

ROCKFALL MODELLING AND RISK ZONING:

A CASE STUDY IN THE FRENCH ALPS USING GEOMATICS, AIRBORNE LASER SCANNING, 2D & 3D RUNOUT MODELS

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ABSTRACT

In mountainous areas, rockfalls represent a major threat to human safety, public infrastructures and economic assets. Accurate mapping and qualification of risk areas are required so that public authorities can make secure and efficient decisions regarding urban planning. In France, Risk Prevention Plans (PPR) are standard documents that determine risk areas and building authorisations for ten-year periods. During the PPR revision of the town of Veyrier-du-Lac (France), we implemented a new methodology based on geomatics for rockfall risk assessment. Analysis of airborne laser scanning data, field data, 2D and 3D rockfall simulations was performed with geographic information system to accurately map hazard areas. The use of LiDAR data and algorithms allowed a refined delineation of risk maps with quantification of forest protection effect in a complex environment. The coordination of information in a GIS improved the interactions between experts and decision makers.

Keywords: Rockfalls, Hazard, Risk Zoning, GIS, 2D & 3D Simulations, Protection Forest

INTRODUCTION

In alpine environments, natural hazards such as rockfalls are common but their occurrences are difficult to predict. To protect human lives and infrastructures without hampering town development and economic activities, public authorities must adequately map risk zones and take them into account in town development schemes. Nowadays, trajectory simulation models are increasingly used with the aim of making rockfall hazard maps (Jaboyedoff et al., 2005). Regarding rockfall risk zoning, common practices rely on a limited number of 2D numerical simulation results manually extrapolated to whole hillsides. In areas such as the French Alps, with highly variable topographic and soil conditions, such approaches may overlook local effects which have decisive consequences on rock propagation. Moreover the protective function of forests and vegetation is frequently underestimated or even ignored, because most of numerical simulations only consider bare soil (Dorren, 2003; Dorren et al., 2006).

Before 1995 in France, several documents dealt with natural hazards and planning schemes and each one had its own specificity. The subtlety of these documents and some disasters obliged the French state to define a new single document in 1995: The Risk Plan Prevention (PPR in French). Each town subjected to natural hazards must update its PPR every ten years (Garry et al., 1997). A PPR is a legal document which maps and defines the risk zones by natural hazard such as rockfalls. It's composed of hazard maps, describing the hazard frequency and sometimes intensity, and of a risk map, depending on assets at risk and hazard levels. 3 risk levels are so defined (see Tab. 1).

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Tab. 1 Risk zones in a Risk Prevention Plan

Color code	Hazard level	Construction possibilities
Red	High	None
Blue	Medium	Under architectural conditions
White	Low or none	Allowed

The town of Veyrier du Lac (France, Haute-Savoie, 45° 52' 59" N, 06° 10' 41" E) is highly concerned by rockfalls: its 8km² are situated downslope of 150 to 200 m high limestone cliffs oriented NW-SE. Residential areas are located at the footslope between the Annecy lake located at the South-West and the 4km long cliffs. A previous PPR had been validated in 1994, but risk areas were not based on numerical simulations. Since, several rockfalls occurred, and the mayor decided to ask a PPR revision.

In 2007, a first simulation study was made on the whole area of Veyrier du Lac. Five others studies on small part of the town, were also made. On the common areas, results were quite different and hard to compare: each risk map was based on different criteria of frequency, intensity or/and probability for a rock release. Due to these divergences, the Amenagement and risk service of the Direction Départementale des Territoires (DDT) asked the Cemagref in July 2008 to make a rockfall and trajectory expertise.

We implemented a new methodology based on geomatics for rockfall risk assessment. Analysis of airborne laser scanning data, field data, 2D and 3D rockfall simulations were performed with geographic information system (GIS) to accurately map hazard and risk areas and their associated intensity and frequency.

AIRBORNE LASER SCANNING DATA

The quality of the results of the 2D and 3D run-out simulation models is strongly linked with the quality of the input data. For several years, high precision digital terrain models (DTM) based on remote sensing technologies such as airborne laser scanning (ALS or LiDAR) are available (Monnet, 2010). Lan et al. (2010) showed the advantages of using a DTM obtained by ALS for assessing hazards over long railway sections in Canada. ALS is also used for forest parameters estimation (Hyypä et al., 2008). For the study, the laser data were acquired during late summer 2008. Acquisition parameters are summarized in Table 2. The point density of the final echo was 10m⁻². The point cloud was classified into ground and non-ground echoes using the TerraScan software to compute by linear interpolation a DTM and a Digital Surface Model (DSM) of metric resolution (see Fig. 1).

Tab. 2 Laser scanner acquisition parameters

Item	Value
Scanner model	RIEGL LMS-Q560
Wavelength	1550 nm
Pulse repetition rate	220 kHz
Scan frequency	111.1 Hz
Scan angle	± 30°
Flight height	550 m
Laser footprint	0.29 m
Theoretical point spacing	0.47 m

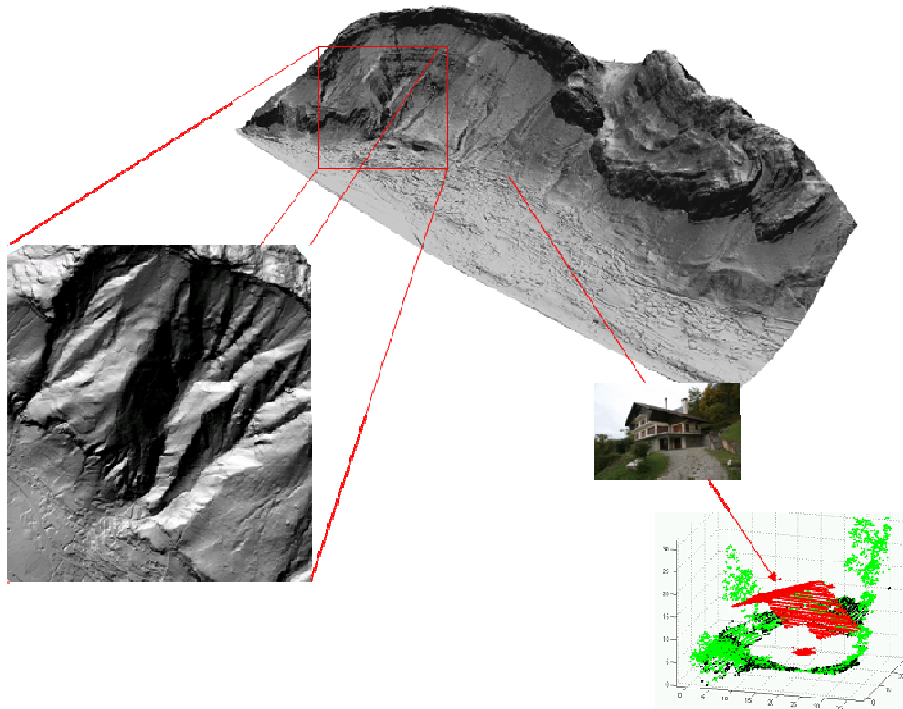


Fig. 1 LiDAR Digital Terrain Model of Veyrier du Lac with snapshots on the accuracy of the cloud points

PRELIMINARY WORK

A PPR refers to a reference hazard, which is defined by the occurrence probability of 1% per year for a rockfall ($10^{-2} \text{ year}^{-1}$). This centennial event is needed to choose the rock volume for our numerical simulations. An important analysis of the past events allows us to determine the volume of the centennial event:

- Historical data are the main source of information to assess the intensity and frequency of rockfalls. The Service de Restauration des Terrains de Montagne (RTM) of the French National Forest Office records all major natural events since 1882. From 1950 to 2008, 21 rockfall events were recorded in Veyrier-du-Lac. 52% of the rocks reached a road or a building. Historical data and observation of rocks on the ground give information on the individual volume and propagation distance of rocks.
- Dendrogeomorphological study also has a significant part in the centennial event characterization: the growth disturbances visible in tree-rings sequences after a bloc impact can be analyzed to date rockfall events (Lopez-Saez, 2010). On eight plots located at the cliff foot and along the rockfall corridor, 20 trees were nicked to estimate the number and age of impacts.

At the end, the study area was divided into 9 sectors, depending on the topography (watersheds) and the geology (fracturing). 7 sectors have a reference volume of 1m^3 , 1 sector with a volume of 2m^3 and one with a volume of 5m^3 .

A risk is defined by the combination of a hazard and human stakes. It's also crucial to dispose of the land-use map. This map includes all present human facilities: industrial, commercial, residential and agricultural areas, public buildings, transport and communication infrastructures. This information is extracted from the BD TOPO® of the French National Geographic Institute (IGN) or from existing town planning schemes maps.

Whatever the number of historical data or the precision of remote sensing data, it is necessary for rockfall simulations to undertake field surveys to measure local soil characteristics and get additional informations about the size and frequency of rockfalls. 104 circular plots of 10 m diameter, distributed every 100 m along the 500, 700, 900 and 1100 m contour lines of the hillside, were inventoried. Plot centers were georeferenced using a Trimble® GPS Pro XRS receiver. After

differential correction with the Pathfinder software, the position precision (35% confidence radius) ranged from 2 to 3 m. In each plot the following features were inventoried:

- forest: species, stand density and diameter at breast height (DBH) of all trees with a DBH larger than 7.5 cm;
- landform: macro topography type, micro topography roughness, mean obstacle height, soil stiffness;
- rockfall activity: number, shape and size of recently deposited rocks, and number and height of rock impacts on trees.

Forest stand attributes were then computed for each plot: mean diameter at breast height (dbh in *cm*), its standard deviation (*stddbh* in *cm*), basal area (*G* in *m²/ha*) and stand density (*N/Ha*).

Data collected during the field surveys were integrated and preprocessed in GIS software ArcGIS 9.2. Plot centers were georeferenced thanks to GPS and imported in vector format. Estimated values of soil characteristics (roughness, stiffness, mean obstacle height) were computed on a regular grid from the irregularly localized sample points using nearest neighbor interpolation. Forest parameters were extrapolated from the sample points of the field survey using photointerpretation with LiDAR data and orthophotos. The topography and the slope surface rasters were computed from the metric resolution DTM. Regarding rockfall characteristics input files, block size and rock density were defined by analysis of the historical data and field observations. Due to the high number of cliffs, the localization of potential release zones was determined by DTM modelling. A threshold was applied to the slope surface raster according to the equation (1):

$$\alpha = 55^\circ \times RES^{-0.075}, \text{ where RES is the DTM resolution} \quad (1)$$

All cells with values higher than the threshold α were qualified as potential release zones for rockfalls (Cemagref and Arpa, 2008). Then a flow analysis is performed to only retain upper points. With this method, 51552 potential release points have been determined.

2D & 3D MODELLING

Before the 3D simulations, we used a 2D numerical simulation model to localize the probable maximal runout envelopes of rockfalls, to have a first idea of block propagations. This model, called RockForLINE, is based on the Energy Line model (Heim, 1932), which allows relating rockfall runout envelopes to slope angles (see Fig. 2).

The maximal spread of a block is determined by intersecting the ground and an imaginary line drawn from its release point with an angle β (Clouet, 2010). We used different values for β : 32, 35 and 38° (see Fig. 2). Areas between 32 and 35° have a low but not null probability to be reached by rockfalls ; between 35 and 38°, a intermediate probability ; and higher than 38°, a high probability. On 21 past events recorded by the RTM, 20 are in the high probability and 1 in the medium one. No blocks have been recorded in the “low probability area”. The forest, covering the all hillside can explain this: repeated impacts on trees slow down blocks and can stop them. It’s the first element for the forest to have a protective role against rockfalls.

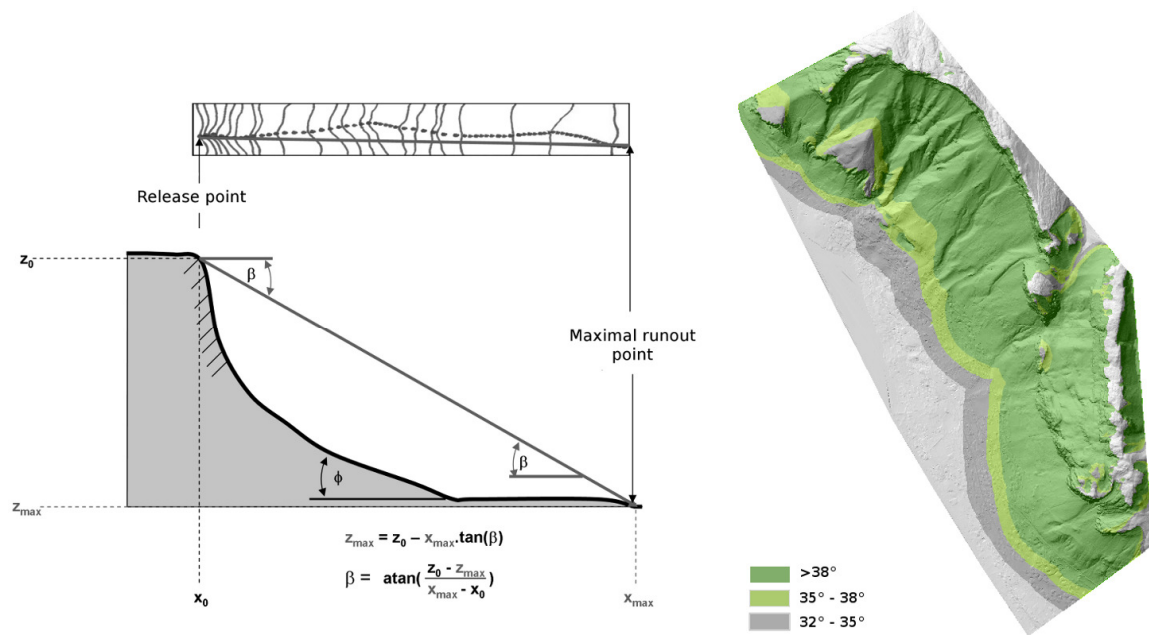


Fig. 2 Energy Line Principle and results on Veyrier du Lac with different angles

Rockyfor3D is a simulation model that calculates trajectories of single, individually falling rocks, in three dimensions (Dorren, 2010 - Dorren et al., 2005) taking into account or not the forest effect. The required input data consists of a set of ASCII rasters (ESRI format), which define slope surface, forest and block characteristics and topography. All input rasters and DTM were resampled to 5m resolution before they were supplied to Rockyfor3D. Experience showed, indeed, that a 1 m × 1 m resolution does not necessarily improve the quality (Dorren, 2010). From each of the 51552 potential release points (see Fig. 3), 500 rockfall trajectories were simulated on bare soil, and 500 more with integration of forest effect. In each case, the following output rasters were created:

- mean and the 95 % confidence level of the kinetic energy, translational and rotational energies (KJ) of passing blocks,
- mean and the 95 % confidence level of the normal passing height (m),
- event frequency (see Fig. 3),
- volume of the biggest block deposited per cell (m³).

Comparison of the run out envelops obtained with and without forest integration shows that the current vegetation cover reduces rock propagation in sectors where the block volume of the centennial event was 1 m. However, in such areas, the effect is noticeable only when rocks fall through forest areas longer than 250 m.

When comparing maps of event frequency with and without forest integration, it turns out that trees affect the lateral deviation of blocks. In thalwegs vegetation increases the concentration of block trajectories toward the steepest slope direction, whereas blocks are more scattered in homogeneous hillsides.

Regarding maps of mean kinetic energy of blocks, it is noteworthy that the mean energy is significantly reduced in sectors where the centennial reference volume is 1 m. The value of 95% confidence of the kinetic energy (extreme events) is reduced in the forest case only in deposit zones. Besides, higher energies are observed in a small number of pixels when forest is taken into account. This phenomenon is linked to the forest dispersal effect mentioned above.

There was no significant difference regarding passage height between the two sets of simulations.

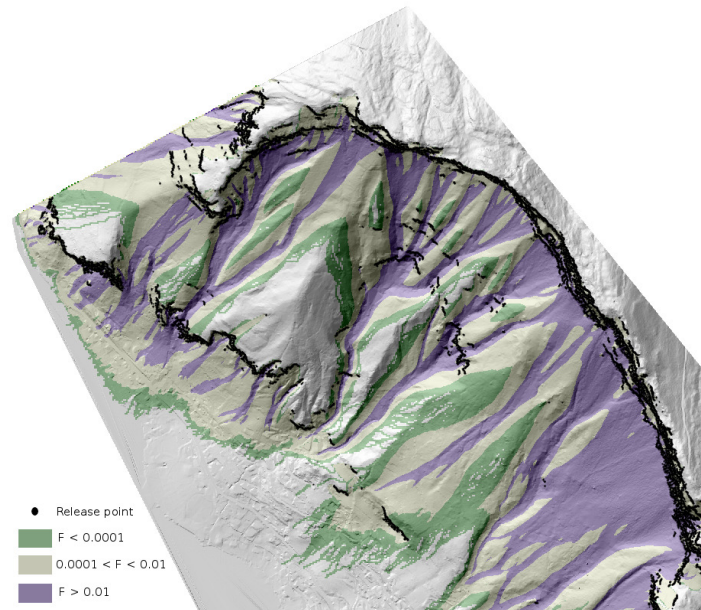


Fig. 3 Frequency level map and release points mapped with the Equation (1). Only the northern part of the studu area is represented

With a 3D approach, propagations and concentration zones, like thalwegs, are easily individualized. Furthermore, hazard maps are much more precise than 2D extrapolated maps from 2D profiles. All the results, especially maximal run-outs, have been compared with the 2D simulations from RockForLINE and the historical data to ensure that simulation results were consistent with field observations.

PROPOSITION OF A NEW “HAZARD MATRIX” FOR RISK ZONING

Nowadays, most of the PPR uses a risk zoning based on the frequency or on the reach probability. But it's also fundamental to study the kinetic energy developed by the projectile, to have a more precise map of risk. The Swiss Confederation proposed to use a matrix based on a crossing between Frequency and maximal kinetic energy to define 3 levels of danger. Consider the maximal kinetic energy would be too pessimistic and would take into account all aberrant values from Rockyfor3D output rasters. We defined 3 hazard levels by cross analysis of 3 mean kinetic energy classes and 4 frequency classes (see Tab. 3).

Tab. 3 Hazard levels determined by combination of rockfall kinetic energy and frequency classes

Frequency F	Mean Kinetic Energy E (KJ)		
	$E \leq 30$	$30 < E \leq 300$	$300 < E$
$F \geq 10^{-2}$	Medium	High	High
$10^{-2} > F \geq 10^{-4}$	Medium	Medium	High
$10^{-4} > F \geq 10^{-6}$	Low	Medium	Medium
$10^{-6} > F$	Low	Low	Medium

A GIS cross analysis is performed with mean kinetic energy and frequency maps to obtain the hazard levels maps with and without forest integration (see Fig. 4).

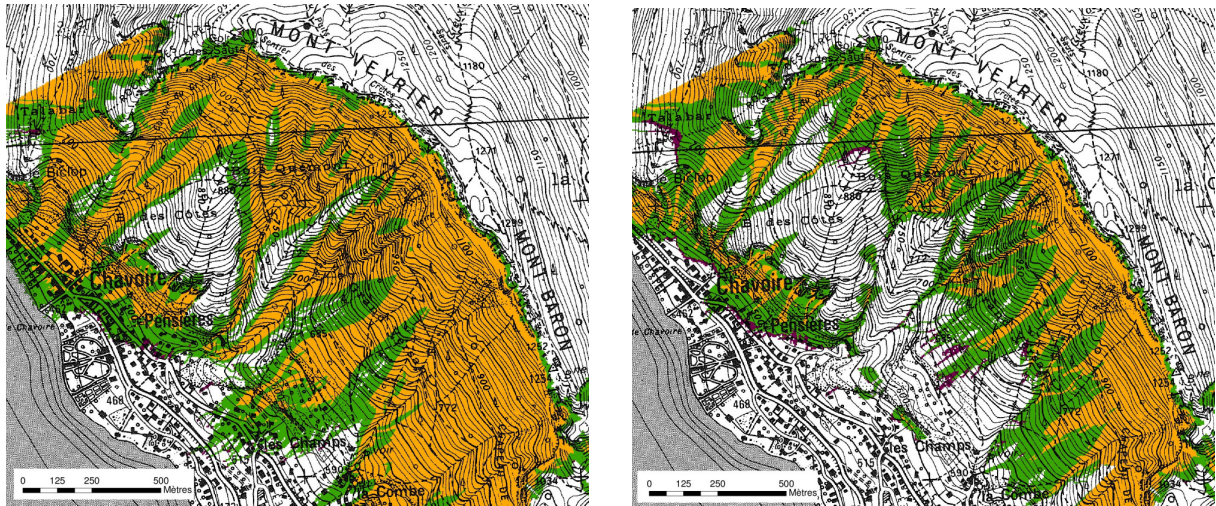


Fig. 4 Hazard levels map obtained by combination of rockfall kinetic energy and frequency classes on bare soil (left) and with forest integration (right). Only the northern part of the study area is represented. Colors are defined in Table 3

RISK ZONES PROPOSITION

Hazard maps, with and without forest integration, have been drawn thanks to the hazard matrix. A new rockfall event, occurred in January 2009, allows us to validate rockfall simulations and hazard maps: the 6.25m^3 block path has been correctly modelled and its stopping point was in the high hazard level envelop.

Then, according to these hazard maps and human stakes, a risk map has been proposed. Comparison of the runout envelopes obtained with and without forest shows that the current vegetation reduces rock propagation in sectors where the block volume of the centennial event was 1m^3 . The forest was classified in the risk map as a potential protection forest. Three levels of risk were mapped: high level of risk, in red, where new buildings are forbidden, medium level in blue, where new buildings are allowed under architectural conditions, and low level, in white, where all new buildings are allowed (see Fig. 5).

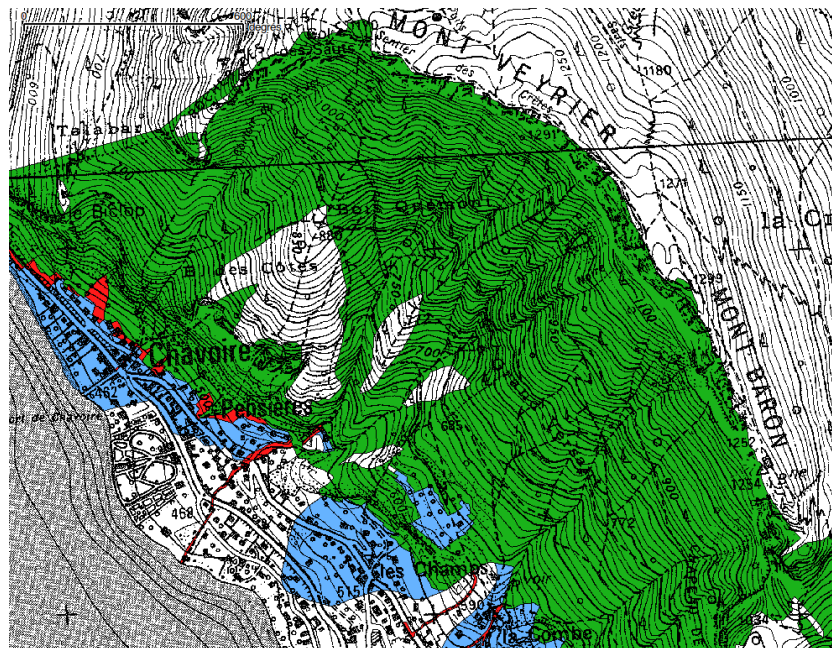


Fig. 5 Official risk zones map after authorities agreement. Only the northern part of the study area is represented. Colors are defined in table 1.

Finally, after a public inquiry, the PPR has been validated by the public authorities in August 2010.

CONCLUSIONS

This study demonstrates the added value of using a 3D Rockfall model and high resolution LiDAR data. The interest of the 3D modelling is the direct production of a zoning avoiding the problem of interpolation between profiles as with the use of a classical 2D modelling. The other key point is the accurate representation of the topography by the use of LiDAR data. Using such data allows risk managers to have a very realistic and accurate modelling of the topography. The interest of LiDAR data is also the possibility to extract semi-automatically forest data that can be directly used in Rockfall trajectories models which are able to integrate the effect of forest stands on rockfalls propagation. The use of these data and 3D Rockfall models, integrating the effect of forest stands, allows risk managers to produce more accurate and adapted risk zoning, prevention plans and protection forests management plans. The next step now, is to integrate forest stands dynamics and forest management models in order to evaluate the evolution in time of the protection offered by forest stands.

In spite of these positive aspects, high resolution data and 3D modelling also generate negative points. The first one is the time need to process the data and to make the field survey. The use of 3D models needs to realize exhaustive field surveys on all the study area. For the data processing, this is depending on one hand, on the storage and calculation capacities of the computer used, and on the other hand, on the algorithms of the model. The second negative point is the false perception, by the public and practitioners, of the “reality” coming out from high spatial resolution modelling. Even if very high resolution data and models are available, there is always a need of field validation of the initial data quality and of the model’s results.

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