course;
- the alluvial cone, or lower zone.

On the map, a torrential basin thus appears as a sort of diabolo, with the central part corresponding to the flow channel between the upper basin and the alluvial fan, both of which are dilated, but the catchment basin, or flow channel, can be very small.

The catchment area is the zone where, by concentration of water, the torrent is formed, each stream digs there, scouring the friable ground during each rainfall, moving back its source, causing landslides, mudflows; the result of all these actions is an enlargement which goes hand in hand with the deepening: the digging wins over the other modes of fluvial work, and the torrent is loaded with a mass of torn off materials: it becomes a muddy river with fast speed.

The flow channel is the bed of this river; erosion and accumulation go hand in hand, because the flood current sometimes abandons blocks or fine materials which accumulate between the blocks, sometimes digs in depth and laterally, undermining its banks. All in all, it is the transport that dominates, but the breaks in slope are frequent, and each flat section corresponds to an abandonment of materials constituting what has been called a siding of fluvial erosion.

The alluvial fan is built where the torrent arrives in the main valley where it ends its course. The main valley is usually of low transverse slope: in most mountain ranges it is a trough valley with a flat bottom. Thus the slope of the torrent was suddenly slowed down and the speed of the water was suddenly slowed down. Unable to transport the materials carried until then and which required a very great energy, the torrent deposited them. By depositing them, it has raised its bed, which has allowed it to increase its slope in the section considered and to increase its speed to become more and more capable of transporting its load of materials to the collecting river. The rise must logically increase until it gives this downstream section a longitudinal slope equal to that of the flow channel so that the material capable of being transported in the channel can also be transported on the cone. But, by rising, the torrent dominates the adjacent regions and, at the slightest flood, it will leave its bed to occupy another in a lower position; this bed in turn will rise, and the torrent will occupy another, and so on. Thus is formed a cone or, as the authors of English language say, a "fan" whose top is at the outlet of the flow channel in the master valley. The torrent oscillates on the cone and makes its vicinity all the more dangerous as the villages seek the cone for its fertility. Sometimes it is dammed up, but the floods can burst the dam and * determine another bed; most often the course is fixed not in the axis of the flow channel, but following a lateral generatrix.

The slopes of the cones generally exceed 5%; they are particularly feared by builders and road users. In the Isère valley, downstream of Grenoble, the railroad line passes under a tunnel cone. The cones can push the main watercourse against the opposite side of the valley; thus, the Rhone in Valais meanders between cones that press it successively against the right wall, then against the left wall of the trough in which it flows. Two alluvial fans that meet can even block the main valley and determine the formation of a lake, like the lake, now dried up, of Bourg-d'Oisans, in the French Alps.

Torrentiality has been linked to deforestation, and it has been concluded that reforestation would "extinguish" torrents. In fact, afforestation restricts scouring wherever it is possible, but many torrents have their origin in areas above the forest, and reforestation cannot have there, reason of torrentiality. When the rock is particularly scourable (Marne, gypsum), the slope steep, the climate with violent showers separated by long periods of drought during which the vegetation cover degrades, the reforestation is precarious, especially near the upper limit of altitude of the trees, and the torrents can develop considerably (frequent cases in the French Alps of the South).

If reforestation is not an infallible remedy, one can at least correct the bed of the torrents so as to limit their ravages; the surest method consists in slowing down the speed of the torrent, thus limiting its digging power, by cutting the bed, in the flow channel and even in the catchment basin, by transverse dams which divide it into calm reaches cut by small waterfalls. Upstream of each dam, landing beaches are formed, and it can be estimated that the correction is complete if each of these beaches ends at the foot of the upstream structure. But the beach located behind the first dam encountered by the watercourse is not long in being raised by accumulation of torrential materials until its longitudinal slope becomes sufficiently steep so that the speed of the corresponding torrent is great enough to ensure the transit as in the past to the beach located immediately downstream, which will also be raised, and so on. The correction of the flow channel is therefore never definitive.

This precariousness has worried hydraulic engineers, since **the correction of torrents can only delay, not prevent, the transit of materials to the lakes of hydroelectric dams.** For the correction to be definitive, it would be necessary that the structure blocking the canal could be raised indefinitely. To achieve this indefinite rise, the idea was to replace the classic dam wall with a screen, or retention net, placed across the bed and anchored both in the bed and on the sides. The material stopped by the net is

immobilized and, therefore, becomes very difficult to mobilize. As soon as an element is fixed, a second element coming up against the first one is immobilized in its turn, and so on, without intervention of the net resistance. In this way, a cumulative landing process was achieved, independent of the resistance of the artificial obstacle, and its retaining cable was found to be relaxed. The net only served as a starting point for a chain reaction.

On the alluvial cone, to avoid the torrent's divagations, it is dammed up in order to fix its bed, but care is taken to keep a sufficient distance between the two dykes for the flow of the biggest floods.

The torrent makes it possible to pose most of the problems relating to fluvial erosion and to grasp some of the mechanisms of the work of the rivers: problem of the assumption of responsibility of the materials which erosion provides, of the modalities of the transport of these materials and their deposit. As noted by Surell:

"The waters subjected to follow at first the relief of an uneven ground destroyed little has little, the irregularities of the slope... Here, they gnawed; there they exhausted... The result of all these actions was to create a new curve, which is better suited than the primitive profile of the ground to the flow of water."

Thus is approached the concept of profile of equilibrium. Concerning the torrents, Surell also posed the problem of the relations of the slope and the load with the divagations of the watercourse; in other words, that of the relations of the profile and the layout. So many problems that we must now address."

Appendix 3: technical report after the damage due to the flood of 2019

From:

Talancieux J., Vinai L., (2020).

Les Duyes et ses principaux affluents :

visite pour analyse des enjeux hydromorphologique dans la vallée des Duyes et entretien de ripisylve.

Rapport de visite du bassin versant des Duyes du Syndicat Mixte Asse Bléone.

(SMAB) Digne. 37 pages. (Reference [26])

General context of this report from the technical services of the SMAB: it gives an account of the dynamics of hydrogeomorphological processes in the main bed of the Duyes and some of its tributaries. It clearly highlights the renewed incision of the Duyes river due to a loss of sediment load resulting from reforestation and the natural extension of forest cover as a result of agricultural abandonment of marginal land as observed by the hydrologist Luc Descroix (IRD) since the early nineties (cf. [10] [11]). The following report from 2020 on the Duyes valley mentions the "absence of morphogenic flooding" with the exception of the autumn 2019 flood and the revegetation of banks and alluvial banks.

"The bed of the Duyes :

The morphological trends observed bear witness to the impoverishment of the inflows from the main tributaries, closure of the bed by vegetation, channelling of the watercourse, incision in the bed materials, disconnection of a large part of the active band, and the absence of morphogenic flooding over a very long period. As a result of the long-term reforestation of the region, the sediment deficit seems irremediable. The trend towards incision is likely to continue, possibly until lateral erosion is able to reopen an active strip, at the mercy of very large floods. In addition, the strong morphogenic floods at the end of 2019 allowed the river to reopen slightly. However, incision remains marked upstream of Le Chevalet.

The vegetated landings upstream of the Planas bridge have stabilised to a significant extent, and grubbing operations can be carried out in these areas to maintain an active bed. Downstream of Le Chevalet, the aim of the operations will be to maintain an active bed and therefore the transit of the alluvial load of the watercourse.

At the Thoard bridge, downstream of the confluence with the Combes ravine, the bed of the Duyes is tending to channelise due to an increase in gradient and a small area at the bottom of the valley. The management objective for this section is to maintain an open bed so that the river can have as large an expansion field as possible during floods. In addition, some grubbing work will be carried out to maintain the non-vegetated landings and to allow the alluvial cone to re-establish itself at the confluence with the Combes ravine.

Downstream of the confluence of the ravin des Combes at Barras, this reach of the Duyes has a large area of divagation. However, it has been greatly reduced by the vegetation on the landfills. In addition, the floods of 2019 have created numerous logjams that have largely blocked the bed of the Duyes. This sector is beginning to show signs of incision due to the channelling

of the main bed. The management plan for this sector is to significantly reopen the bed of the Duyes by numerous grubbing operations over the entire section. The main works will take place between the confluence of the Combes ravine and downstream of Les Bourres, as well as upstream of Barras.

From Barras to the confluence with the Bléone, the lower valley shows little evidence of incision. The sediment load at the bottom of the bed is still very high. However, there has been a reduction in the active strip of the watercourse, characterised by a widening of the riparian vegetation on each bank. Management of this section must maintain the active strip by maintaining the riparian vegetation, or even by grubbing out the narrowest areas. At the very least, large trees at the foot of the banks should be treated preventively to avoid the formation of logjams during future floods.

Torrents and ravines:

Reported as "very active" during a study in 1987, the **Bramefan torrent** still carries solid matter, but it is no longer as active as it was 30 years ago. This is due to the vegetation on its slopes (the main areas of input) and its banks, which greatly limit solid transport in the bed of the watercourse.



At the confluence of the **Riou Blanc torrent** with the Duyes in the Hautes Duyes commune, its alluvial cone is now completely stabilized by vegetation. There are no traces of scouring linked to the December 2019 floods, although it was indicated as being very active in 1987.

The bed of the **Ravin du Chevalet** between the ford and the boulder fall appears to have been raised. The boulders have probably blocked the load upstream. The Patouilles tributary continues to show signs of strong activity. It is the main supplier of alluvial materials to the bed of the Duyes for the Haute Vallée. The works planned are to maintain an active bed between the Patouilles bridge and the confluence with the Duyes, including grubbing of the alluvial cone with a view to recovery, intervention at the level of the 3 rockfalls in order to re-establish solid transport downstream and limit the deepening of the bed upstream and

to the right of the Tuilière culvert, and finally management of the confluence by grubbing of the alluvial cone to enable the transport of alluvial deposits.

The Riou torrent, which was also "very active" in 1987, shows that the landings have been slowed down by the crossing structures (in line with their purpose) and by the vegetation. **This low level of solid transport activity is reflected in a very significant deficit at the confluence (incision of more than 2 m)**. This ravine contributes very little alluvial material to the bed of the Duyes and does not allow any alluvial recharge of the Duyes bed.

The Ravin des Combes: Activity maintained today, however, as the alluvial cone is vegetated and occupied by a field on the left bank, the sediment load does not circulate optimally to the Duyes' live bed. Vegetation management interventions favouring solid transport, including grubbing up the confluence with the Duyes with a view to reclaiming the material accumulated on the alluvial cone and creating a preferential channel with a view to favouring the movement of sediment.

Ravin des Combes: Activity maintained today, however, as the alluvial cone is vegetated and occupied by a field on the left bank, the sediment load is unable to flow optimally down to the Duyes. Vegetation management measures to promote solid transport include grubbing up the confluence with the Duyes to recover the material accumulated on the alluvial cone and creating a preferential channel to promote solid transport to the confluence and limit sediment deposits on riverside plots.

The Saint-Pierre ravine, a torrent indicated as "very active" in 1987. It is less active today, with a major blockage at the OH ford: two 1000mm nozzles blocking sediment. In addition, the asphalt covering the ford is regularly washed away by floods, polluting the river. The significant reduction in solid transport is also linked to the blockage of the RD3 bridge over the Claus ravine, and to a deficit in the input from the slopes (reforestation). Traces of incision can be seen at the confluence downstream of this ford (bank protection wall with exposed foundations). Vegetation maintenance work to limit the tipping of trees caused by bed incision in the vicinity of structures (bridge, wall, culvert).

Ravin de Vauvanes: Torrent indicated as "active" in 1987 and still active today. Upstream of the RD17, the flow channel was reopened by mechanical shovel during a flood in March 2018. A channel approximately 1 to 2 m deep and 2.5 m wide was created. In January 2019, the area that had been recalibrated showed a marked incision. This sector has now been partially recharged by an ice jam. Downstream of this logjam, the Vaunavès still has a canyon profile, with banks over 2.5 m high, up to the crossing of the wall upstream of the RD17. Downstream of the RD17 bridge, the riverbed has been reworked during recent floods. There is a succession of deposits and overcreasing of the bed, up to the final cone where the deposit is massive on the left-hand side. The vegetation has blocked large quantities of sediment. The water has created a channel on the right bank of the cone to join the Duyes. The work recommended is an intervention to manage the vegetation and encourage solid transport. The main objective is to enable alluvial materials to be transported to the bed of the Duyes. At present, this is complicated by extensive vegetation in the middle of the bed. The aim of the works will be to reopen the confluence of the Vaunavès with the Duyes by grubbing up the alluvial cone and creating a preferential channel in the lower part, in order to direct the flow to the Duyes and encourage the evacuation of sediments. Secondly, in order to ensure that the materials are transported properly from the top of the basin to the confluence, a one-off operation will be carried out in line with the logjam upstream of the RD17. The logjam will be removed and a preferential channel created by earthworks.

Ravin de Saze: this torrent was not considered active in 1987. This ravine brings in a lot of material that is blocked by the OH under the road. Dredging and bunding are in progress. The recommended work involves recharging the sediment in the Duyes by reusing the materials stored in the embankments.

Ravine des Pelots: the bed is well stabilised where it crosses the RD17, and there is no trace of bottom movement on this bed (moss-like vegetation on the stones). It seems that the overflows (water and sediment) may be upstream of the road. This tributary does not appear to contribute any sediment to the Duyes.

Ravin de la Frache: Indicated as "very active" in 1987 because its slope is conducive to significant sediment transport. It is still connected to the Duyes, although the confluence indicates a step of around 0.6 m between the two beds. Work recommended and, where appropriate, included in future campaigns

Ravin de Beaudun: Torrent indicated as "active" in the 1987 study. It retains the characteristics of an active bed, despite the vegetation on its alluvial cone. Traces of numerous dredging operations and the formation of embankments are visible at the RD17 structure. These operations appear to have had a significant impact on the longitudinal profile upstream and downstream (channel erosion). The irrigation pipe at the confluence is a major block to sediment transit. There is a risk that it will break during future floods. The recommended work is to maintain the vegetation in order to keep the ravine's bed active.

Ravin de Beaudun: Torrent described as "active" in the 1987 study. It retains the characteristics of an active bed, despite the vegetation on its alluvial cone. Traces of numerous dredging operations and the formation of embankments are visible at the RD17 structure. These operations appear to have had a significant impact on the longitudinal profile upstream and downstream (channel erosion). The irrigation pipe at the confluence is a major block to sediment transit. There is a risk that it will break during future floods. The recommended work is to maintain the vegetation in order to keep the ravine's bed active.

Ravin de la Barradine: Torrent indicated as "active" in the 1987 study. It shows significant sediment transport activity, controlled by the clearing associated with the maintenance of the OH under the road. The bed is blocked by vegetation at the confluence. The recommended work involves maintaining the vegetation in order to keep the gully bed active, and will be carried out in the lower part of the gully, without any earthworks. If necessary, the bed should be reopened downstream to encourage sediment transport."

Appendix 4: water issues are simple but capricious: "too much, not enough, too dirty"

From:

Excerpt from a not published paper :

C. Depraetere, 2024 ?.

« Exploitation hydro-géomorphométrique des MNT haute résolution de l'IGN :
Le cas des 'chemins de l'eau' dans la vallée des Duyes (Alpes de Haute Provence) ».

Revue semestrielle « Dynamiques environnementales », Université d'Orléans

(Translation in English from French, partly with DeepL)

"The expression **"too much, not enough, too dirty"** comes from the professor of agrohydrology Roland Shulze from the university of Natal (1982) : "too much" means floods, landslides, gully erosion, damage on roads and bridges, and crop devastations, "Not enough" relates drought and crop depletions, "too dirty" refers that either there are too much sediment deposit or the water is polluted.

In summer 2022 in Southern Alps, the drought was very severe and the public fountains of Thoard stop flowing. What this year 2023 be like? "Too much water, perhaps, not enough may be! Historical chronicles show that it is in the shoulder seasons that these excesses are most frequent, with catastrophic floods causing tremendous damage to farmland and buildings at the whim of the torrents and the antics of the rivers. In the archives of Mrs Alice Cavanna [cf. appendix 5], a resident of Thoard, there are several transcriptions of events in the 18th century recounted by the Bailly, consuls and other mayors of the time; They mention "continuous rains", mention that the underground waters also caused many "collapses", "landslides", "openings", "crevasses", and even evoke "strange inconceivable revolutions", as the following extracts indicate in the face of the "disasters" of 1774:

As these are purely factual reports, the authors limit themselves to mentioning that the "continuous rains" that lasted until 10 April 1774 were accompanied by "two earthquake tremors" on 8 April, without mentioning any causal link. One hypothesis is that deep seepage into the bedrock after several days of heavy rain helped to lubricate the fault planes, causing tremors that further destabilised the slopes. The reports do not specify whether the "earth tremors" occurred before or after 8 April. However, they do make it clear that the numerous "landslides" were linked to "groundwater that had no way out", in addition to the damage to buildings and farmland caused by high water and flooding. In 1782, there was still mention of "the ravages and flooding of the D'Esduyes river" and "the eruption of the Duyes valley" (AC p.140-141). In 1784, in a report on "repairs to the river Duyes", damage was reported to have occurred in the Les Bourres district on the right bank of the Duyes, 1 km south of Thoard and close to the confluence of the Ravin de Saint-Pierre. It is important to place these observations in the historical and environmental context of the time.

These events took place against a backdrop of a "full world", as all the land in the valley was farmed by a dense rural population spreaded throughout the villages and hamlets, as was the case until the middle of the 19th century. It has been established that the forest cover and even the "garrigues" were much less extensive then than they are today, as can be seen from photographs taken at the end of the 19th century. Emmanuel Leroy-Ladurie (2011) refers to the fact that "the French Revolution and the climate is a much-discussed theme" and that "no serious historian would dare to claim that bad weather conditions were responsible for the outbreak of the French Revolution", while pointing out that the climatic context that preceded 1789 may have encouraged revolutionary events by creating a fruit crisis. The author of "L'histoire du climat depuis

l'an mille" uses the term "climat", which is not found in the chronicles mentioned above; this remark suggests that **this abstract notion of an average year in terms of rainfall and temperature was not anchored in the minds of the time**, familiar as they were with the vagaries of the skies and the antics of the rivers, what our contemporaries call climatic hazards. For a historian of mentalities, without going into the reasons for this development here, a comparison with our own time shows that, on the contrary, the average climatic year has become dominant, with any deviation being seen as an anomaly. This tendency is conducive to a sometimes overly "catastrophist" and journalistic vision of the moods of celestial manna.

To come back to the transformation of landscapes and terroirs following the rural exodus and agricultural decline, not to mention the haemorrhage of the First World War in the farming world (more than 52 names on the Thoard war memorial! In Haute Provence, this rural decline was accompanied by **a policy of Restoration of Mountain Land (RTM)** carried out since the end of the 19th century; as the soil was better protected, this progressively favoured infiltration, reduced run-off and reduced erosion on the slopes. However, this has less beneficial effects (Descroix, Gauthier and Olivry (2002)):

- Greater infiltration favours solifluction and other landslides, which 18th-century chroniclers called "collapses", "crumbles" or "upheavals";
- The reduction in the solid load in watercourses causes rivers to become entrenched in their beds, which ultimately leads to the undermining of dykes and bridge pillars, the destabilisation of banks and the lowering of alluvial water tables;

The re-vegetation of mountain soils could only be gradual, and its effects on the hydrological and sedimentary balance even more so. Referring to the catastrophic floods that hit Mediterranean France between 1924 and 1933, the hydrologist and potamologist Maurice Pardé described the power of the torrents as follows: "**The riviérettes, the most puny streams, the gullies of our Mediterranean countryside can carry insane flows**" (Pardé, 1934, p. 675). This greening is transforming the harsh landscapes of yesteryear into a "new Eden", as Jean Giono poetically wrote in his book "L'homme qui plantait des arbres" (1953)¹¹. The action takes place in the French Southern Alps during the first half of the 20th century, where it takes on a "neo-Edenist" aspect that is already in tune with our modern times. Having observed the situation since 1974, the author himself has noted that year after year the old roubines (gullies in Provençal) have been recolonised by vegetation, particularly in the commune of Roubine-sur-Galabre, near Thoard. This is an example of the long-term evolution of landscapes and rural societies.

Although the buffering role of vegetation and soil reconstitution is real, **the risk remains because the power of the water should not be underestimated**; we will mention here the comparison made by the hydrologist Yves Gautier between a heavy downpour causing flash floods and the power ... of the atomic bombs of Hiroshima and Nagasaki (See table down below). Taking his example and applying it to the Riou basin, we arrive at a power greater than the cumulative power of the two bombs for a 50 mm rainfall in one hour.

<i>Hypothèse</i>	Averse*	Superficie	Dénivelé	Terajoule
<i>Lieu</i>	P (mm)	(S) km ²	ΔZ (m)	P _{tj} (TJ=10 ¹² J)
Gautier (1998)	55	1	300	140
Bassin du Riou	50	2,44	330	200
<i>Hiroshima</i>				70
<i>Nagasaki</i>				84
<i>* Pluie efficace correspondant à la lame ruisselée en 1 heure</i>				

The energy of floods compared with the Hiroshima and Nagasaki atomic bombs
 (From Gautier, 1998, p.383, cf. **appendix 1**).
 (For the Riou, the estimation comes from simulation in **appendix 7**)

Does this mean that Thoarders are living at the foot of a 'hydrological bomb'? In a sense, yes; to use Maurice Pardé's aforementioned flowery expression, the villagers know that the Riou "rivulet" ("riviérette") is prone to wild swerves, particularly in the shoulder seasons; the technical services are well aware of this if you consider the size of the culvert passing under the bridge at the entrance to the village.

¹¹ This book was magnificently adapted in an animated film of the same name by Frédéric Back (1987).

As a matter of principle, however, it is important to avoid indulging in unrepentant sensationalism tinged with doom and gloom, and thereby adding fuel to the fire of journalists or other communicators. What's more, the potential energy of the mass of precipitated water, converted into kinetic and mechanical energy, is dissipated to an extent of more than 90% due to the resistance of the ground to run-off and the slowing of the flow caused by the vegetation, particularly the riparian vegetation.”

Appendix 5: chronicles of floods and landslides in the Duyes in 1774

From:

Personal archives of Ms Alice Cavanna (AC)

(Available at the bibliothèque municipale de Thoard with help of Dr Michel Giraud)

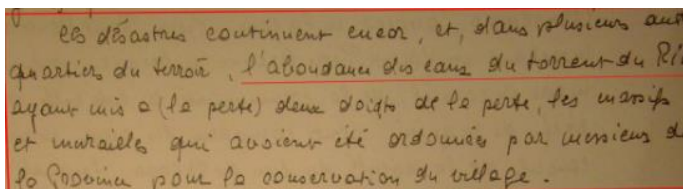
(Translation in English from French partly with DeepL)

These chronicles come from retranscription of archives dating back from the XVIIIth century by Ms Alive Cavanna, an inhabitant of Thoard (Down below, some samples of the original transcription) . The original documents are in French as written at that time. Therefore, some words and expressions are outmoded even outdated. The present translation in English tries to simplify and clarify the original text. The following excerpts only refers to the “disasters” in the vicinity of Thoard and the Riou torrent.

“Report on the disaster in Thoard, May 1774” (AC pages 13-14)

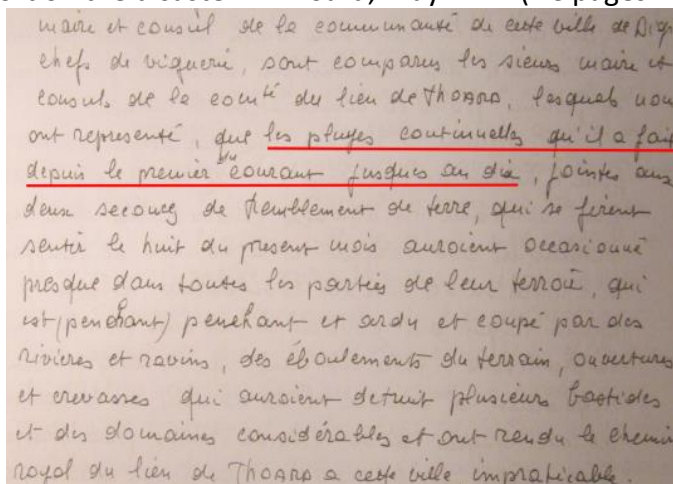
“The mayor and the consuls of Thoard have informed us that the continuous rain that fell from the first of April to the tenth, combined with the two earthquakes on the eighth, caused landslides, openings and cracks in almost all parts of their territory, which is steep and difficult and cut by rivers and ravines, destroying several country houses and considerable estates and making the royal road from Thoard to Digne impassable.”

“The disasters continued and, in several parts of the region, the abundance of water from the Riou torrent brought the massifs and walls that had been ordered by the gentlemen of the Province to preserve the village to within an inch of their lives.”



Les diastres continuent encor, et, dans plusieurs autres parties du terroir, l'abondance des eaux du torrent du Riou ayant mis à la perte deux doits de la perte, les murailles et murailles qui avoient été ordonnées par messieurs de la Province pour la conservation du village.

Report on the disaster in Thoard, May 1774 (AC pages 13-14)



Le maire et consuls de la communauté de cette ville de Digne chefs de vicairie, sont comparés les sieurs maire et consuls de la comté du lieu de Thoard, lesquels nous ont représenté, que les pluies continuelles qu'il a fait depuis le premier courant jusqu'au dix, jointes aux deux secoues de tremblement de terre, qui se firent vers le huit du present mois auroient occasionné presque dans toutes les parties de leur terroir, qui est (pendant) penchant et ardu et coupé par des rivières et ravins, des éboulements du terrain, ouvertures et crevasses qui auroient détruit plusieurs bastilles et des domaines considérables et ont rendu le chemin royal du lieu de Thoard à cette ville, impraticable.

« Disaster in Thoard in May 1774: site report » (AC pages 136-137)

Appendix 6: multidirectional versus monodirectional drainage from DTM

Excerpt from Habilitation à Diriger des Recherches (HDR):

C. Depraetere, 2013 : « Introduction à l'hydrogéomorphométrie :

Etude des relations entre le modelé des formes de terrain et les processus hydrologiques dans des contextes insulaires »

. Dossier pour l'Habilitation à Diriger des Recherches (HDR), Ecole Doctorale de l'université Paris-Diderot.

(Translation in English from French partly with DeepL)

A major limitation of the D8 monodirectional drainage method is that, by definition, it cannot include diffluences, as it is the case in deltas, anastomosed channels or alluvial fans. The need for an alternative in the form of a multidirectional drainage model to deal with these cases is obvious. The first method of this type came from hydrology (Beven and Kirkby [15] [1] [2]) and was later on used as an Index of Potential Soil Water Saturation¹², noted as I_{psws} ([17][18]). Many variants were then developed: the Multiple Flow direction, the Kinematic routing algorithm, the DEM Network and The D-Infinity algorithm. For Instance, downstream drainage with the D-Infinity method can only be bi-directional. For Kinematic routing, the algorithm takes into account the kinetic energy of upstream flows to define the downstream flow, which tends to reduce excessively random divagations.

The “Beven and Kirkby” method, also known as TOPMODEL method, and its variants share two basic assumptions about sub-surface percolation within porous and permeable soils:

- It is proportional to the drained surface $\ln(\alpha)$ in the sense of multidirectional drainage weighted for each direction according to the difference in level. This is an estimation of the amount of water flowing through a specific point with multidirectional percolation in soil or other permeable superficial formations;
- It is inversely proportional to the local slope $\tan(\beta)$. Lower the slope gradient, higher the probability to have soil saturation;

This can be formulated like this: $I_{psws} = \ln(\alpha) / \tan(\beta)$

The method in this document refers only to the parameter α without β because the purpose is the multidirectional sub-surface flow mapping (i.e. **Map 20 and Map 21**) for hydrogeomorphological applications and not for the parametrization of potential saturation of soil (or “source area”) required by distributed and physical based hydrological modelling like TOPMODEL and its variant. The values given by the DRAMP method correspond to an Index of potential sub surface flow (ISSF) rather than an Index of potential soil sater saturation (I_{psws}) mentioned previously.

As seen previously, the drainage network with the monodirectionnal algorithm is quite easy to sketch on a map as for instance on small subset of elevations as given in **Figure 13A** with its D8 octodirectional steepest descent from one of the “source” meshes for instance M(3,4) with an elevation of 105 (**Figure 13B**). If 100 mm of rainfall in this meshed flows on the surface (Surface totally impervious or “oilcloth” hypothesis), then all the water will pass through meshes M(2,3) and M(3,2) down to the “outlet” mesh M(4,1) which collect also 100 mm of surface flow coming from the “source” mesh M(3,4).

The computation and mapping of α representing the pattern of subsurface pathways for the same “source” mesh is more intricate as shown in **Figure 13C**. Depending of local topography in the 8 surrounding meshes (Shifting 3x3 meshes window), the amount or probability of water percolating downstream will be proportional to the gradient (Tangent value). In this case, the hypothesis is that all rainfall will infiltrate in soils and superficial permeable formation (So to say, the “sponge” hypothesis). Taking the same monodirectional flow line as Figure 13B with the same amount of rain in the “source” mesh M(3,4), only 16

¹² In French, indice de saturation potentielle en eau des sols

mm will percolate down to the “outlet” mesh M(4,1) as detailed in **Figure 14**. The rest of sub surface coming from the “source” (84 mm) will follow multiple percolation pathway and only a part of it will reach the “outlet” mesh.

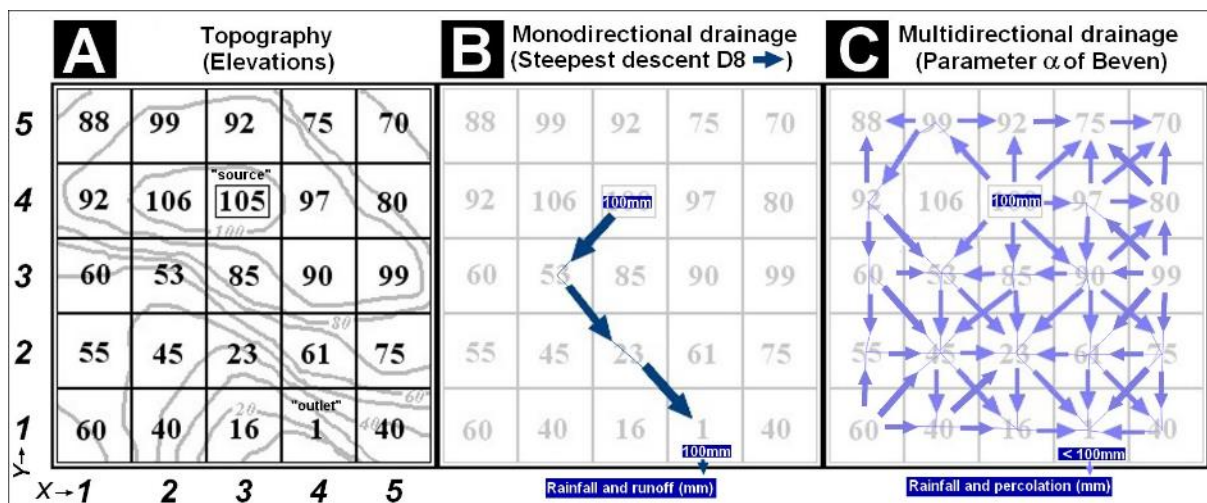


Figure 13 : example of monodirectional and multidirectional drainage lines from one mesh.

A./ Elevations on a subset of 5x5 meshes.

B./ Monodirectional lineD8 from the “Source” Mesh M(3,4) elevation 105 (“oilcloth” hypothesis)”

C./ Multidirectional percolation lines from the “source” Mesh M(3,4)) (“sponge” hypothesis).

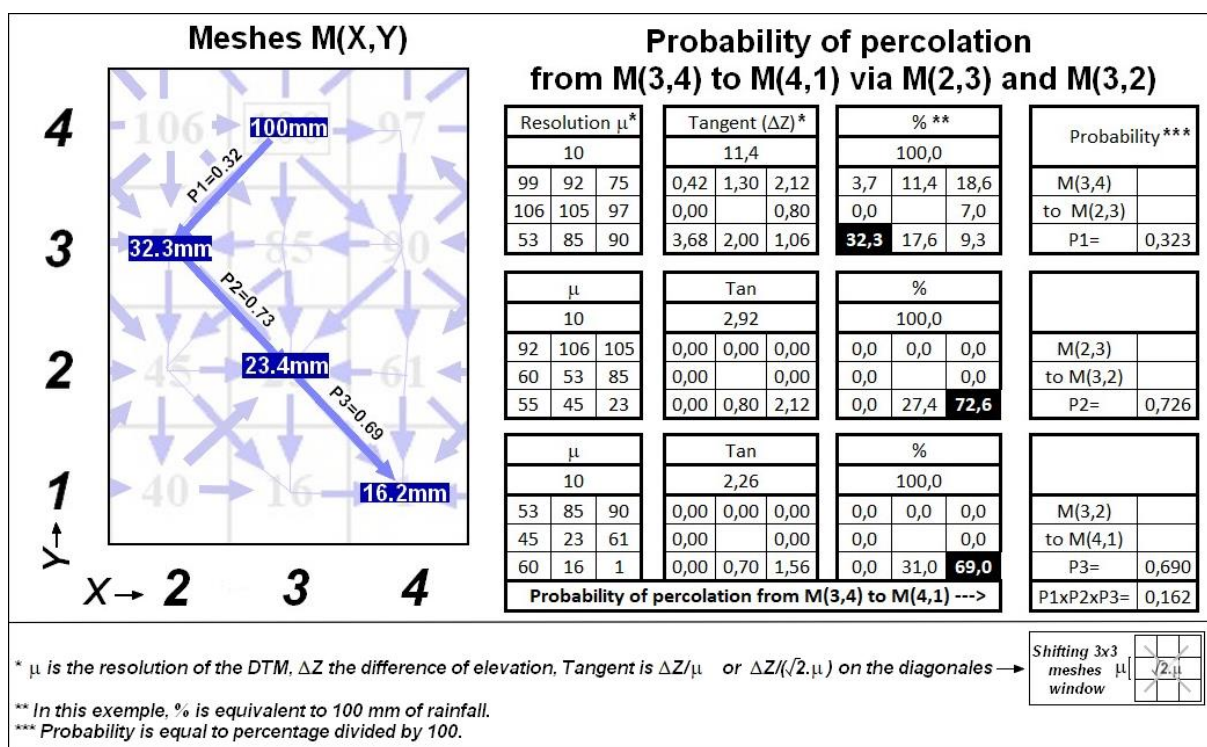


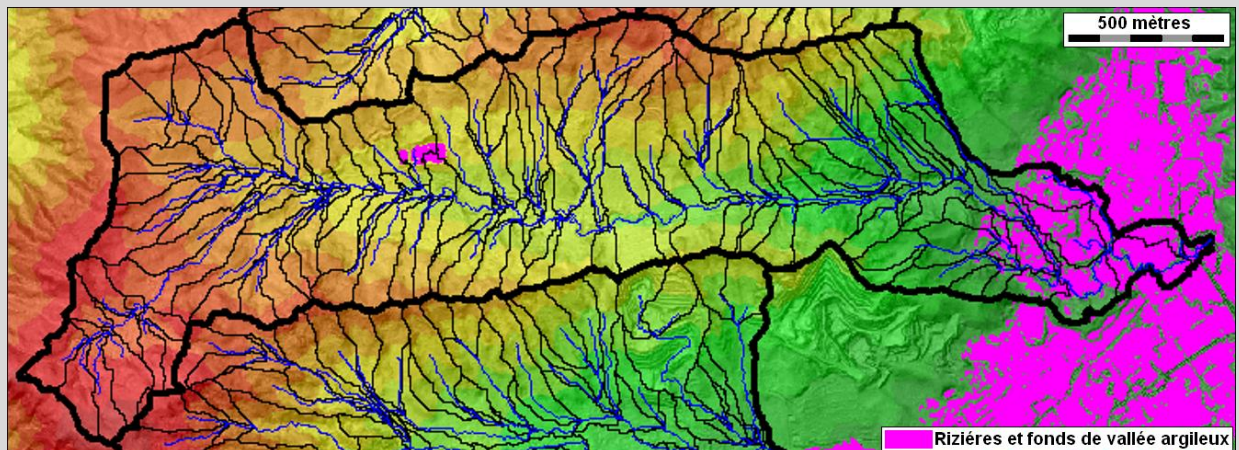
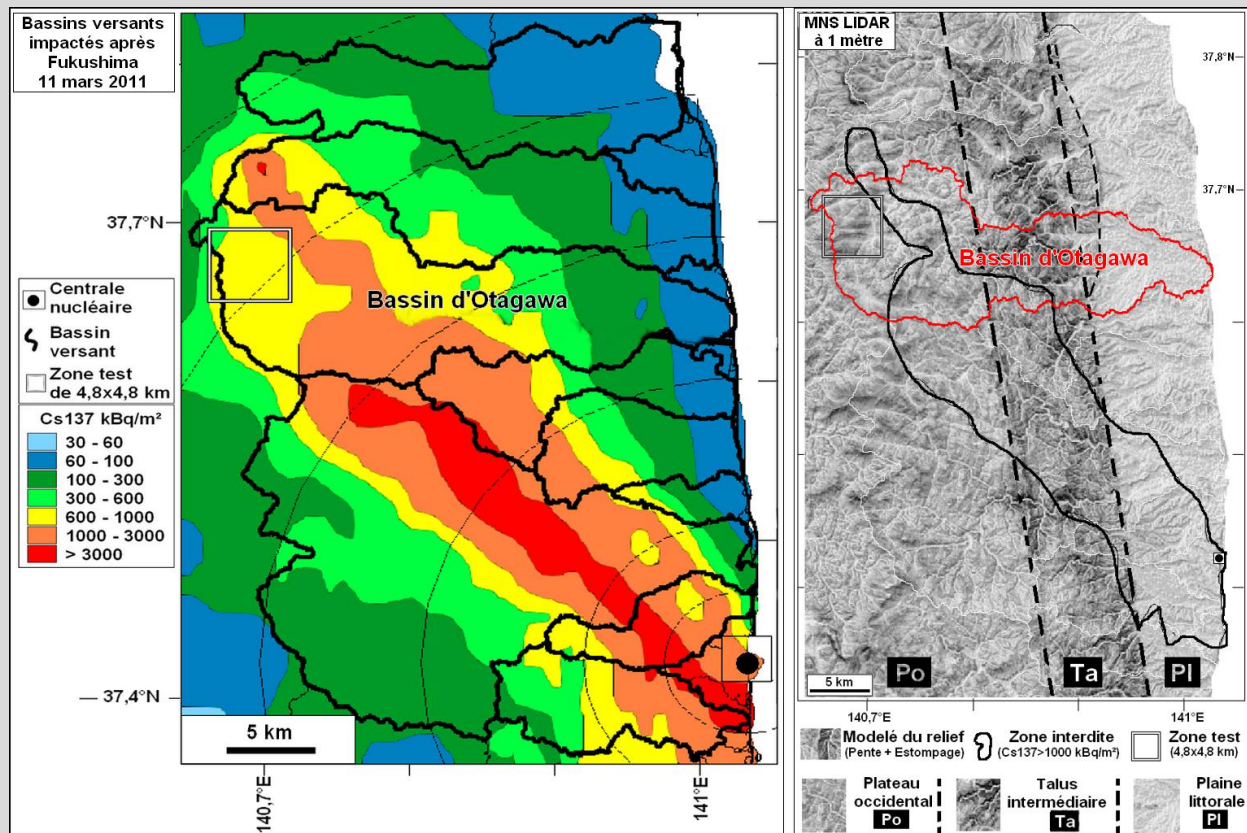
Figure 14 : example of probabilistic sub-surface percolation of 100 mm of infiltrated rainfall on one of the multidirectional drainage lines flowing from mesh M(3,4) down to the outlet on mesh M(4,1) via the meshes M(2,3) and M(3,2).

Nota bene: The DRAMP¹³ method as used in this document computes the number of upstream multi directional lines passing through and not the cumulative amount of water as explain in **Figure 14**.

¹³ DRAMP : DRAINage Multidirectionnel Probabiste

What's the hell with multidirectional sub superficial percolation methods?

Apart from hydrogeomorphological mapping, these methods could help in the process of modelling pollutant in soils and superficial pervious geomorphological formations. One example is about the percolation of some radioactive particles after the blast of the Fukushima nuclear power station in March 2011. In the context of the project "Improving models for predicting dispersion and assessing the impact of radionuclides in the environment"* , one objective was to model the redistribution of radionuclides, in particular caesium 137, over the catchment areas affected by the plume of radioactivity. Field measurements in 2014 suggested that these specific radionuclides could be trapped ("adsorption") by the clay layers associated with the crop and rice fields at the bottom of the valleys, while their concentration had fallen sharply on the slopes. An upgrade of the DRAMP combined with TOPMODEL could help in the process of modelling the radionuclides percolation within soil apart from solution transport by surface runoff and rivers. To test this, we had a sample of the 1-metre LIDAR DEM produced by the Japanese authorities following the events. Due to the complexity of the geology and the tectonic of this region, it was necessary to implement the basic outline of the sub surface percolation routing with complementary field measurements about the dynamic of water in various geomorphological contexts.



* AMORAD : Amélioration des modèles de prévision de la dispersion et d'évaluation de l'impact des radionucléides au sein de l'environnement (projet ANR-11-RSNR-0002), 2014.

Appendix 7: geomorphological hydrograph of the Riou Catchment

Excerpt from an unpublished paper:

C. Depraetere, 2024. « Exploitation hydro-géomorphométrique des MNT haute résolution de l'IGN :
Le cas des 'chemins de l'eau' dans la vallée des Duyes (Alpes de Haute Provence) ». *Revue semestrielle « Dynamiques environnementales », Université d'Orléans*
(Translation in English from French partly with DeepL)

The methods for unit geomorphological hydrograph¹⁴ (UGH, [22][23][4][24]) used on catchment basins where no gauging and no precipitation data are available. This is the case of the Riou Catchment. Despite their limitations, they gives an estimate on the main characteristic of hydrograph: the lag time to the peak of storm flow and the peak flow in m³/s. The hypothesis of uniform rainfalls for intense storm is tolerable for small catchment like the Riou. Assuming a storm of 200 mm in one hour and a water runoff of 25% (50 mm/h) all over the catchment, the resulting hydrograph would have a time lag of about one hour and a peak flow of 15 m³/s.

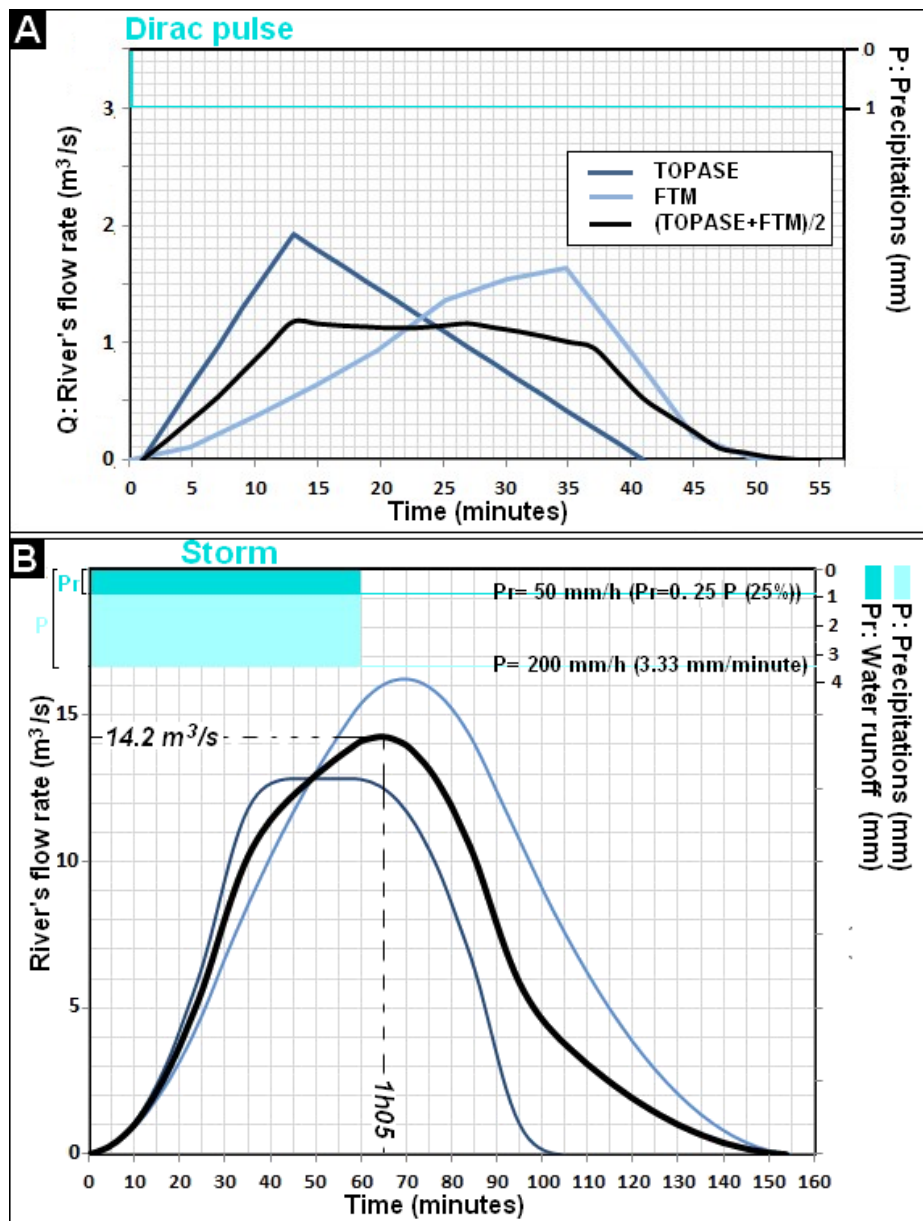


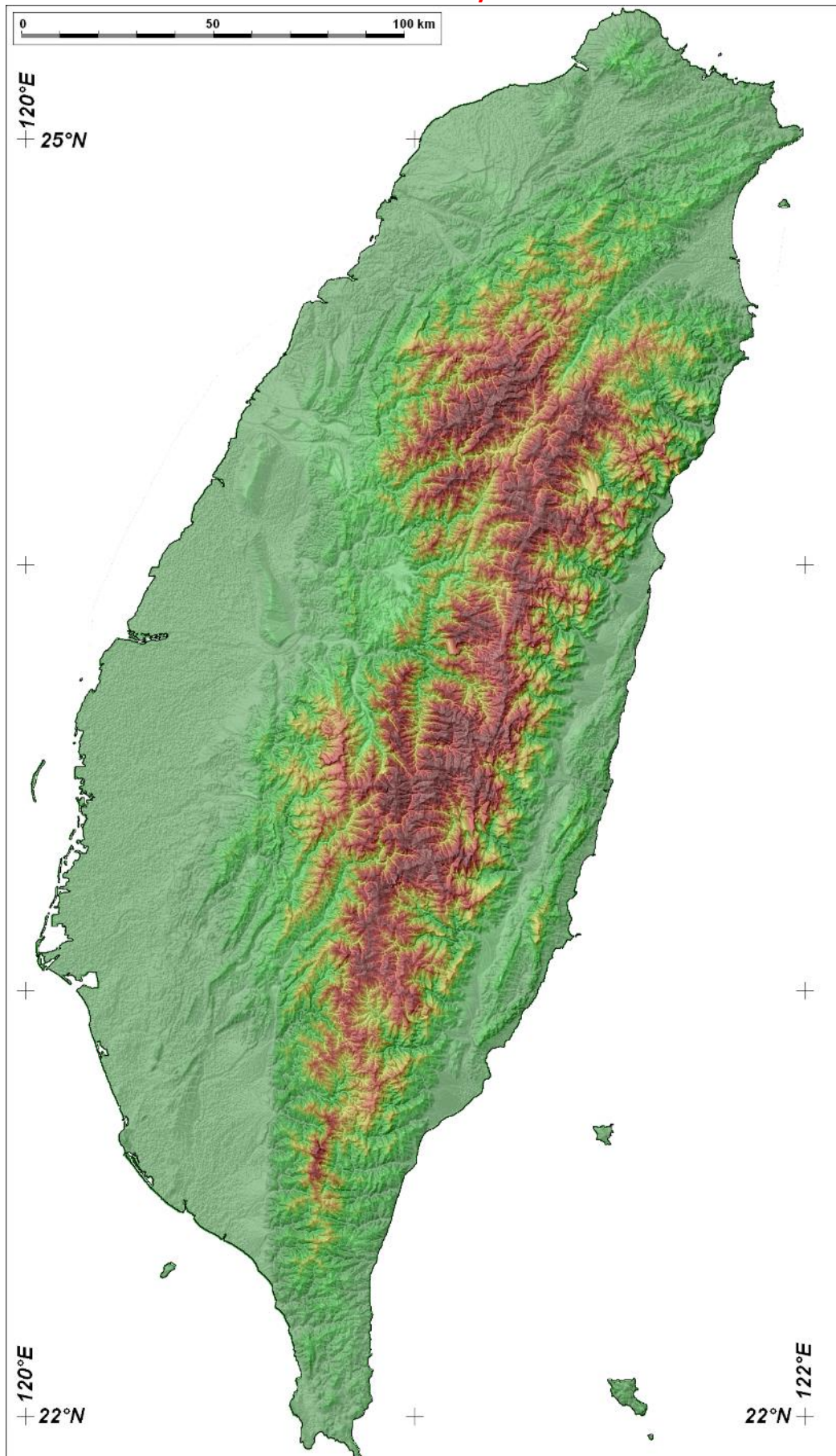
Figure 15 : Unit Geomorphological hydrograph (UGH) of the Riou catchment A./ Two UGHs of the Riou with a Dirac rainfall pulse (1 mm) with the two methods TOPASE and FTM.

B./ Convolution and combination of the HGUs with a rainfall event such as a storm of one hour duration with a rainfall intensity of 200 mm/h with 25% of surface water runoff.

¹⁴ In French, Hydrogramme géomorphologique unitaire (HGU).

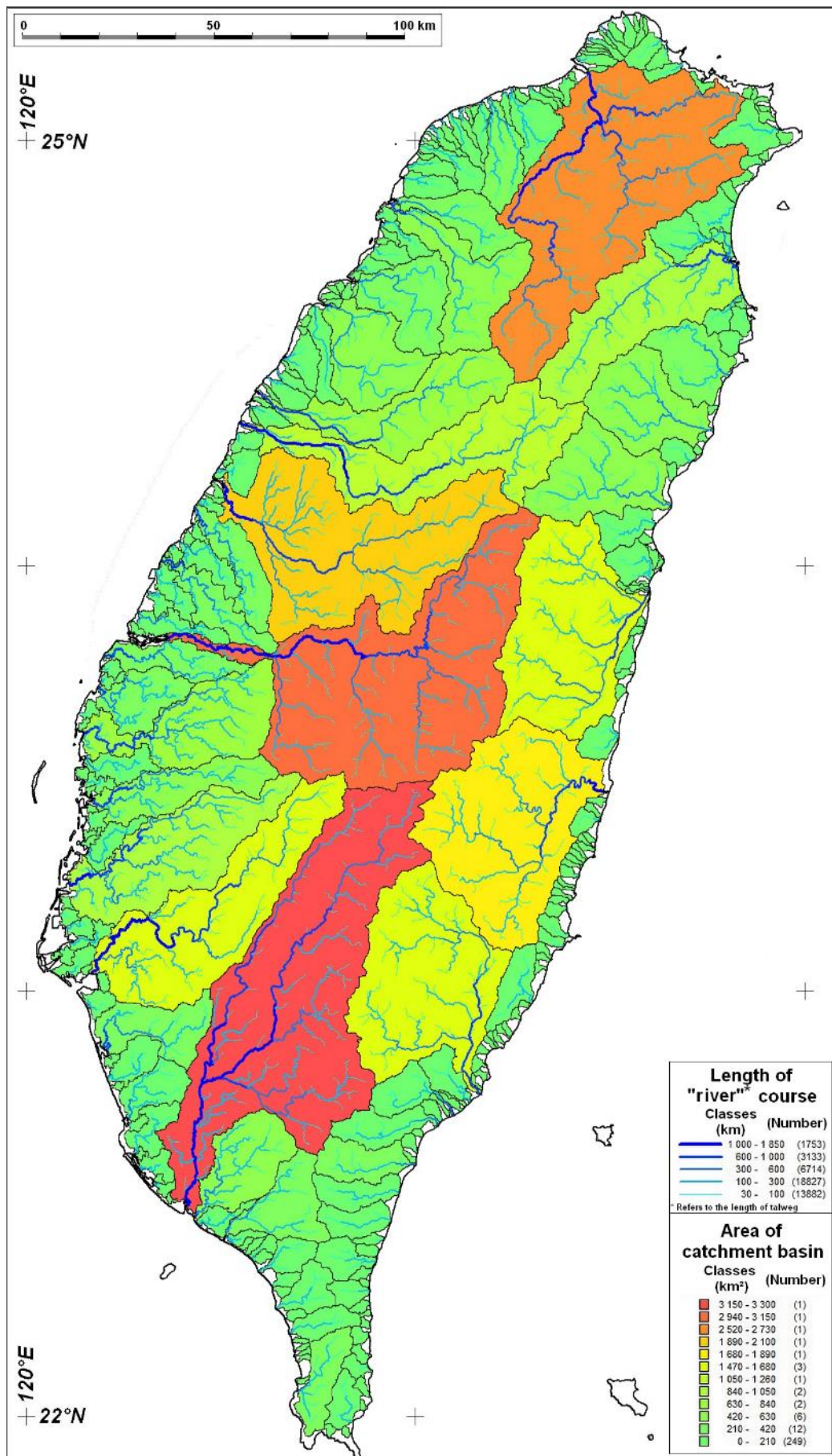
Appendix 9: relief of Taiwan (from SRTM DEM 3 arc second, about 90 meters resolution)

No comment yet.



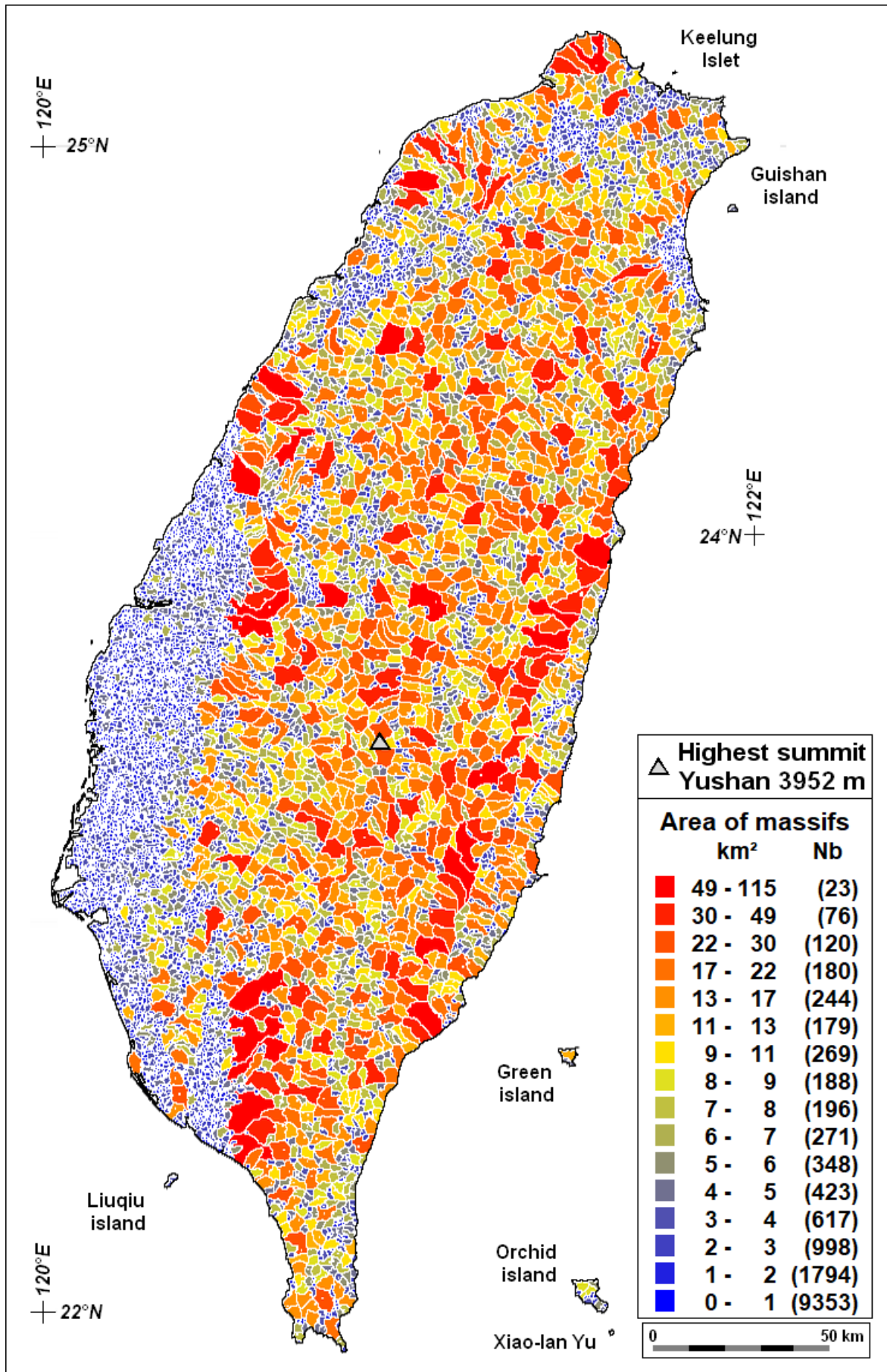
Map 26 : Relief map of Taiwan (from 3 arc second SRTM DEM, resolution about 90 meters)

« rivers » network and catchment basins tessellation.

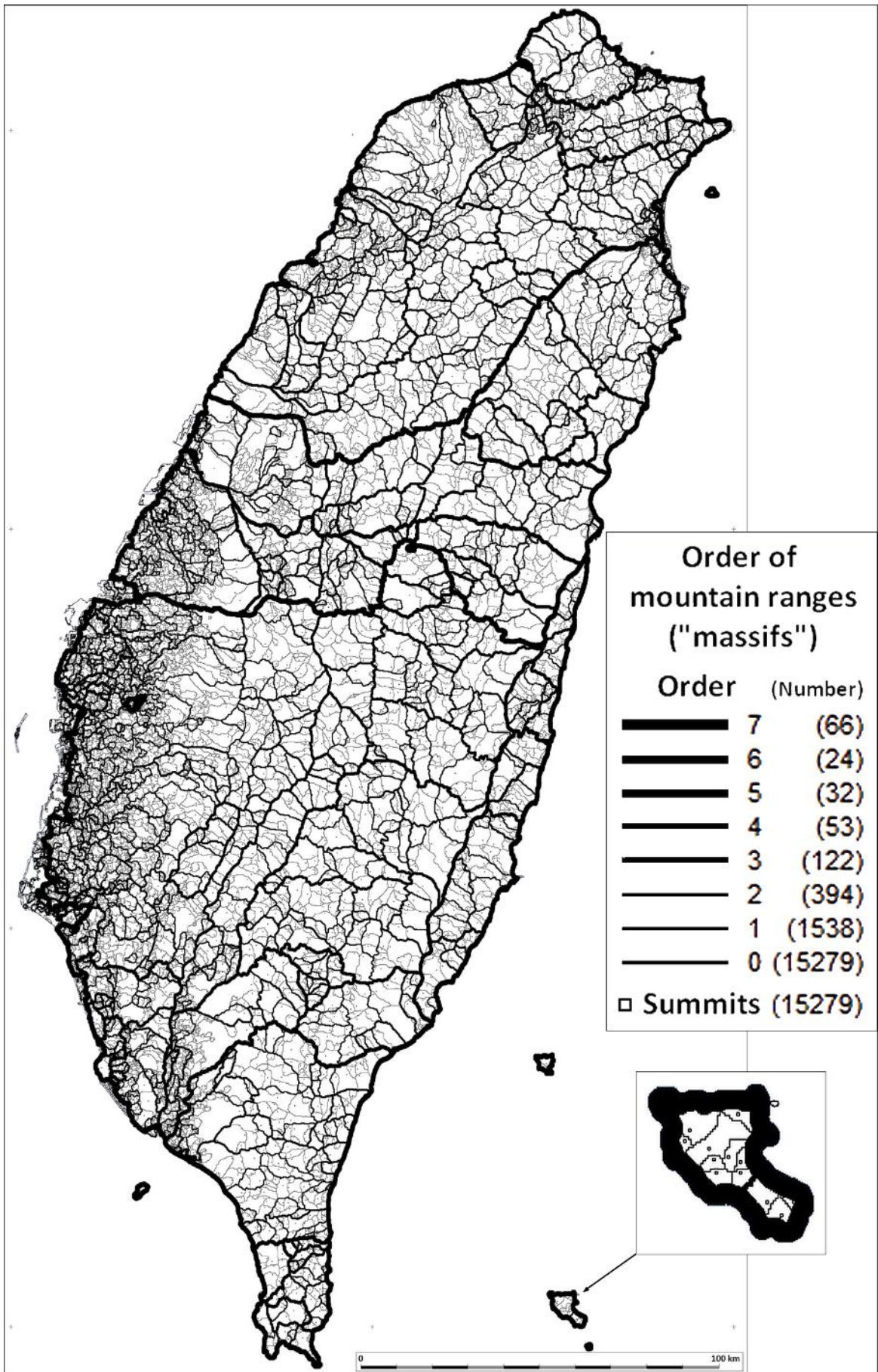


Map 27 : « rivers » and catchment basins

Massives tessellation:



Map 28 : elementary massifs tessellation



Map 29 : massifs tessellation from order 0 (Elementary massives, cf. Map 26) to 7 on Formosa.

Directional variogram of elevation on Formose Scatter plot of elevation on the WE and SN axis

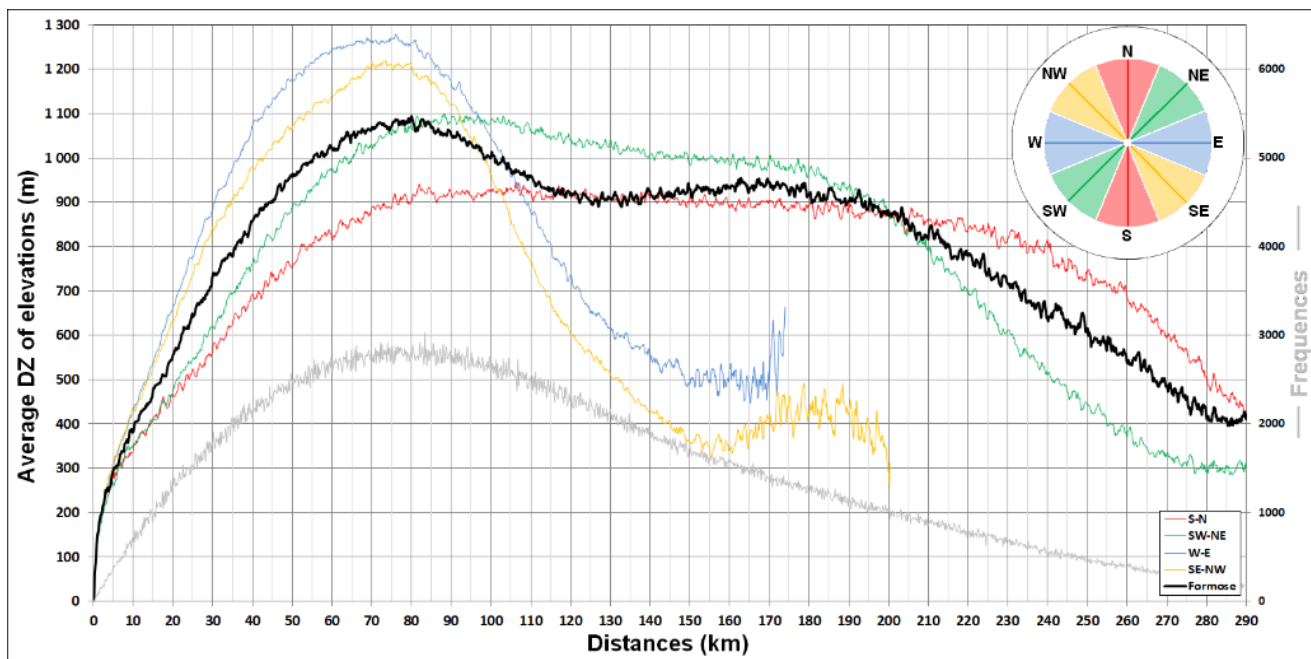


Figure 16 : directional variograms along the four axis SN, SWNE, WE and SENW

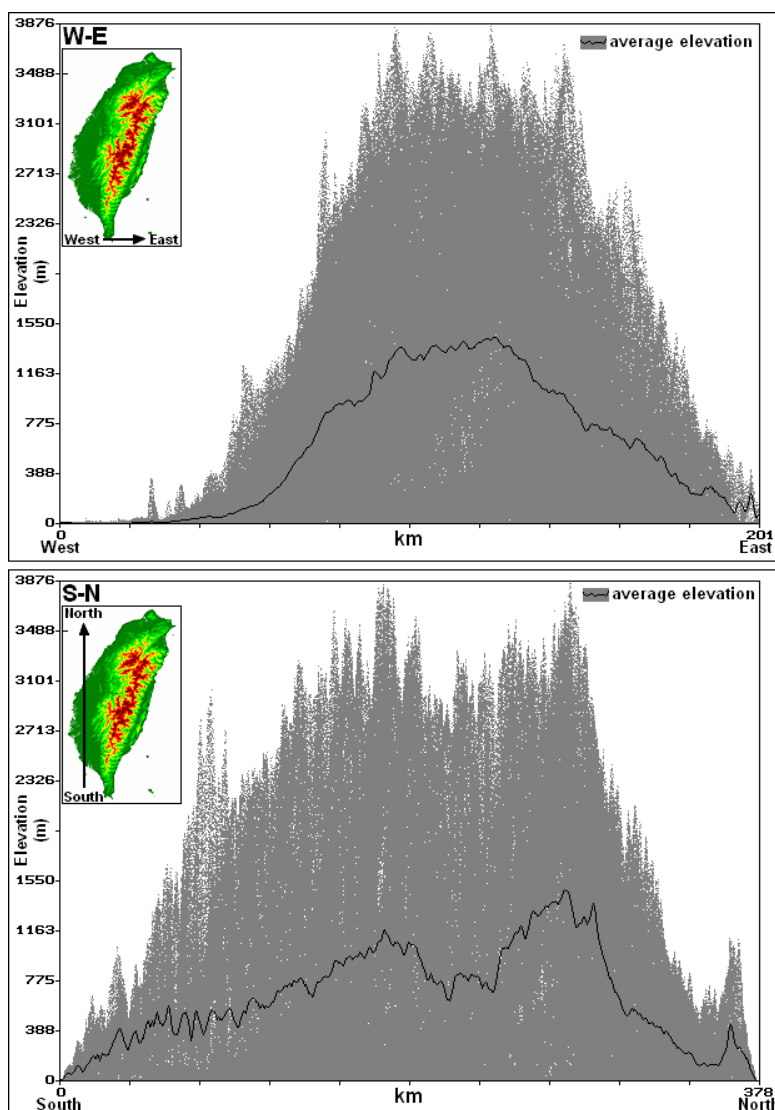


Figure 17 : Scatter plot of elevation along the WE and SN axis.

Cited references:

- [1] Beven K., Kirkby M.J. (1979) : "A Physically Based, Variable Contributing Area Model of Basin Hydrology" Hydrological Sciences Bulletin Vol. 24, No. 1, p 43-69, March 1979. 16 fig, 1 tab, 36 ref.
- [2] Beven, K., and Germann P. (1982): "Macropores and water flow in soils". Water Resour. Res., Volume 18, Issue 5, pages 1311-1325, October 1982
- [3] Depraetere C., (1981): « Le bassin versant de la Bléone (Alpes de haute Provence) : étude de géomorphologie dynamique ». Mémoire de maîtrise de géographie, Université de Paris-Sorbonne, juin 1981.
- [4] Depraetere C. et Moniod F., (1991): « Contributions des modèles numériques de terrain à la simulation des écoulements dans un réseau hydrographique ». Hydrologie Continentale, Vol.6, n°1, pp.29-53, 1991.
- [5] Depraetere C. & **Riazanoff S.**, (2004): « The new Digital Elevation Model data set from the Shuttle Radar Topography Mission: Hydrogeomorphological applications in the Ohrid region (Albania, Greece and Macedonia) ». Conference on Water
- [6] Depraetere C., (2013). « Introduction à l'hydrogéomorphométrie : Etude des relations entre le modelé des formes de terrain et les processus hydrologiques dans des contextes insulaires ». Dossier pour l'Habilitation à Diriger des Recherches (HDR), Ecole Doctorale de l'université Paris-Diderot. Soutenue le 8 novembre 2013
- [19] Depraetere C. & **Riazanoff S.**, (2021). "A Stepwise Massif Partitioning Algorithm Based On Steepest Ascent Method From DEM: Application To Potential Prospection of new archaeological sites". Proceedings of the ICCMSE 2021 conference, Heraklio, Greece, 4-7 September 2021.
- [7] Depraetere C. & **Deffontaines B. and Riazanoff S.**, (2023): "Resampling and hydro-geomorphometrical processing of dense Lidar/DEM: Relationships between landforms and hydrological processes in a Mediterranean peri-alpine catchment basin". To be published in the Proceeding of the Geomorphometry 2023 conference, Iasi, Romania, 8-11 July 2023.
- [8] DEMIURGE version 3.3 (2004): DEM Integrated Utilities for Raster GEomorphometry (Chaîne de production et de traitement de MNT appliquée à l'hydrologie. (Logiciels T2, OROLOG, LAMONT4, TOPASE et FTM sur Cédérom). Christian Depraetere, Institut de Recherche pour le Développement (IRD), Paris, octobre 2004.
- [9] Derruau, M., (1965). Précis de Géomorphologie, 1965. Masson & Cie, Paris, 415 pages
- [10] Descroix L. (1998). « L'érosion hydrique dans les terrains peu résistants des Préalpes françaises du sud : mesures et variables explicatives sur parcelles et bassins-versants ». In : Recherches dans les Alpes françaises du sud : bocages du Champsaur, cartographie des alpages, érosion et mouvements de terrain; tourisme en haute montagne. Revue de Géographie Alpine, (1), p. 43-58. ISSN 0035-1121.
- [11] Descroix L., Gauthier E., Olivry J-C. (2002). « L'influence de la végétation et de son évolution dans les processus d'érosion dans les Alpes du Sud ». In : Roose Eric (ed.), Sabir M. (ed.), De Noni Georges (ed.). Techniques traditionnelles de GCES en milieu méditerranéen. Bulletin - Réseau Erosion, (21), p. 346-357. La Gestion Traditionnelle de l'Eau, de la Biomasse et de la Fertilité des Sols, Base d'une Nouvelle Approche de la Lutte Antiérosive dans les Montagnes Marocaines : Journées Scientifiques, Salé (MAR), 2002/02/08-09.
- [12] Evans I.S., (1972): "General Geomorphometry, derivatives of altitude and descriptive statistics". In Chorley R.J. (editor), Spatial analysis in geomorphology, Methuen, London, pp.17-90.
- [13] Evans I.S., (1981): "General Geomorphometry". In Geomorphological techniques B.G.R.G., A. Goudie et al (Editors), George Allen et Unwin, London, pp.31-37.
- [14] Fairfield J. and Leymarie P. (1991) Drainage networks from grid digital elevation models. Water Resources Research 27: 709-717. CrossRefWeb of Science
- [15] Kirkby M.J., (1993): "Network Hydrology and geomorphology". In Channel Network Hydrology (K. Beven & M.J. Kirkby Ed.) John Wiley Chichester. 1-11.
- [16] Lin J.C, 2022. « Geomorphology ». Centre d'édition de l'Université National Taiwan University Press, Taipei, Taiwan, 2022, 608 pages, couleurs, langue chinoise.
- [17] Mérot Ph., (1988): « Les zones de source à surface variable et la question de leur localisation ». Hydrologie Continentale, Vol. 3, n°2, pp.105-115.
- [18] O'Loughlin E. M., (1986): "Prediction of Surface Saturation Zones in Natural Catchments by Topographic Analysis". Water Resources Research, vol. 22, issue 5, pp. 794-804, 1986
- [20] Pfafstetter, O. (1989). « Classificação de Bacias Hidrográficas – Metodologia de Codificação ». Rio de Janeiro, RJ: Departamento Nacional de Obras de Saneamento (DNOCS), 1989, p. 19.
- [21] Rasemann S., (2004): „Geomorphometrische Struktur eines mesoskaligen alpinen Geosystems“ : mit 19 Tabellen / von Stefan Rasemann. - Sankt Augustin : Asgard-Verl., 2004. - VIII, 240 S. : Ill., graph. Darst., Kt. & 1 Kt.; (ger / dt.) Reihe: (Bonner geographische Abhandlungen ; 111) Zugl.: Bonn, Univ., Diss. Mit e. Zsfassung in dt. u. engl. Sprache
- [22] Rodríguez-Iturbe, Ignacio; Valdés, Juan B., (1979): "The Geomorphologic Structure of Hydrologic Responses". Water Resources Research, vol. 15, issue 6, pp. 1409-1420, 1979.
- [23] Rodríguez-Iturbe I., (1993): "The geomorphological unit hydrograph". In Channel Network Hydrology. (K. BEVEN & M.J. KIRKBY Ed.) John Wiley Chichester. 43-68.

- [24] Serrat P., Depraetere C., (1997): « Incidences de facteurs géomorphologiques sur le fonctionnement d'un bassin en situation de crue : l'exemple de l'Agly (Pyrénées Orientales) ». *Géomorphologie : Relief, processus, environnement*, 1997 n°1, SEDES, Paris, pp 73-88.
- [25] Steyn D.G., (1976). "Computation of azimuth slope angles and surface normals over a given topography". *South African Geographical Journal*, Vol. 58, n°2, September 1976 pp.131-134.
- [26] Talancieux J., Vinai L., (2020). 3Les Duyes et ses principaux affluents : visite pour analyse des enjeux hydromorphologique dans la vallée des Duyes et entretien de ripisylve3. Rapport de visite du bassin versant des Duyes du Syndicat Mixte Asse Bléone. (SMAB) Digne. 37 pages.
- [27] Topography Digital Elevation Modeling, (1982). PacSoft 733 Seventh Avenue, Kirkland, Washington 98033.
- [28] Wood J., (2009). "Overview of software package used in geomorphometry". *Developments in Soils Science*, Vol. 33, 2009. P. 257-267. *Geomorphometry – Concepts, Software, Applications*.
- [29] Dupéret, A. & **Deffontaines, B.** (2004). "Digital Analysis and Basic Shape Relief Extraction from DTM". *International Archives of Photogrammetry Remote Sensing and Spatial Information Sciences* 35.
- [30] Baulig H. (1956). « Vocabulaire franco-anglo-allemand de géomorphologie ». Publication de la Faculté des Lettres de l'université de Strasbourg, Société d'édition des Belles Lettres, Paris, 230 pages.
- [31] Depraetere C., Serge Riazanoff S., (2023). "Catchment basin versus Mountain range tessellations from DTM on islands: Anticosti, Crete, Hawaii, New-Caledonia and Formosa". *Mediterranean Geosciences Union (MedGU) conference*, 27 - 30 November 2023, Istanbul, Turkey. <https://www.medgu.org/index.php>

Other references:

- Ao Tianqi , Takeuchi K. , Ishidaira H., Yoshitani J. & Fukami K., (2003): "Development and application of a new algorithm for automated pit removal for grid DEMs", *Hydrological Sciences–Journal–des Sciences Hydrologiques*, 48(6) December 2003, pp985-997.
- Chorowicz J., Ichoku C., **Riazanoff S.**, Youn-Jong Kim, Cervelle B., (1992): "A Combined Algorithm for Automated Drainage Network Extraction" in *Water Resources Research*, vol.28, n°5, pp.1293-1302. American Geophysical Union,
- Dikau, R., (1989): "The application of a digital model to landform analysis in geomorphology". Chapter 5 in "Three dimensional applications in Geographical Information Systems", Edited by Jonathan Raper, Taylor & Francis, London, New-York, Philadelphia, 1989, pp. 51-77.
- Dikau, R., (1990): „Digital relief models in landform analysis“. In *GIS: Three Dimensional Applications in Geographic Information Systems* ed. J. Raper, 51-77.
- Dupéret, A. et **Deffontaines B.**, (2004): « Digital analysis and basic shape relief extraction from DTM. Congrès ISPRS, Société Internationale de Photogrammétrie et de Télédétection, Geo-Imagery Bridging Continents, XXth ISPRS Congress, 12-23 July 2004 Istanbul, Turkey.
- Dupéret A., **Deffontaines B.**, Passalacqua O., (2003): « Critères géomorphométriques issus des modèles numériques de terrain au service des applications hydrologiques = Geomorphometric criteria from the digital terrain models used for hydrological applications ». *Bulletin de la Société française de photogrammétrie et de télédétection* 2003, n°172, pp. 107-121
- Evans, Ian. (1980): An integrated system of terrain analysis and slope mapping. In *Zeitschrift fur Geomorphologie* 36: 274-295.
- Evans I.S. & McClean C.J., (1995): "The land surface is not unifractal; variograms, cirque scale and allometry". *Zeitschrift Fur Geomorphologie Supplement-Band 101: 127-147*.
- Gonçalves G., Julien P., **Riazanoff S.** & Cervelle B., (1999): « Le problème des courbes intercalaires dans la construction d'un MNT maillé à partir des courbes de niveau », Colloque SIPT/ISPRS, WGII/6, " Production des données géographiques 3-D vers le respect des contraintes applicatives ", Paris (F), 7-9 avril 1999, in *Bulletin de la SFPT n° 153 (1999/1)*, laboratoire MATIS, IGN-SR 990003/C-ART, 1999
- Guth, P.L., (1989): "Microdem+: Comparing Digital Elevation Models on Personal Computer". *Proceedings of Defense Mapping Agency, System Center Symposium 89*, pp. 389-394.
- Guth, P.L., (1992): "Microcomputer application of digital elevation models and other gridded data sets for geologists": in Merriam, D.F., and Kürzel, H., ed., *Use of Microcomputers in Geology*, [Proceedings International Geological Congress], Computer Applications Series, Plenum, pp.187-206.
- Guth, P.L., Ressler, E.K., and Bacastow, T.S., (1987): "Microcomputer program for manipulating large digital terrain models": *Computers & Geosciences*, vol.13, no.3, pp. 209-213.
- Guth, P.L., (1995): "Slope and aspect calculations on gridded digital elevation models: Examples from a geomorphometric toolbox for personal computers": *Zeitschrift für Geomorphologie N.F. Supplementband 101*, pp.31-52.
- Guth, P. L.: Drainage basin morphometry (2011): a global snapshot from the shuttle radar topography mission, *Hydrol. Earth Syst. Sci.*, 15, 2091-2099, doi:10.5194/hess-15-2091-2011, 2011.
- Hjelmfelt A.T., (1988): "Fractals and the river length catchment-area ratio". *Water Res. Bull.* 24, 455-459.

- Hutchinson M.F., (1989) : "A new procedure for gridding elevation and stream line data with automatic removal of spurious pits". *Journal of hydrology*, 1026 : 211 – 232.
- La Barbera, P. and Rosso, R., (1989): "On the fractal dimension of stream networks". *Water Resour. Res.*, 1989, 25(4):735-741.
- Lea NL, Parsons AJ, Abrahams AD Lea NL (1992) An aspect driven kinematic routing algorithm. In: Parsons AJ and Abrahams AD (eds) *Overland Flow: Hydraulics and Erosion Mechanics*. New York: Chapman and Hall, 393-407.
- Liu T., (1992): "Fractal structure and properties of stream networks". *Water Resour. Res.*, 28(11): 2981-2988.
- Mandelbrot B. B., (1977): "Fractals: Form, Chance, and Dimension", Freeman, San Francisco, USA.
- Mandelbrot B. B., (1982): "The Fractal Geometry of Nature". Freeman, New York, USA.
- Merlin P., (1965): « A propos des méthodes de la géomorphométrie ». *Acta Geographica*, Paris, n°56, pp.14-20.
- Microdem MICRODEM, (1990): PETMAR Trilobite Breeding Ranch-Geoscience Software, Stephen C. Guth 107 Claude Street Annapolis MD 21401-1207
- Miller C.L. & Laflamme R.A., (1958): "The digital terrain model". - *Engineer. and Remote Sensing*, 24: 433-442.
- Moniod F., (1983) : « Deux paramètres pour caractériser le réseau hydrographique ». *Cahiers ORSTOM, série hydrologie*, vol. XX, n°3 et 4, pp.191-203.
- Moore I.D., Grayson R.B. & Ladson A.R., (1993): "Digital terrain modelling. A review of hydrological, geomorphological and biological application". In *Terrain analysis and distributed modelling in Hydrology* (K. BEVEN & I.D. MOORE, Ed.). John Wiley Chichester. 7-34.
- Moussa R. et Bocquillon C., (1996): "Fractal analyses of tree-like channel networks from digital elevation model data". *Journal of Hydrology*, "Fractals, scaling and nonlinear variability in hydrology", Volume 187, Issues 1–2, December 1996, Pages 157–172.
- O'Callaghan J.F., Mark D.M., (1984): "The extraction of drainage networks from digital elevation data", *Computer vision, Graphics and image processing* n°28, pp. 323-344.
- O'Loughlin E.M., (1981): "Saturation regions in catchment basin and their relations to soil and topographic properties". *Journal of Hydrology*, Vol. 53, n°3/4, pp.229-246, octobre 1981.
- O'Loughlin E.M., Short D.L., Dawes W.R., (1989): "Modelling the hydrological response of catchment to land use change". *Hydrology and Water Resources Symposium 1989, Christchurch, N-Z*, 23-30 novembre 1989, pp.335-340.
- Perron, J.T., P.W. Richardson, K.L. Ferrier, and M. Lapôtre, (2012): "The root of branching river networks". *Nature*, 492, 100-103.
- Serrat P., (2000): « Genèse et dynamique d'un système fluvial méditerranéen : le bassin de l'Agly (France) ». Thèse doctorat Géographie, MEDI-TERRA et CNRS UPRES-A 6042, université Blaise Pascal, université de Perpignan, 2000 .- 653 p. + annexes. (prix Milon 2002 ex-aequo)
- Tarboton D.G., Bras R.L., Rodriguez-Iturbe I., (1988): "The fractal nature of river networks" *Water Resources Research*, Volume 24, Issue 8, p. 1317-1322, 1988
- Tarboton D.G., Bras R. L. and Rodriguez-Iturbe I., (1991): "On the Extraction of Channel Networks from Digital Elevation Data," *Hydrologic Processes*, 5(1): 81-100.
- Tarboton D.G., Bras R. L. and Rodriguez-Iturbe I., (1992): "A physical basis for drainage density," *Geomorphology*, 5(1/2): 59-76.
- Tarboton D.G., Bras R. L. and Rodriguez-Iturbe I., (1993): "On the extraction of channel networks from digital elevation data". In *Terrain analysis and distributed modelling in Hydrology*. (K. Beven & I.D. Moore Ed.) John Wiley Chichester. 85-104.
- Tarboton D. G., (1993): "Fractal river networks, Horton's laws and Tokunaga cyclicity". *Journal of Hydrology*, Issues 1–2, December 1996, 187 (1996) 105-117
- Tarboton D. G., (1997): "A New Method for the Determination of Flow Directions and Contributing Areas in Grid Digital Elevation Models," *Water Resources Research*, 33(2): 309-319.
- Veltri P. et Maiolo M., (1996): "On the fractal description of natural channel networks". *Journal of Hydrology*, "Fractals, scaling and nonlinear variability in hydrology", Volume 187, Issues 1–2, December 1996, Pages 137–144
- Zeverbergen L. and Thorne C., (1987): "Quantitative analysis of land surface topography". In *Earth Surface Processes and Landforms* 12: 47-56.

Illustrations:

Table 1 : the GIS layers derived from the RGE-ALTI-SEAD DEM at 10 metres resolution	2
Table 2 : terminology related to hydrogeomorphology	2
Map 1 : main hydrological parts of the Duyes catchment bassin (Delineated from RGE-Alti-SEAD-10m).	4
Map 2 : topography of the Duyes catchment basin (From RGE-Alti-SEAD-10m)	5
Map 3 : gray scale of slope gradients	10
Map 4 : shading	11
Map 5 : composite map of slope gradient and shading.	12
Map 6 : north and south facing slopes (ubac et adret)	13
Map 7 : slope gradients in percentage (%)	14
Map 8 : slope gradients in degree (°)	15
Map 9 : plan convexities (convexités horizontales)	18
Map 10 : profile convexities (convexités verticales)	19
Map 11: transverse convexities (convexités transversales)	20
Map 12 : Mean curvature (Courbure moyenne)	22
Map 13 : log of mean quadratic curvature (Courbure moyenne quadratique)	23
Map 14 : monodirectionnel drainage on the Adrech catchment basin (From [3])	24
Map 15 : detail of the D8 drainage pattern on the Riou catchment basin	25
Map 16 : distances to the outlet in km.	26
Map 17 : lengths of drainage in km (Alias length of river)	30
Map 18 : area of the upstream catchment basin.	31
Map 19 : Examples of various Log(ISSF) flow patterns.	32
Map 20 : sub-surface flow paths (Method DRAMP)	33
Map 21 : sub-surface flow paths with Log(DRAMP) (see Map 20).	34
Map 22 : extraction and coding of sub catchments (Pfafstetter-Bocquillon method and coding)	36
Map 23 : pattern of massifs from level 0 (elementary massifs) to level 5	39
Map 24 : the elementary massifs at the East of Thoard and nearby the Riou catchment.	41
Map 25 : combination of sub catchments (Map 22) and elementary massifs (Map 23).	43
Map 26 : Relief map of Taiwan (from 3 arc second SRTM DEM, resolution about 90 meters)	59
Map 27 : « rivers » and catchment basins	60
Map 28 : elementary massives tessellation	61
Map 29 : massives tessellation from order 0 (Elementary massives, cf. map 26) to 7 on Formosa.	62
Photo 1 : « Reading landscape » tutorial for kids on the Duyes valley from Thoard's spur (August 2006)	1
Photo 2 : the Montagne de Mélan (Left) and Geruen (Center).....	17
Photo 3 : view of the Adrech Valley from the village of Esclangon, Haute Provence	24
Figure 1 : the book of professor Lin-Chuan Lin [16] and the concept of “reading landscape”	1
Figure 2 : combination of elevations and slope gradients on the Duyes catchment	16
Figure 3 : long profile of catchment basins from distance to the outlet.....	27
Figure 4 : the standardized hypsometric curve for the Duyes catchment	28
Figure 5 : the standardized hypsometric curve for the Duyes catchment	Erreur ! Signet non défini.
Figure 6 : extended topological PB coding for the Duyes catchment basin related to Map 21.	35
Figure 7 : influence of plan curvature on the course of a slope line. Slope lines derived up and down the slope take different courses when plan curvature occurs (from [21] [19]).	37
Figure 8 : maps of massif from level 0 to level 5	37
Figure 9 : Area of elementary massifs (Level 0)	40
Figure 10 : The Vançon and Duyes valleys, seen from the south-west, in their regional context	42
Figure 11 : directional variograms of elevations on the Duyes catchment.	44
Figure 12 : scatter plot of the Duyes catchment elevations.....	45

Figure 13 : mono (A, B and C) and multidirectional drainage (A', B' and C') patterns according to the DTM resolution (5 meters in A and A', 10 meters for B and B', 25 meters for C and C') on the Riou Catchment.	46
Figure 14 : example of monodirectional and multidirectional drainage lines from one mesh.	56
Figure 15 : example of probabilistic sub-surface percolation of 100 mm of infiltrated rainfall.....	56
Figure 16 : Unit Geomorphological hydrograph (UGH) of the Riou catchment A./ Two UGHs of the Riou with a Dirac rainfall pulse (1 mm) with the two methods TOPASE and FTM.....	58
Figure 17 : directional variograms along the four axis SN, SWNE, WE and SENW	63
Figure 18 : Scatter plot of elevation along the WE and SN axis.	63