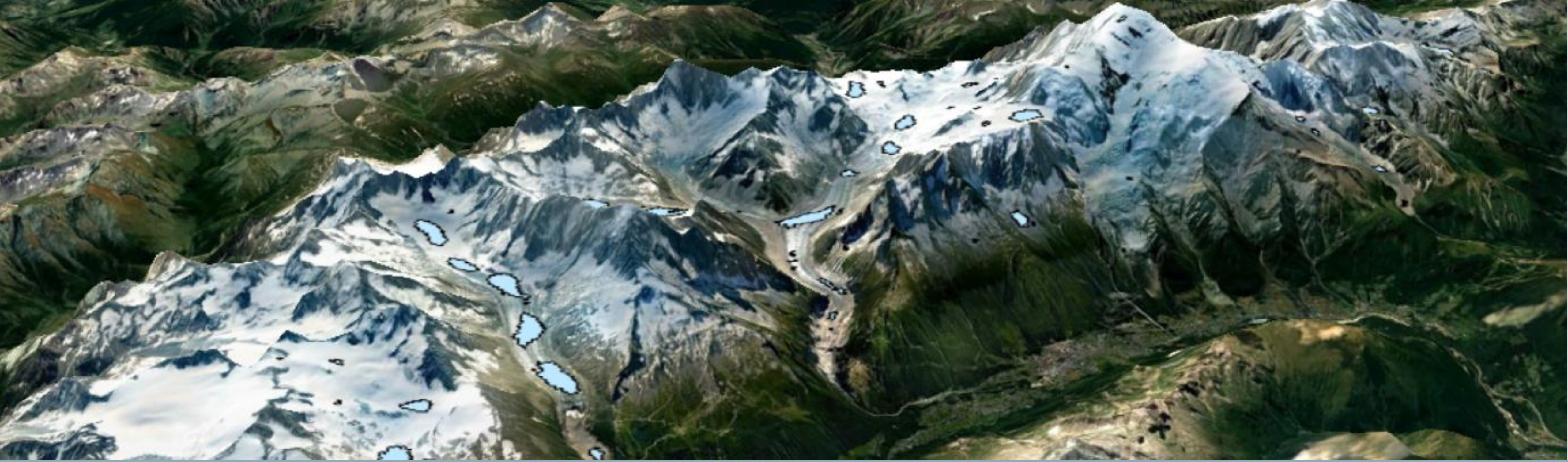

Modelling glaciers bed overdeepenings as sites for possible future lakes in deglaciating landscapes of the French Alps

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EGU 2020

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Introduction

DEGLACIATING LANDSCAPES : WHAT ARE THE ISSUES ?

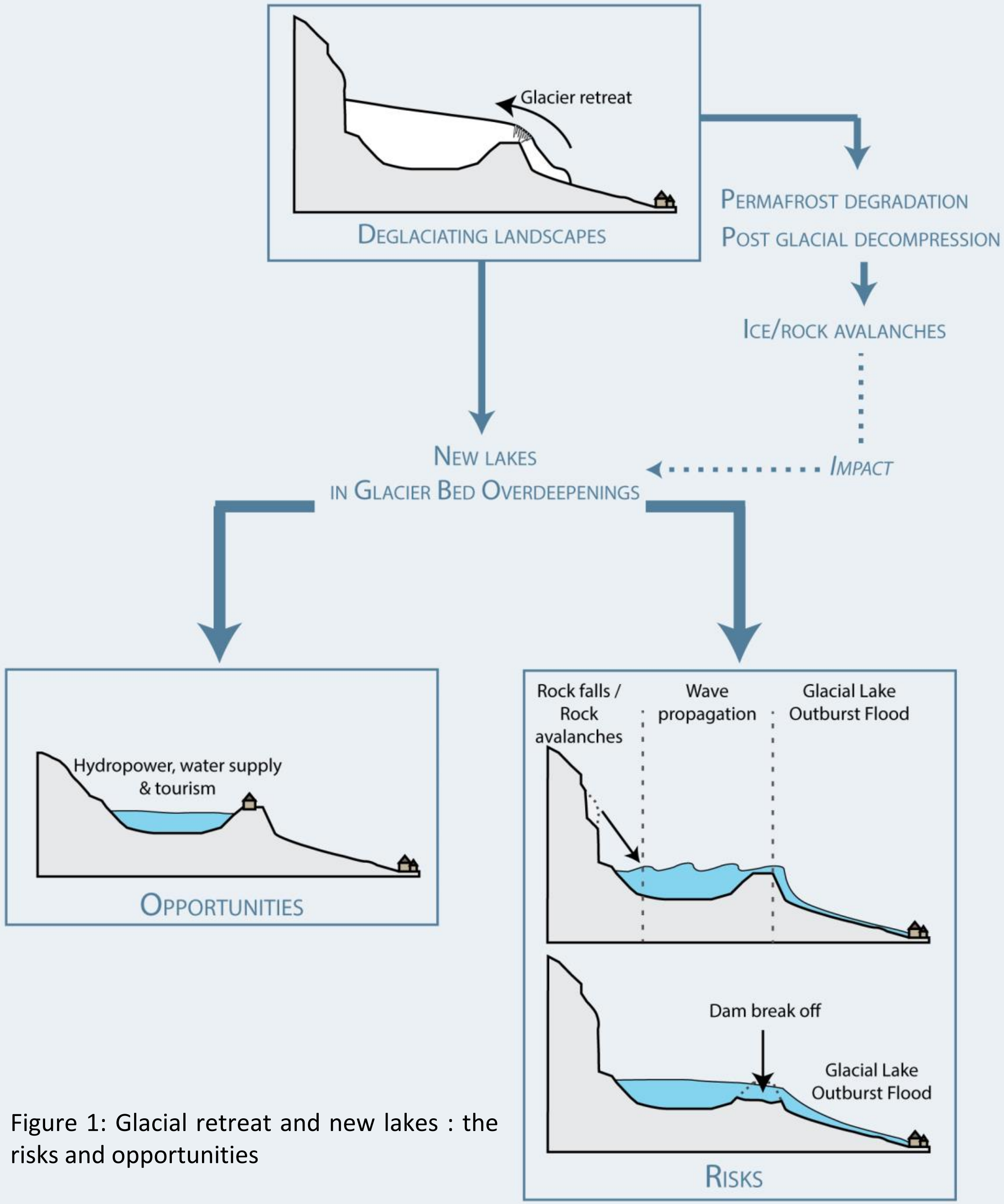


Figure 1: Glacial retreat and new lakes : the risks and opportunities

Issues :

- Human
- Socio-economics

Necessity

- Anticipate risks and opportunities associated with future proglacial lake formation
- Constitute a baseline for decision for decision-makers in long term planning

Approach

- Modelling glacier bed topography with GlabTop and GlabTop 2

→ Objectives : anticipate the location and formation of potential future lakes to apprehend possible risks and seize opportunities in the French Alps

The French Alps, a deglaciating mountain range

FRENCH ALPS :

- **581 glaciers** (surface area : **275,4km²**) during the 2006-2009 period
- **A loss of 50% of their surface** between the end of the Little Ice Age (LIA) and the 2006/2009 period in the Ecrins, Vanoise and Mont Blanc massifs (Gardent et al., 2014)
- Glacier recession **2.5 times faster** between the periods 1967-1971 and 2006-2009 (-25% over the period ; Gardent et al., 2014)

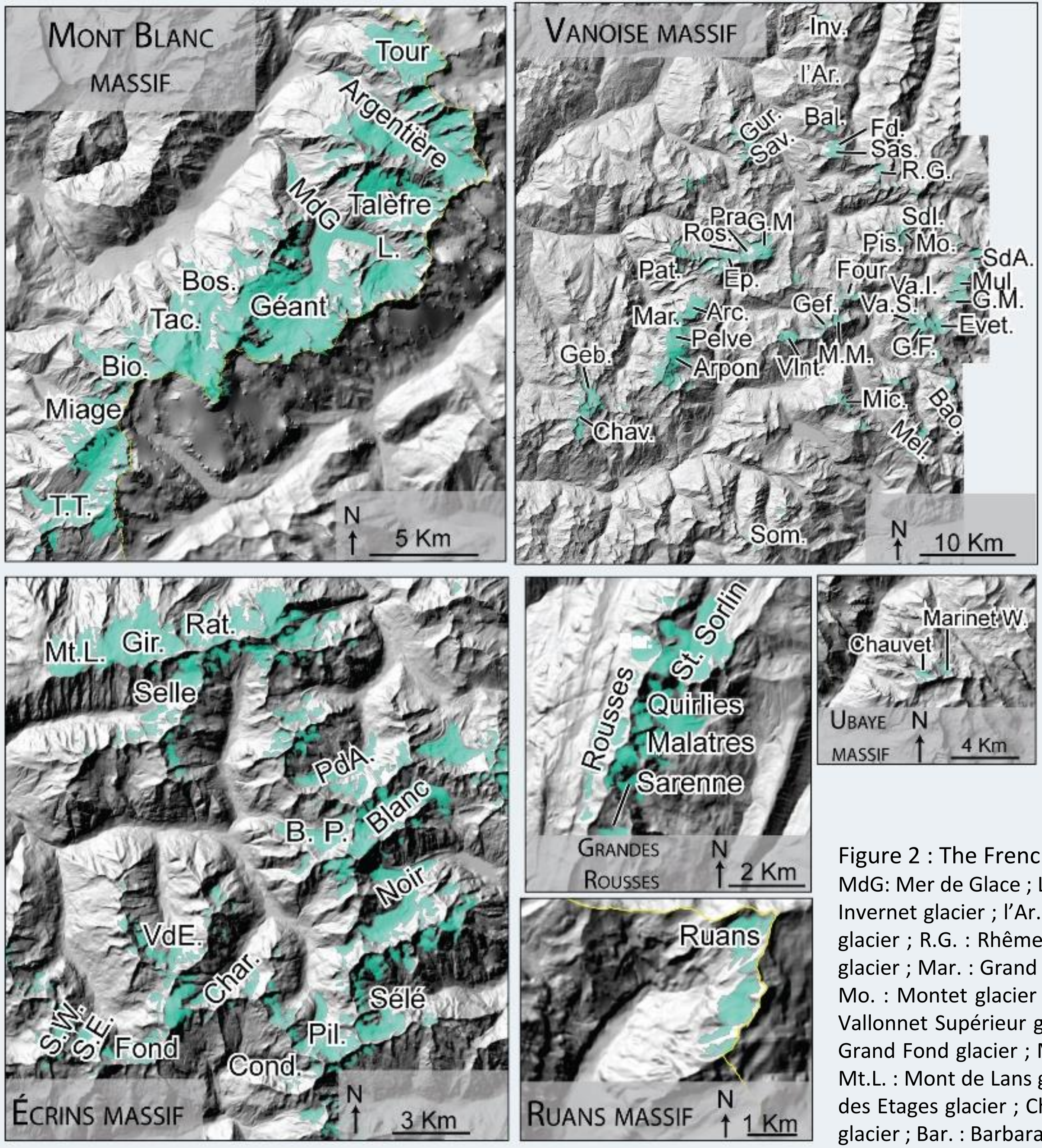
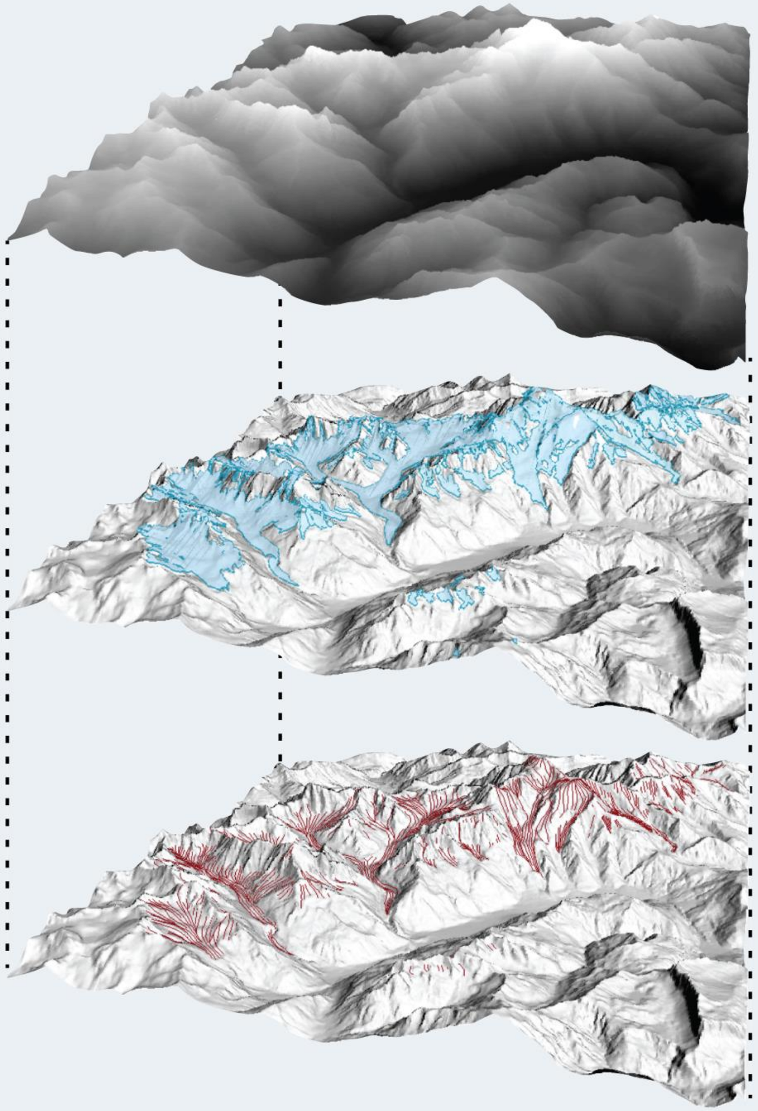


Figure 2 : The French Alps and their main ice-covered massifs. Blue areas are glaciers.
MdG: Mer de Glace ; L.: Leschaux glacier; Bos. : Bossons glacier ; Tac. : Taconnaz glacier ; Bio. : Bionnassay glacier ; T.T. : Tré la Tête Glacier ; Inv. : Invernet glacier ; l'Ar. : l'Argentière glacier ; Bal. : Balmes glacier ; Gur. : Gurraz glacier ; Sav. : Savinaz glacier ; Fd. : Fond glacier ; Sas. : Sassière glacier ; R.G. : Rhêmes Golette glacier ; Pra. : Pramort glacier ; Grande Motte glacier ; Ros. : Rosolin glacier ; Ep. : Epéna glacier ; Arc. : Arcelin glacier ; Mar. : Grand Marchet glacier ; Geb. : Gebroulaz glacier ; Chav. : Chavière glacier ; Sdl. : Sources de l'Isère glacier ; Pis. : Pisaillas glacier : Mo. : Montet glacier ; Gef. : Géfret glacier ; M.M. : Méan Martin glacier ; Vlnt. : Vallonnet glacier ; Va.I. : Vallonnet Inférieur glacier ; Va.S. : Vallonnet Supérieur glacier ; SdA. : Sources de l'Arc glacier ; Mul. : Mulinet glacier ; G.M. : Grand Méan glacier ; Evet. : Evettes glacier ; G.F. : Grand Fond glacier ; Mic. : Roche Michel glacier ; Bao. : Baounet glacier ; Mel. : Rochemelon glacier ; Som. : Sommellier glacier ; Ecrins massif. Mt.L. : Mont de Lans glacier. Gir. : Girose glacier ; Rat. : Rateau glacier ; PdA : Plate des Agneaux glacier ; B.P. : Bonne Pierre glacier ; VdE : Vallon des Etages glacier ; Char. : Chardon glacier ; S.W. : Sellettes glacier West ; S.E. : Sellettes glacier East ; Pil. : Pilatte glacier ; Cond. : Condamines glacier ; Bar. : Barbarate glacier

Methods and datas

INPUT DATAS



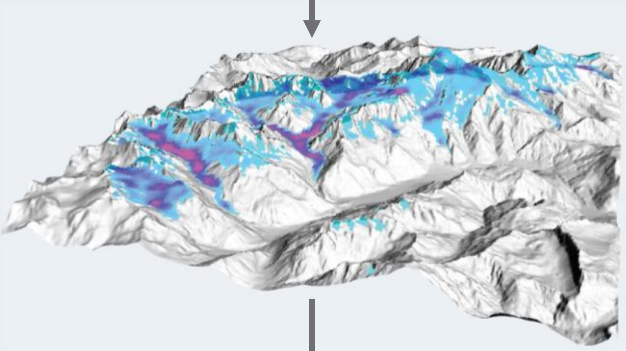
Digital Elevation Model

Glacier outlines

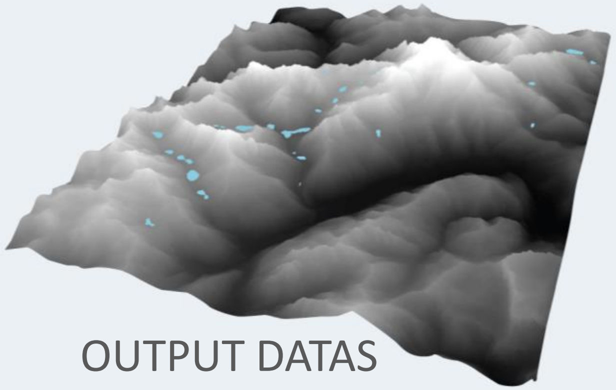
Branch lines
(only for GlabTop)

GLABTOP AND GLABTOP 2

Calculation of **ice thickness** from surface slope, assuming a relation between the **basal shear stress** and **glacier elevation range as a governing factor of mass turnover** (Linsbauer et al., 2012 ; Paul and Linsbauer, 2012)



- Ice thickness is subtracted from the original DEM



OUTPUT DATAS

→ **DEM without glaciers**, where Glacier Bed Overdeepenings (GBOs)can be interpreted as potentials **futures lakes** places

Methods and datas

EVALUATION :

- **Comparison** between **GBOs** predicted by GlabTop and the **already formed lakes** at recently deglaciated areas

MORPHOLOGICAL ANALYSIS based on 4 criteria (Frey et al., 2010) :

- (i) **Slope angle** at predicted GBO
- (ii) Presence/absence of a **break in slope angle** downstream of the predicted GBO
- (iii) Presence/absence of a **bedrock threshold** and/or a **glacier narrowing** at the predicted GBO outlet
- (iv) presence/absence of a **transition** between a **crevasse free area** and a **crevasse field** downstream of the predicted GBOs

VISUAL IDENTIFICATION AND CLASSIFICATION :

- **Other potentials GBOs are detected** at each place where the criteria (i) and (ii) are ≥ 3 (Magnin et al., 2019).
- Same **morphological analysis** as the one used with predicted GBOs to **classify those visually detected**

Figure 3: Example of already formed lakes : the Patinoire glacier, Vanoise massif (image from Google Earth)

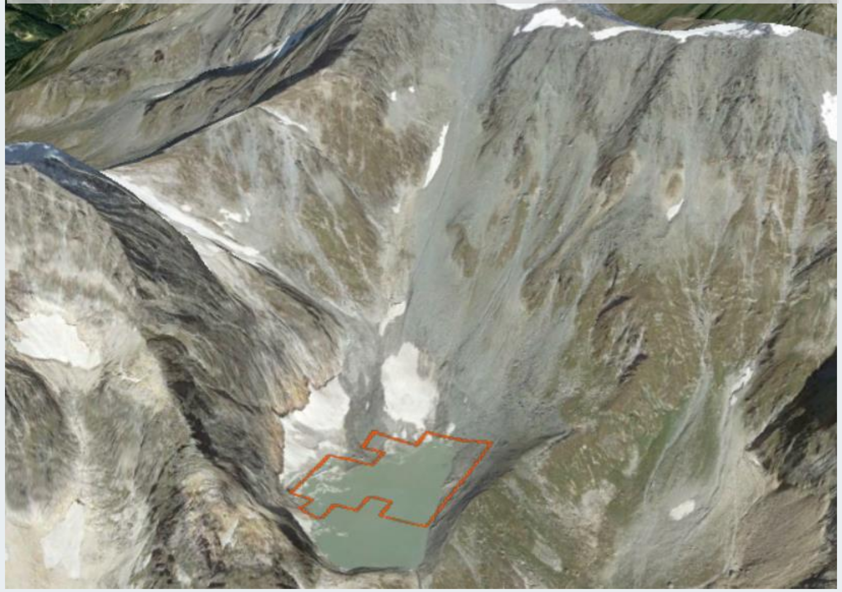
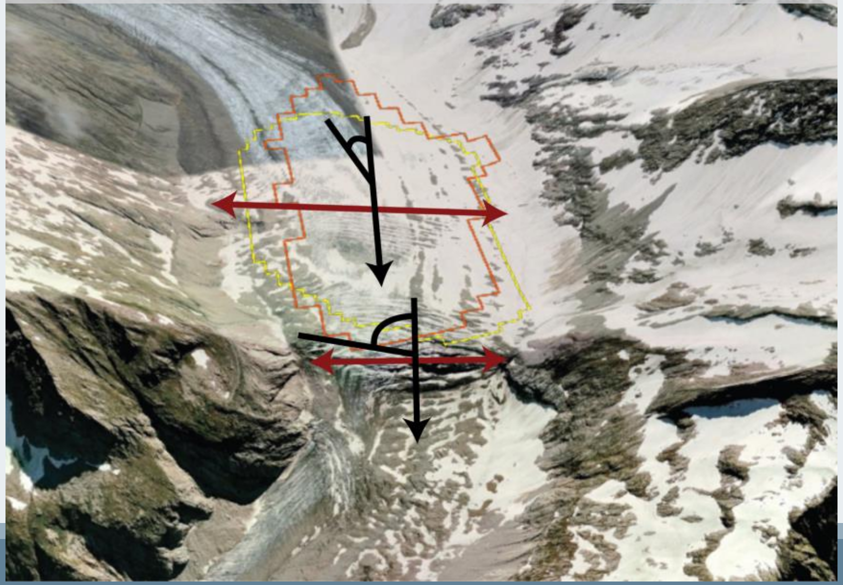


Figure 4: Example of morphological analysis on Tré la Tête glacier, Mont Blanc massif (image from Google Earth)



Results

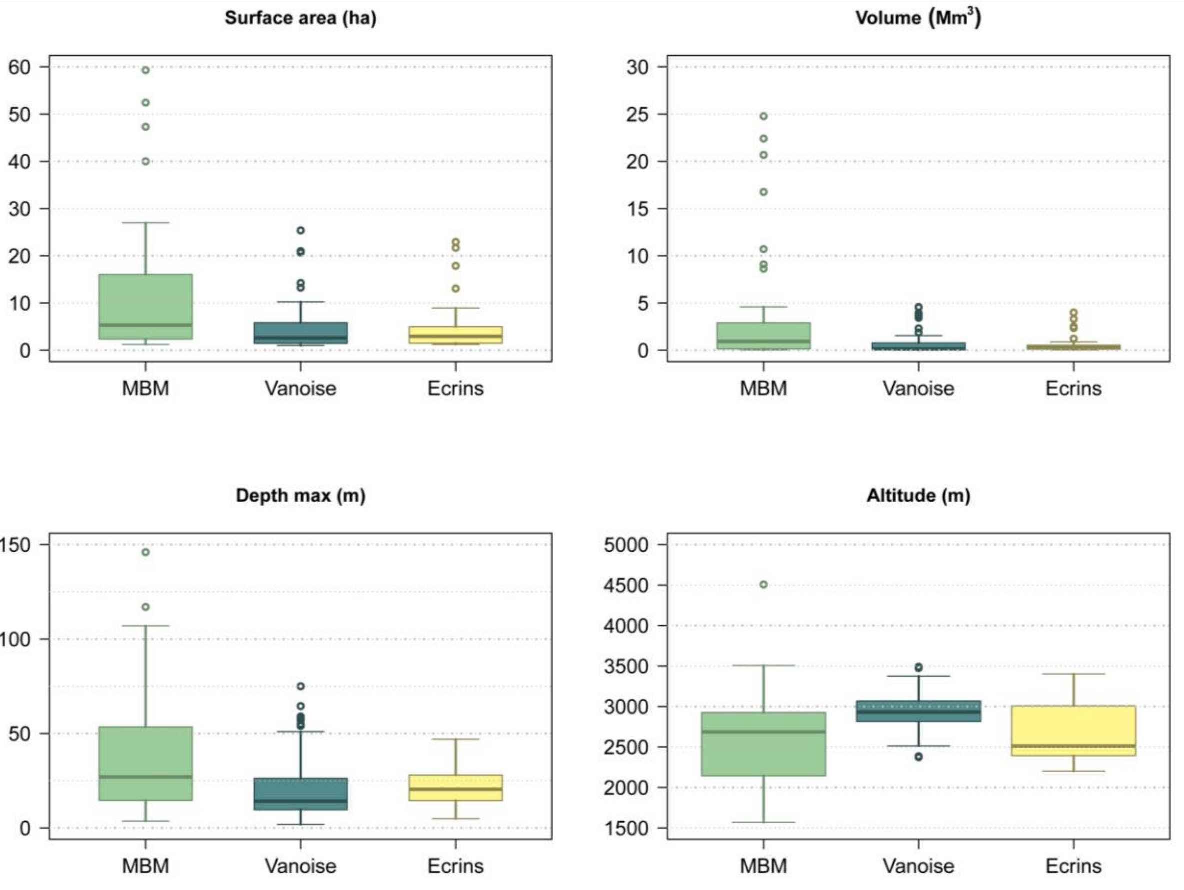


Figure 5 : Comparison of the surface, volume and depth of the GBOs predicted by GlabTop between the Mont Blanc massif, the Vanoise massif and the Ecrins massif

SURFACE AREAS OF PREDICTED GBOs

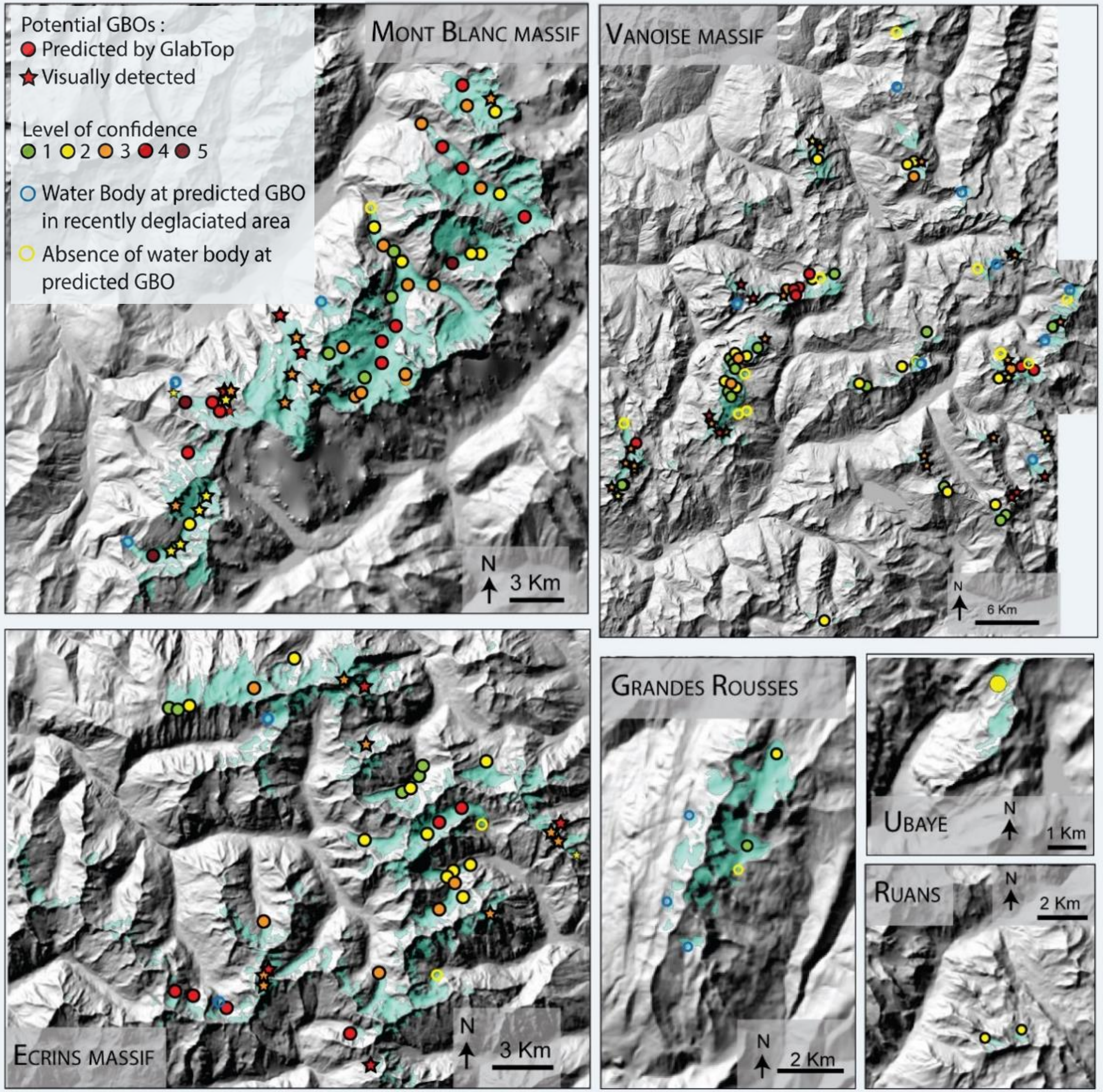
- In the **French Alps : total surface area of 948 ha** (3.5% of the glacier surface area)
- Mont Blanc massif : **481 ha** (4.7% of the glacier surface area in the MBM)
- Vanoise massif : **274 ha** (3% of the glacier surface area in Vanoise massif)
- Ecrins massif: **156 ha**(2.3% of the glacier surface area in Ecrins massif)

DEPTH OF PREDICTED GBOs

- The **deepest GBOs** are in the **Mont Blanc massif** : under the Argentière glacier (146 m and 117 m) and the Tré la Tête glacier (107 m)
- The deepest in the Vanoise : Evettes glacier (75 m)
- The deepest in the Ecrins : Noir glacier (47 m)
- The deepest in the Grandes Rousses : Saint Sorlin glacier (81 m)

VOLUME OF PREDICTED GBOs

- In the **French Alps : total volume of 217.4 Mm^3**
- Mont Blanc massif : **145.5 Mm^3** (67% of the total volume of the predicted GBOs)
- Vanoise massif : **41.3 Mm^3** (19% of the total volume)
- Ecrins massif: **20.6 Mm^3** (9% of the total volume)
- **The GBOs with the higher volumes are in the Mont Blanc massif** : Talèfre glacier (24.8 Mm^3), Tré la Tête glacier (22.4 Mm^3) and the Argentière glacier (20.7 Mm^3).



Results

MORPHOLOGICAL ANALYSIS AND LEVEL OF CONFIDENCE OF GBOs

139 predicted GBOs :

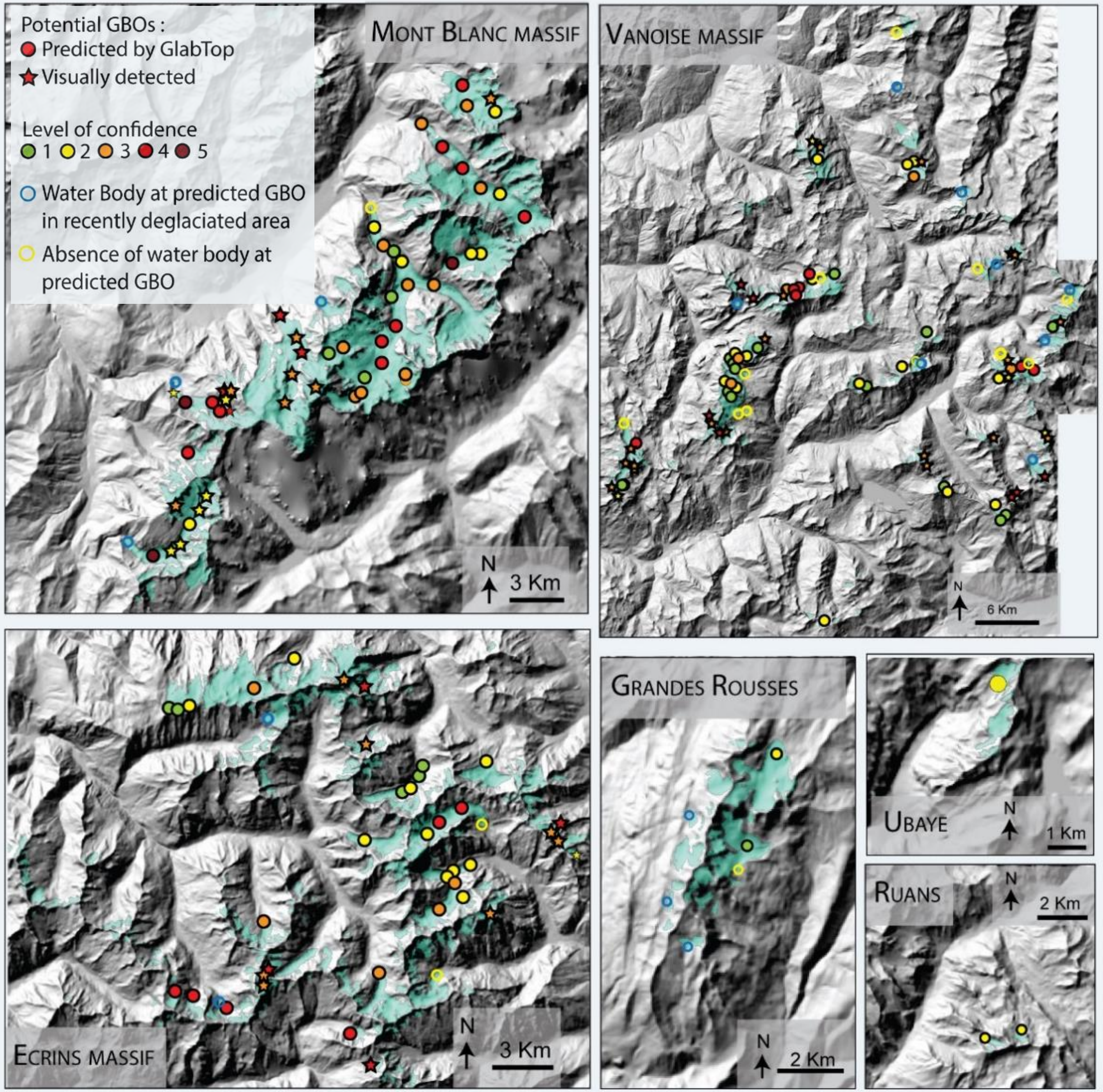
- Extremely high level of confidence (**5/5**) : **5** GBOs in the Mont Blanc massif.
- Very high level of confidence (**4/5**) : **30** GBOs
- High level of confidence (**3/5**): **23** GBOs
- Moderate level of confidence (**2/5**) : **45** GBOs
- Low level of confidence (**1/5**) : **34** GBOs
- Very low level of confidence (**0/5**): **2** GBO

→ The deepest GBO (Argentière glacier) and the most voluminous one (Talèfre glacier) are both characterised by very high levels of confidence.

→ 40% of GBOs with a high level of confidence (≥4/5) are in the Mont Blanc massif.

→ 67% of GBOs with a low level of confidence (≤1/5) are in the Vanoise massif.

Figure 6 : Level of confidence of the GBOs predicted by GlabTop and GlabTop 2 and GBOs visually detected



Results

VISUAL IDENTIFICATION AND CLASSIFICATION OF OTHER POTENTIAL GBOs

- **58 GBOs visually detected** by analysing glacier morphologies
  - Vanoise massif : 30 GBOs
  - Mont Blanc massif : 15 GBOs
  - Ecrins massif : 12 GBOs
  - Grandes Rousses massif : 1 GBO

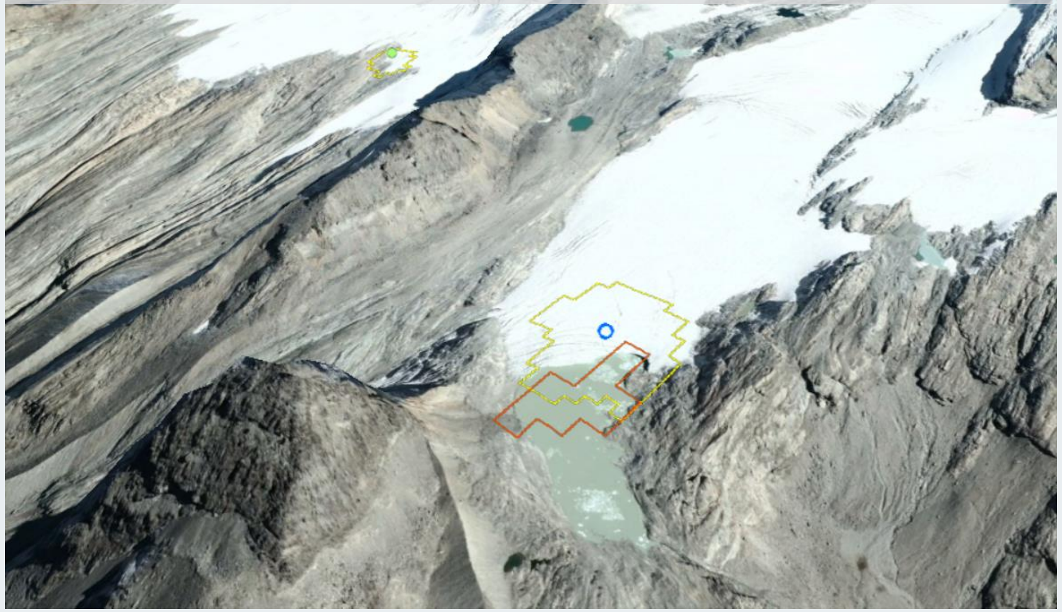
- **Level of confidence** :
  - 5/5 : 1 GBOs
  - 4/5 : 13 GBOs
  - 3/5 : 33 GBOs
  - 2/5 : 11 GBOs

Figure 6 : Level of confidence of the GBOs predicted by GlabTop and GlabTop 2 and GBOs visually detected

Results

EVALUATION OF PREDICTED GBOs WITH RECENTLY FORMED WATER BODIES

Figure 7 : Example of already formed lakes : the Grand Méant glacier, Vanoise massif (image from Google Earth)



16 lakes or water bodies found at or below the snout of glaciers. (3 in the Mont Blanc massif, 8 in the Vanoise massif, 2 in the Ecrins massif and 3 in the Grandes Rousses massif)

Figure 8 : Example of not formed lakes : the Sélé glacier, Ecrins massif (image from Google Earth)

However, 15 lakes did not form in the predicted GBOs. (1 in the Mont Blanc massif, 11 in the Vanoise massif, 2 in the Ecrins massif and 1 in the Grandes Rousses massif)

Discussions

LIMITATIONS OF THE METHOD :

- **Underestimation of the predicted volumes and depths** of the GBOs (up to 50% ; Magnin et al., 2020)

→ More detailed field investigation to assess GBOs depths and volumes are required (*e.g.* IPR measurements)

- **GBOs can be filled by sediments**, hindering the formation of lakes.
- **Debris-covered glacier** : sediments inputs may yield only **temporary lakes** in permeable non consolidate materials.

→Modelling sediment transport remains a challenge to be integrated into such approaches (*e.g.* erosion-sedimentation index ; Zemp et al., 2005)

IMPLICATIONS FOR HAZARDS ASSESSMENT AND FUTURE APPLICATIONS :

GBOs downstream **unstable slopes** debuttressing and/or permafrost degradation
Example : The Epena and the Rosolin Glacier

Lakes formed in **morainic materials**
Example : Pèlerins glacier (Mont Blanc massif)

→ **Possible "hot spots" for hazard assessment**

Voluminous GBOs not directly overhung by unstable slopes (unlikely hazards)
Example : the Tour glacier (Mont Blanc massif)

→ **Future opportunities for water supply, hydroelectricity and/or tourism**

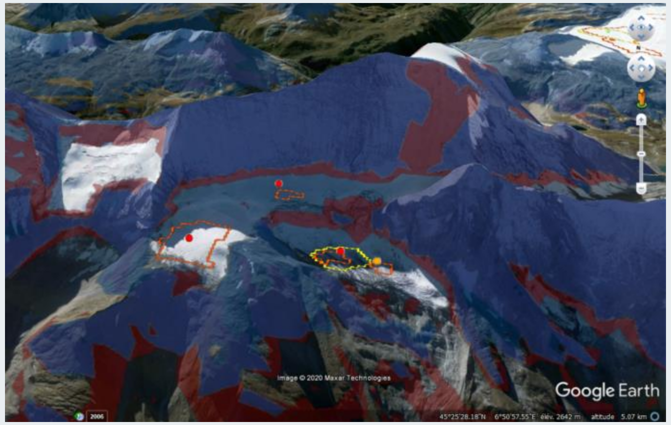


Figure 9 : Example of possible hot spots in the Vanoise massif: The Epena and the Rosolin Glacier (red areas : slope > 30° ; blue areas : permafrost favourability index > 0.5 (Marcer et al., 2017))

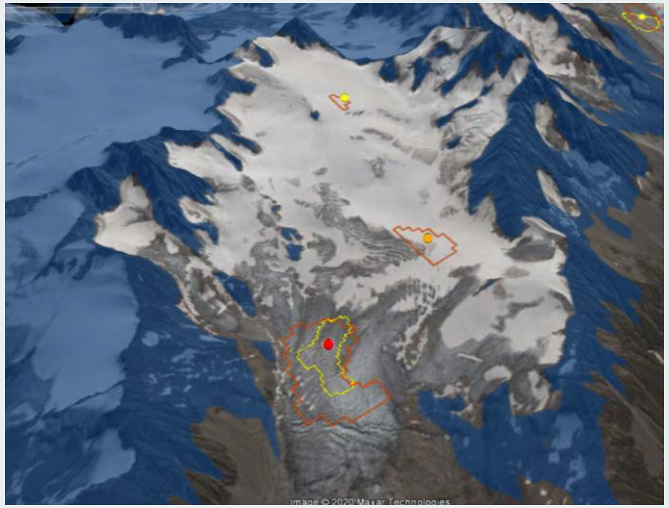


Figure 10 : Example of possible future opportunities in the Mont Blanc massif : The Tour glacier (blue areas : permafrost favourability index > 0.5 (Marcer et al., 2017))

Future applications

- Assessing the **time range for formation** of potential future lakes
- Determining potential hotspots by **multi-criteria approaches** (*e.g.* Rock Avalanches Impact Disposition (RAID), Schaub 2015)
- Modelling the **trajectory of cascading hazards** in this “hot spots” (*e.g.* RAMMS ; Christen et al., 2012)

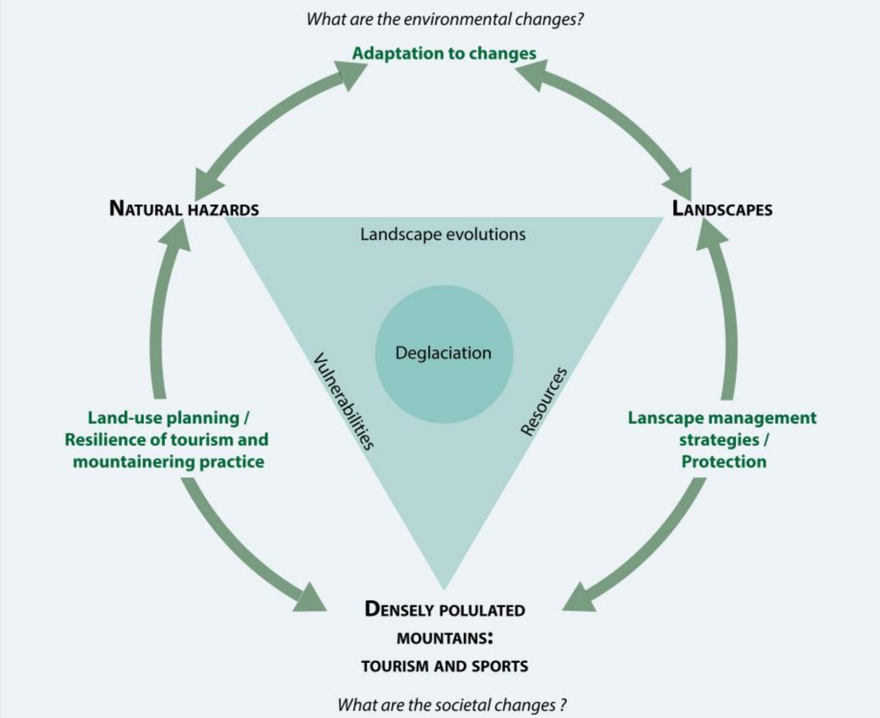


Figure 12: An integrated approach of Human-environment dynamics

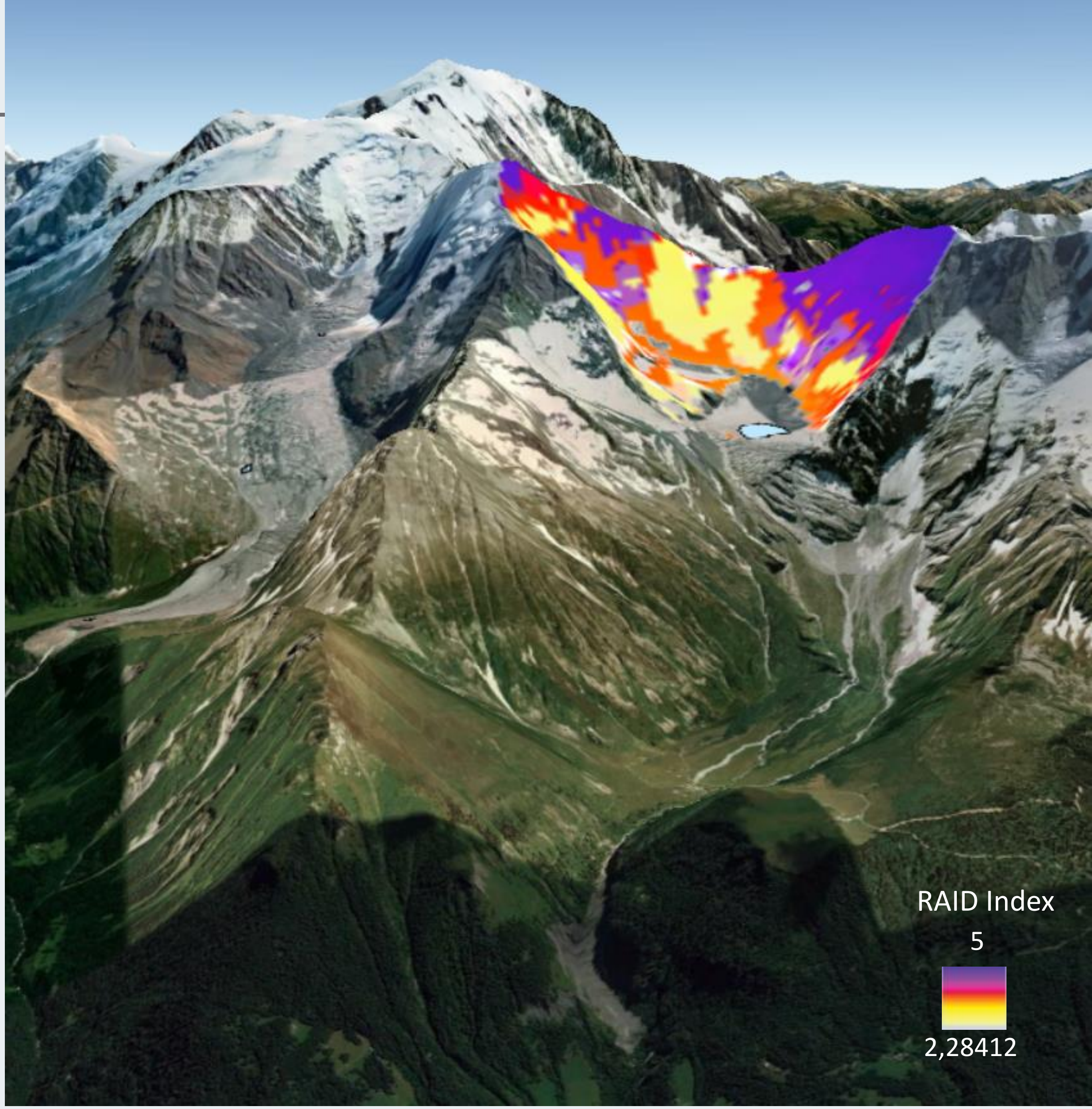


Figure 11 : Example of application of the RAID model on the Miage watershade (Cathala, 2019). RAID model is a multi criteria approach to determine the susceptibility of the lakes to be impacted by an ice/rock avalanche, using the topography, the lithology, the presence/absence of permafrost and the presence/absence of post glacial decompression (Schaub, 2015)

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