Scuola universitaria professionale della Svizzera italiana
Dipartimento ambiente costruzioni e design
Istituto scienze della Terra

SUPSI

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Modelling of landslide-generated tsunamis with GRASS

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Landslide-generated tsunamis

- Vajont 1963 tsunami

Source: wikipedia

On 9 October 1963, a landslide above Vajont Dam in Italy produced a 250 m (820 ft) surge that overtopped the dam and destroyed downstream villages.

- Lituya Bay a few weeks after the 1958 tsunami

Source: wikipedia

On 9 July 1958, a giant landslide at the head of Lituya Bay in Alaska, caused by an earthquake, generated a wave with an initial amplitude of 524 meters (1,719 ft).

Objectives of the study

a) to investigate the capability of a tests derived model by Heller et al. (2009) to be spatially implemented into the GIS GRASS

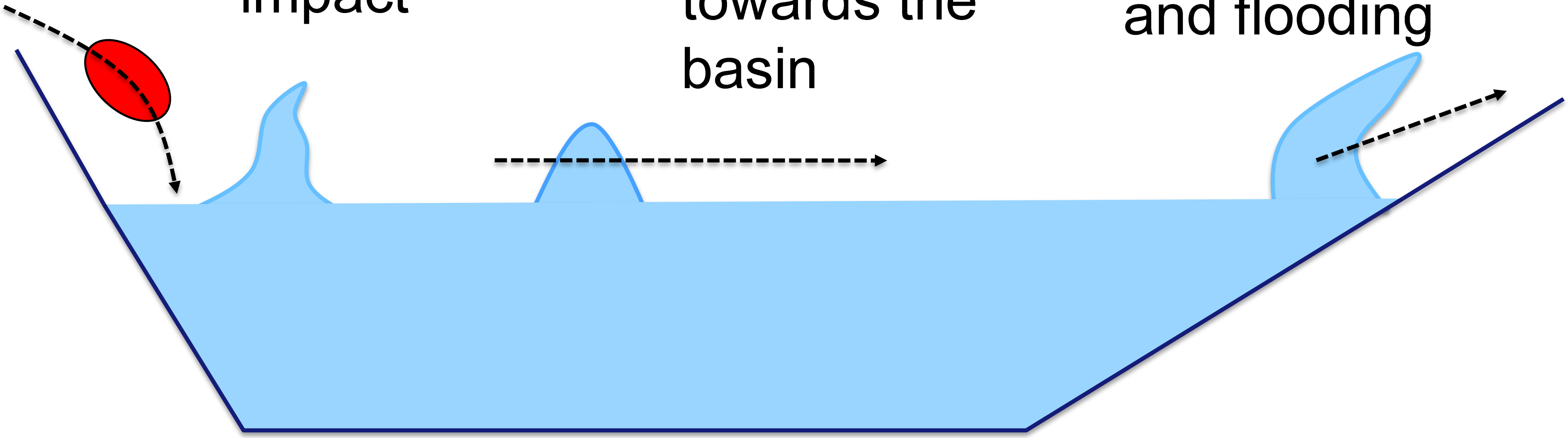
b) to test the model in a case study

c) to evaluate the uncertainty and sensitivity of the developed module

d) to infer the model validity based on the analysis the results and their comparison with respect to the non linear shallow water equations, as implemented by Cannata and Marzocchi (2011) in a GRASS dam break simulation module

The phenomenon

- 3 phase process



1) wave generation due to impact

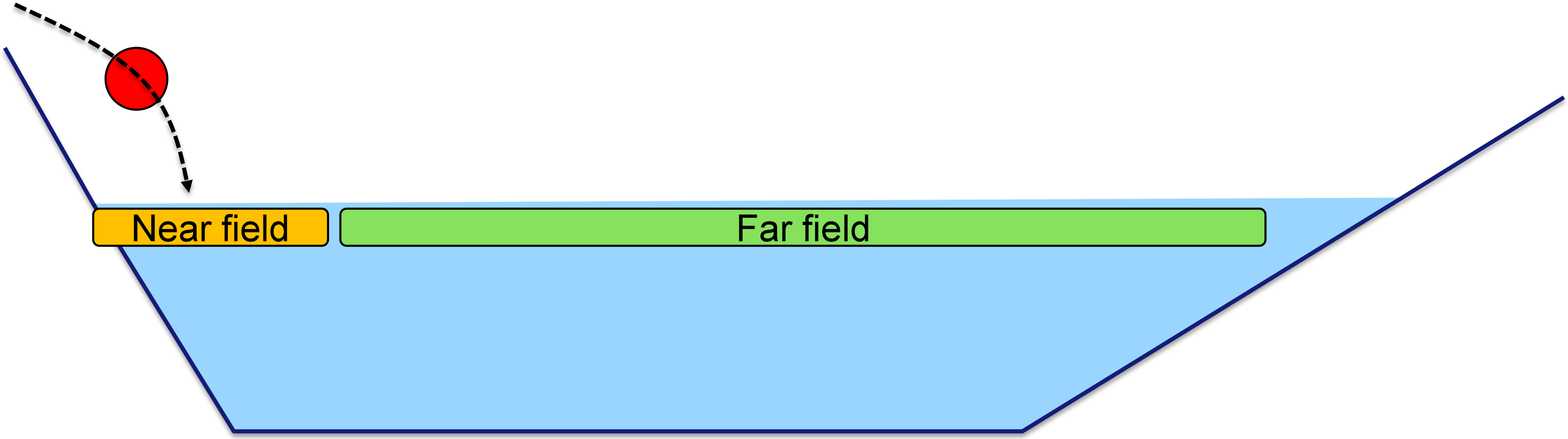
2) wave propagation towards the basin

3) wave run-up and flooding

Impact wave

- Two zones are identified when a mass impact the still water

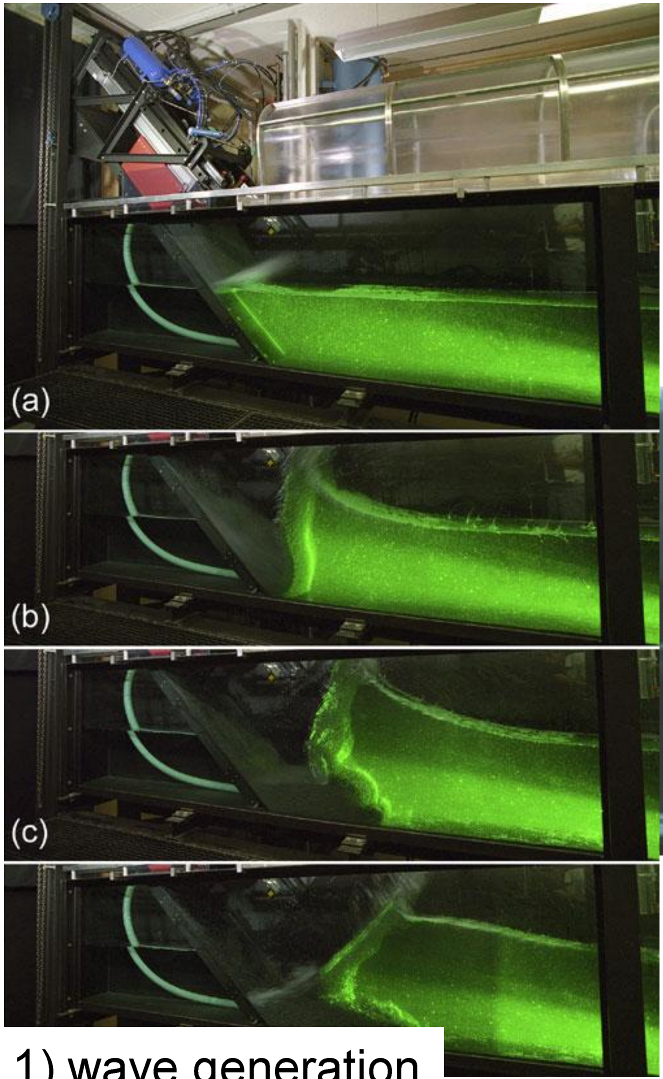
- <u>near field</u>: wave generation / perturbation area
- <u>far field</u>: wave propagation area



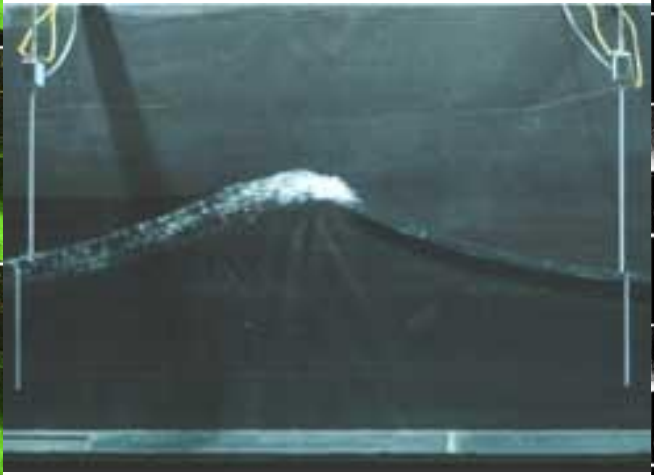
Heller et al. 2009 (H2009)

- Model derived by laboratory tests at ETH Zurich

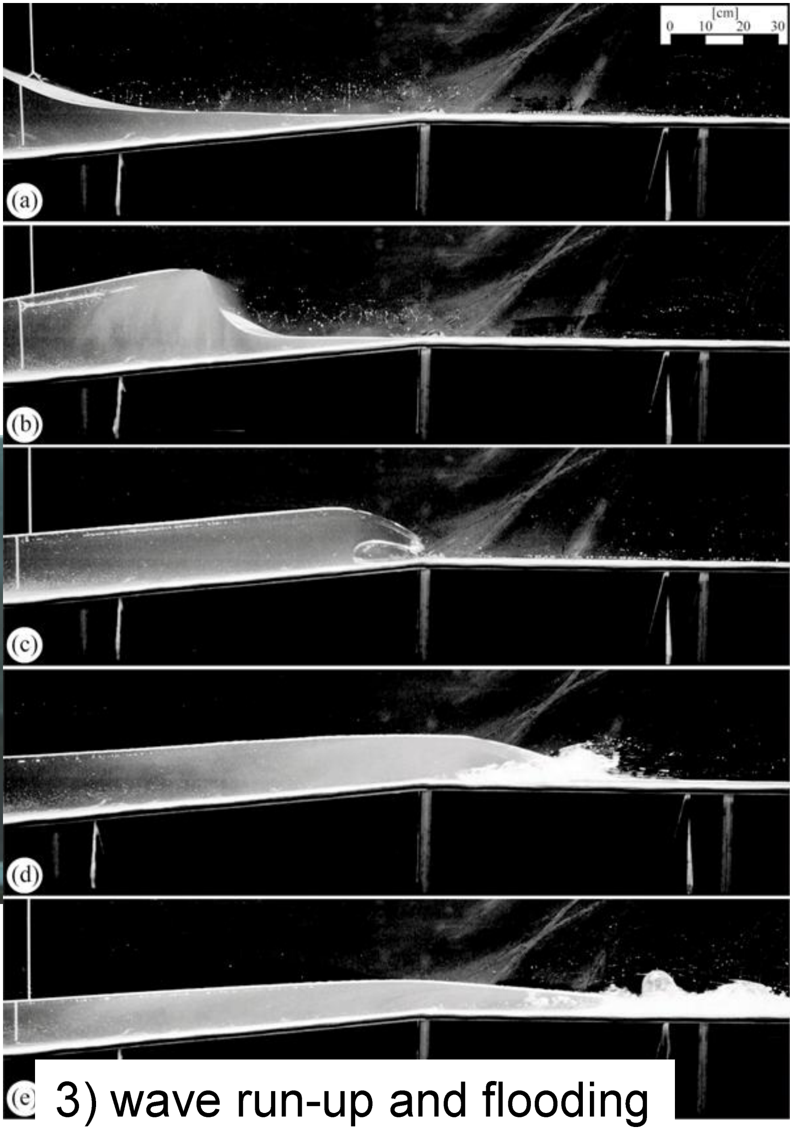
Laboratory of Hydraulics
Hydrology and Glaciology



1) wave generation

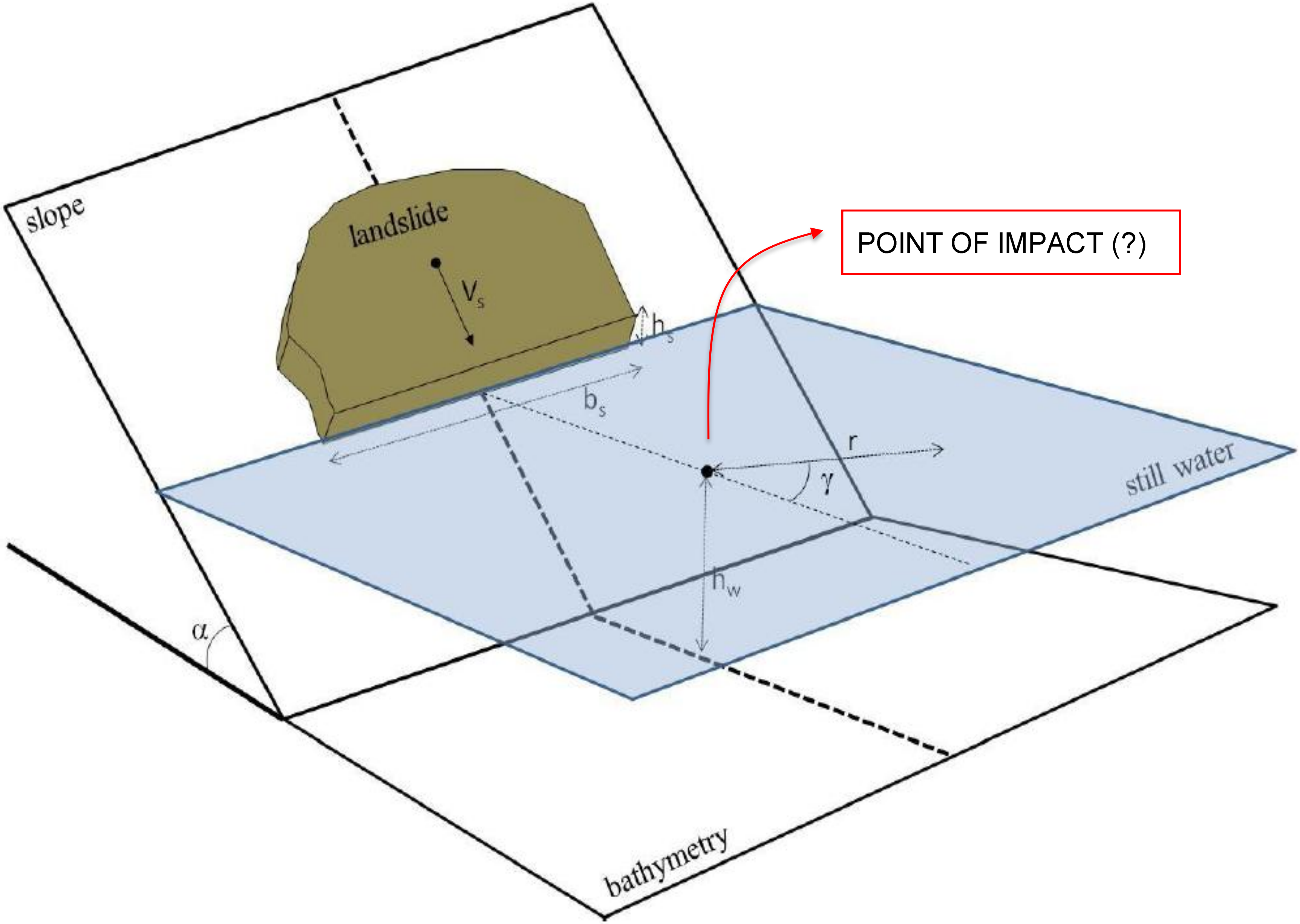


2) wave propagation



3) wave run-up and flooding

H2009: (near field) impact wave



POINT OF IMPACT (?)

H2009: (near field) impact wave

- The maximum wave height (H_M) and the corresponding distance from the impact (r_M) which limits the near zone, the wave period (T_M) and the wave length (L_M) can be estimated as follow:

$$H_M = h_w \cdot (5/9) \cdot P^{4/5}$$

$$r_M = h_w \cdot (11/2) \cdot P^{1/2}$$

$$T_M = 9 \cdot (h_w / g)^{1/2} \cdot P^{1/2}$$

$$L_M = T_M \cdot c = T_M \cdot \{g \cdot [h_w + (4/5 \cdot H_M)]\}$$

ρ_w = the water density [Kg/m^3]
h_w = still water depth in the impact zone [m],
ρ_s = slide mass bulk density [Kg/m^3]
V_s = slide mass bulk volume [m^3]
b_s = slide mass width [m]
h_s = slide mass thickness [m]
g = gravity acceleration [m/s^2]
α = slide impact slope [degree]

The maximum wave height (H_M) depends on the impulse product (P) parameter that depends on the Slide Froude number (F), relative slide thickness (S), relative slide mass (M) and slide impact angle (α)

$$P = F \cdot S^{1/2} \cdot M^{1/4} \cdot \{\cos[(6/7)\alpha]\}^{1/2}$$

$$M = (\rho_s \cdot V_s)/(\rho_w \cdot b_s \cdot h_w^2)$$

$$F = V_s / \sqrt{g \cdot h_w}$$

$$S = h_s / h_w$$

H2009: (near field) impact wave

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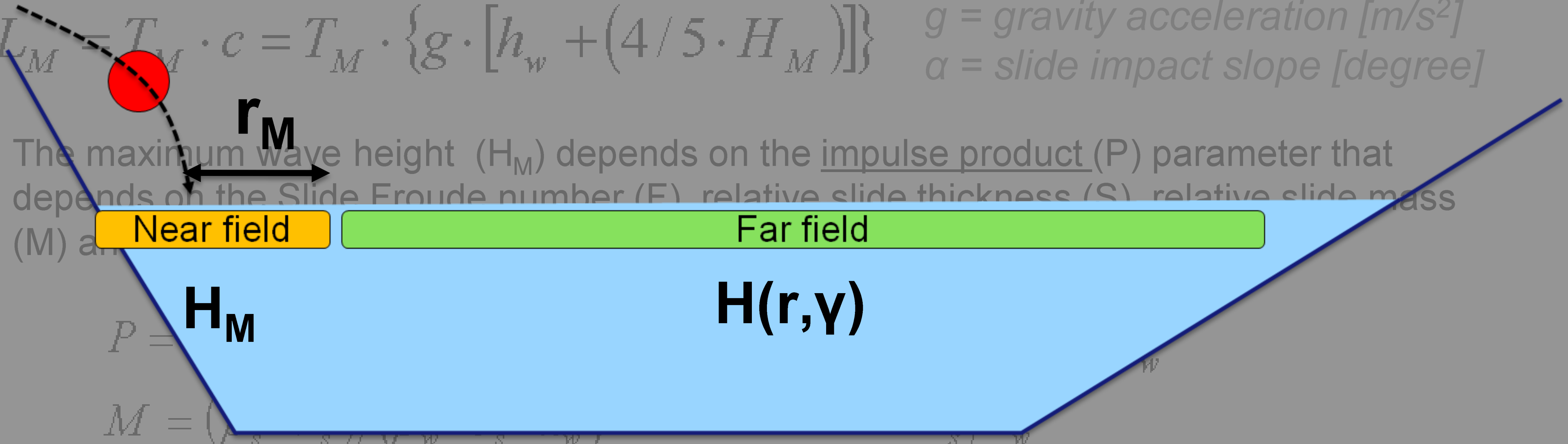
h_s = slide mass thickness [m]
g = gravity acceleration [m/s^2]
α = slide impact slope [degree]

$r < r_M$ ▪ H_M
$r > r_M$ ▪ $H(r,\gamma)$



The maximum wave height (H_M) depends on the impulse product (P) parameter that depends on the Slide Froude number (F), relative slide thickness (S), relative slide mass (M) an

$P =$

$M =$

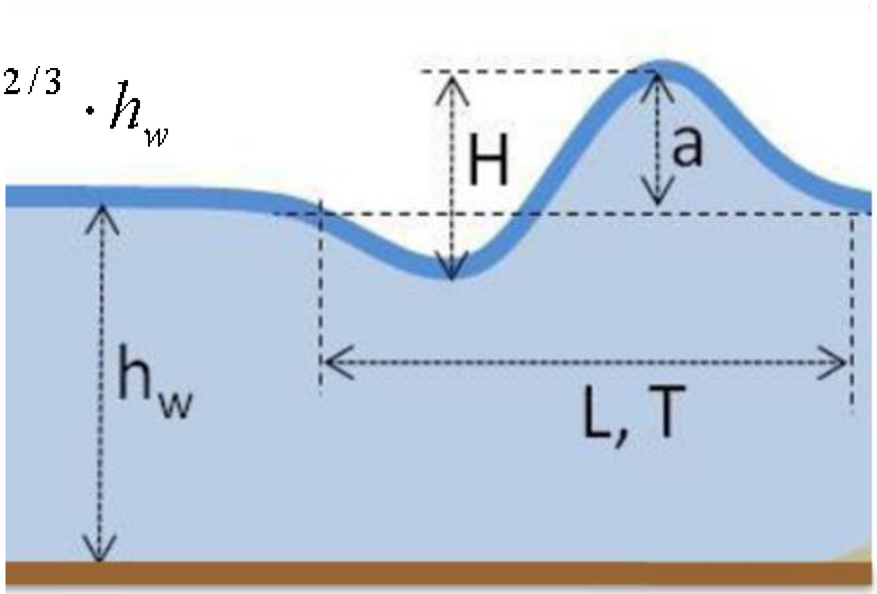
H2009: (far field) wave propagation

- In the far field, the solitary wave propagates regularly

$$H(r,\gamma) = (3/2) \cdot P^{4/5} \cdot \cos^2(2\gamma/3) \cdot (r/h_w)^{2/3} \cdot h_w$$

$$T(r,\gamma) = 15 \cdot [H(r,\gamma)/h_w]^{1/4} \cdot (h_w/g)^{1/2}$$

$$L(r,\gamma) = T(r,\gamma) \cdot c(r,\gamma)$$



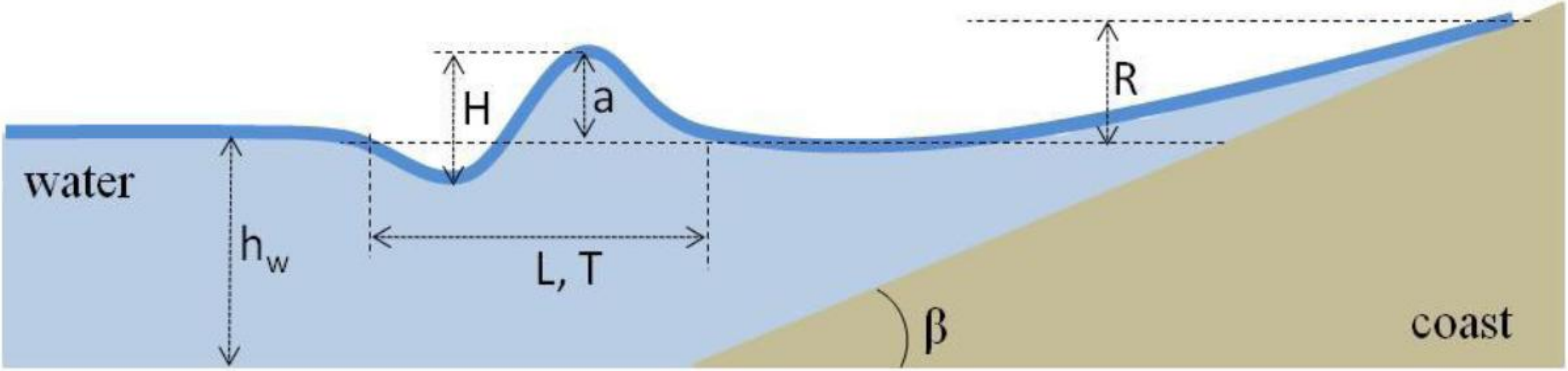
Apart from energy dissipation due to irregular bathymetry estimated with Shoaling equation:

$$S(r,\gamma) = [h_w(0)/h_w(r)]^{1/4}$$

H2009: (far field) run-up

When approaching the shore, the wave decreases its velocity and increments its height: according to Heller et. al (2009) the run-up process is estimated with Müller (1995) formulation:

$$R = 1.25 \cdot (H / h_w)^{5/4} \cdot (H / L)^{-3/20} \cdot (90° / \beta)^{1/5} \cdot h_w$$



r.impact.tsunami

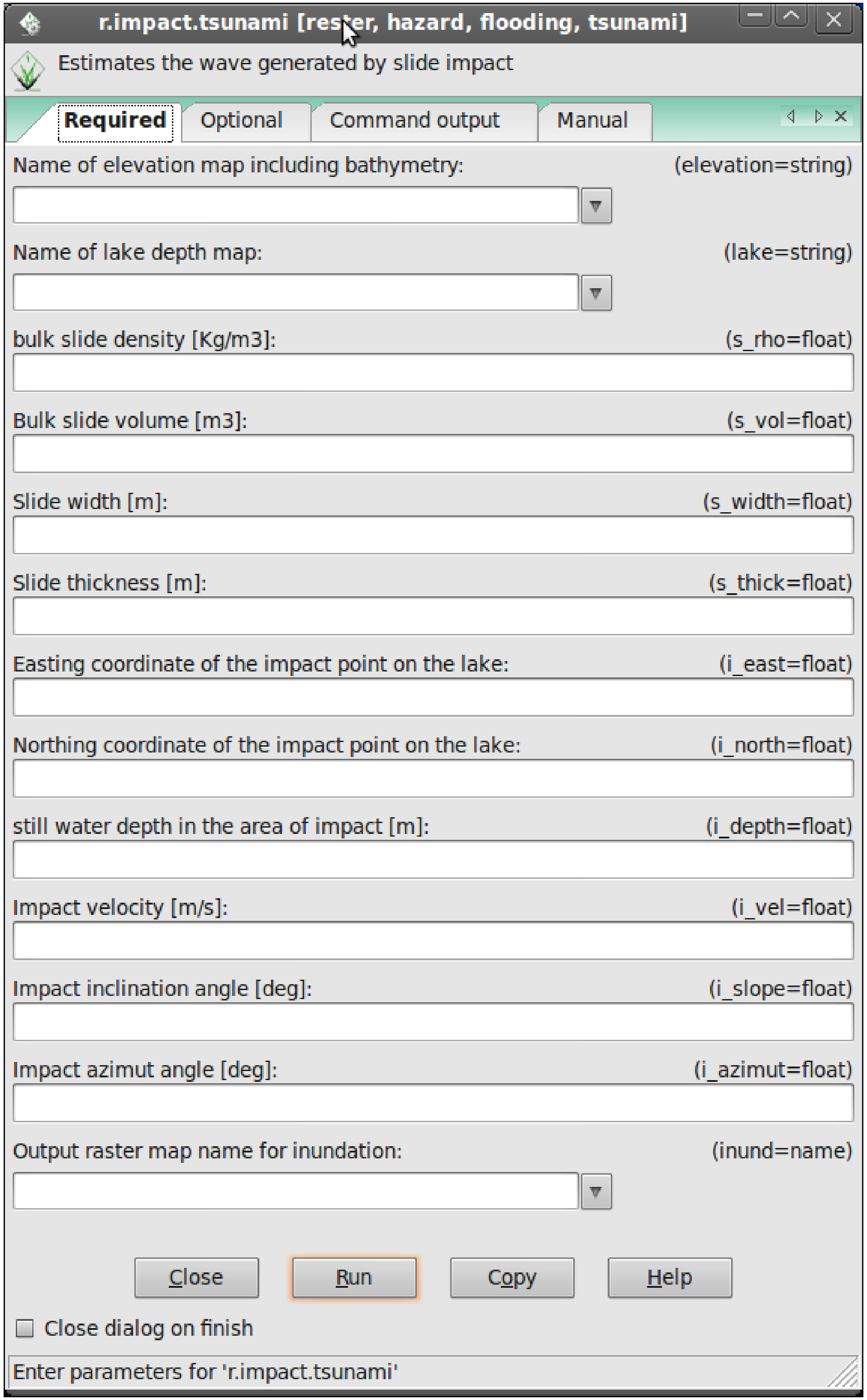
The H2009 model has been implemented in a new GRASS 7 module by using the Python script approach.

- H2009 in GRASS: required inputs

A. elevation map including bathymetry
B. lake water depth map
C. slide mass information (density, porosity, volume, width, thickness)
D. impact information (coordinates, water depth, velocity, inclination angle, azimuth angle)

- H2009 in GRASS: output

A. Output inundation height raster map
B. Output wave height raster map (opt.)



r.impact.tsunami [raster, hazard, flooding, tsunami]

Estimates the wave generated by slide impact

Name of elevation map including bathymetry:	(elevation=string)
Name of lake depth map:	(lake=string)
bulk slide density [Kg/m3]:	(s_rho=float)
Bulk slide volume [m3]:	(s_vol=float)
Slide width [m]:	(s_width=float)
Slide thickness [m]:	(s_thick=float)
Easting coordinate of the impact point on the lake:	(i_east=float)
Northing coordinate of the impact point on the lake:	(i_north=float)
still water depth in the area of impact [m]:	(i_depth=float)
Impact velocity [m/s]:	(i_vel=float)
Impact inclination angle [deg]:	(i_slope=float)
Impact azimut angle [deg]:	(i_azimut=float)
Output raster map name for inundation:	(inund=name)

☐ Close dialog on finish

Enter parameters for 'r.impact.tsunami'

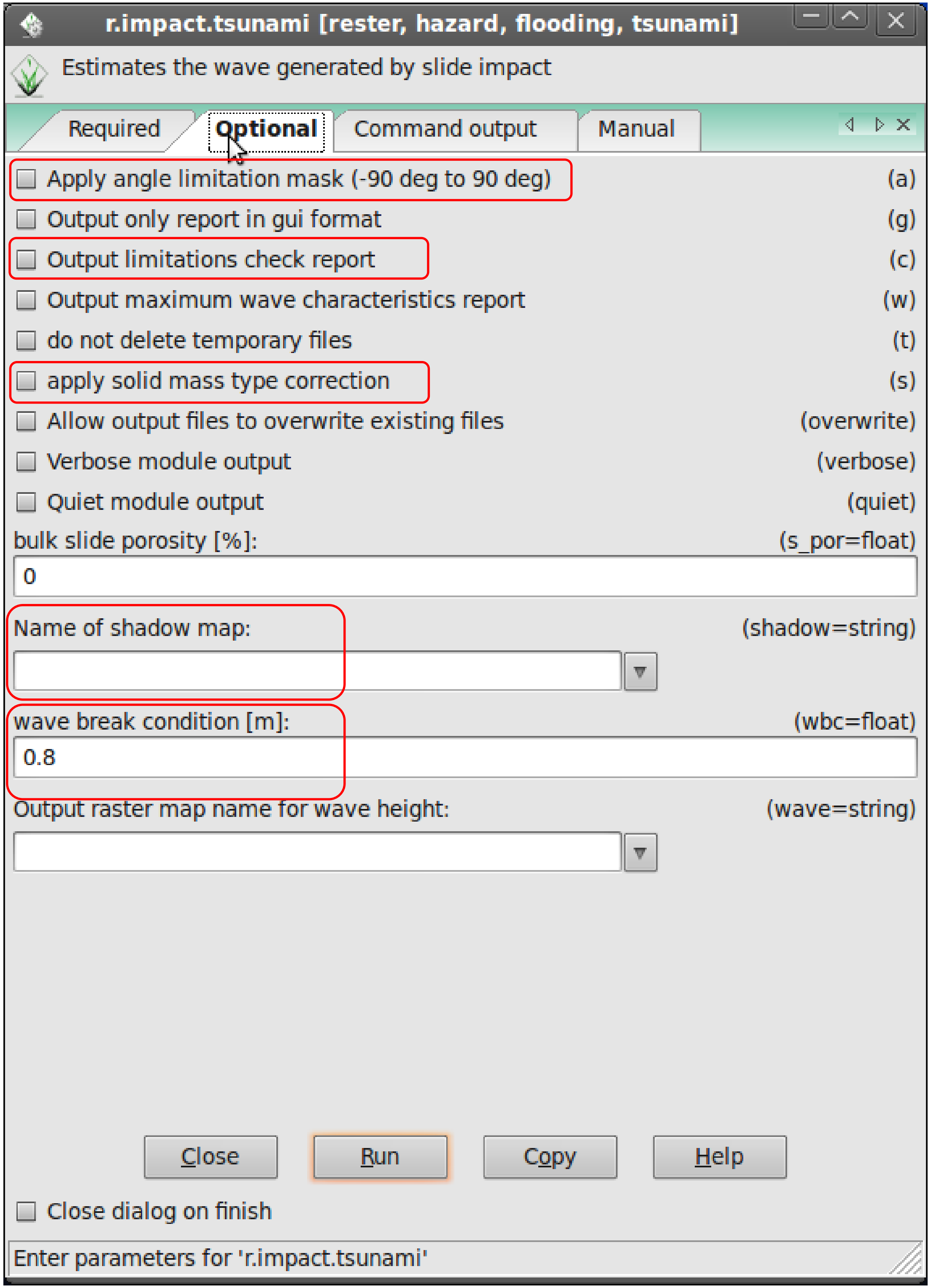
r.impact.tsunami

- H2009 in GRASS: optional settings

A. a shadow raster map, for masking the results (i.e.: a line of sight map from the impact location, can identify locations directly impacted by the wave),

B. a numerical value for the wave break condition or select one

C. Optional flags are:
   A. applying angle limitation mask (-90 deg to 90 deg);
   B. outputting report in GUI format;
   C. outputting limitations check report;
   D. outputting maximum wave characteristics report;
   E. saving temporary files;
   F. applying solid mass type correction factor



Estimates the wave generated by slide impact

☐ Apply angle limitation mask (-90 deg to 90 deg) (a)
☐ Output only report in gui format (g)
☐ Output limitations check report (c)
☐ Output maximum wave characteristics report (w)
☐ do not delete temporary files (t)
☐ apply solid mass type correction (s)
☐ Allow output files to overwrite existing files (overwrite)
☐ Verbose module output (verbose)
☐ Quiet module output (quiet)

bulk slide porosity [%]: (s_por=float)
0

Name of shadow map: (shadow=string)

wave break condition [m]: (wbc=float)
0.8

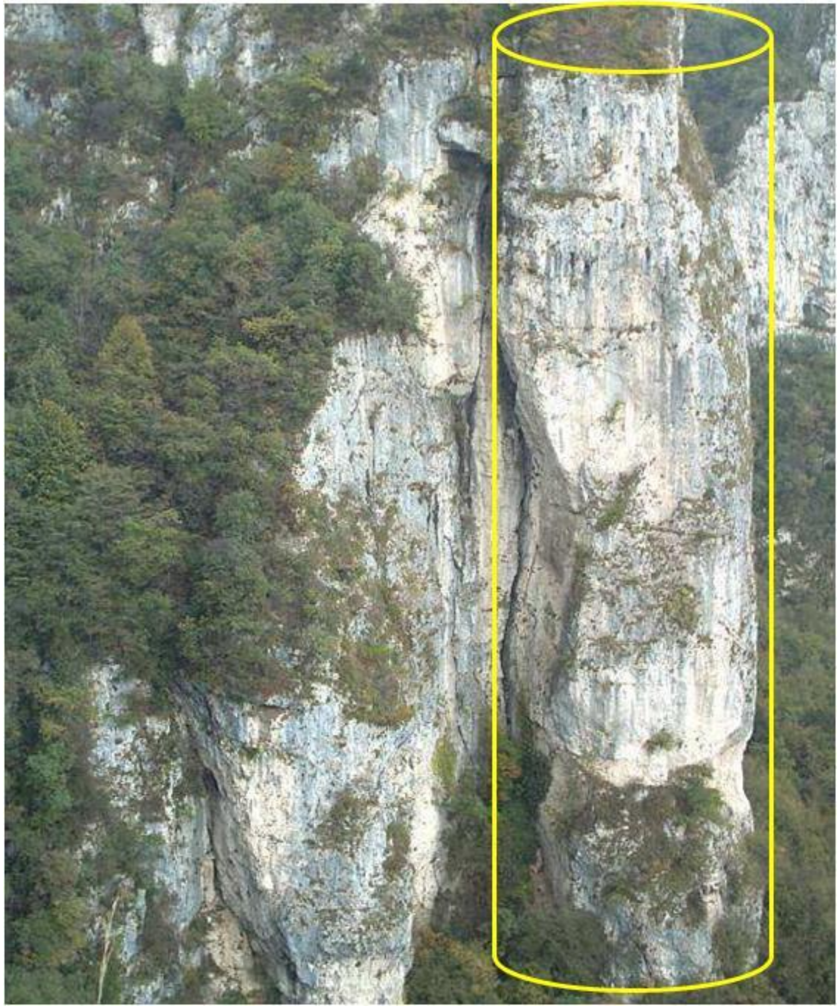
Output raster map name for wave height: (wave=string)

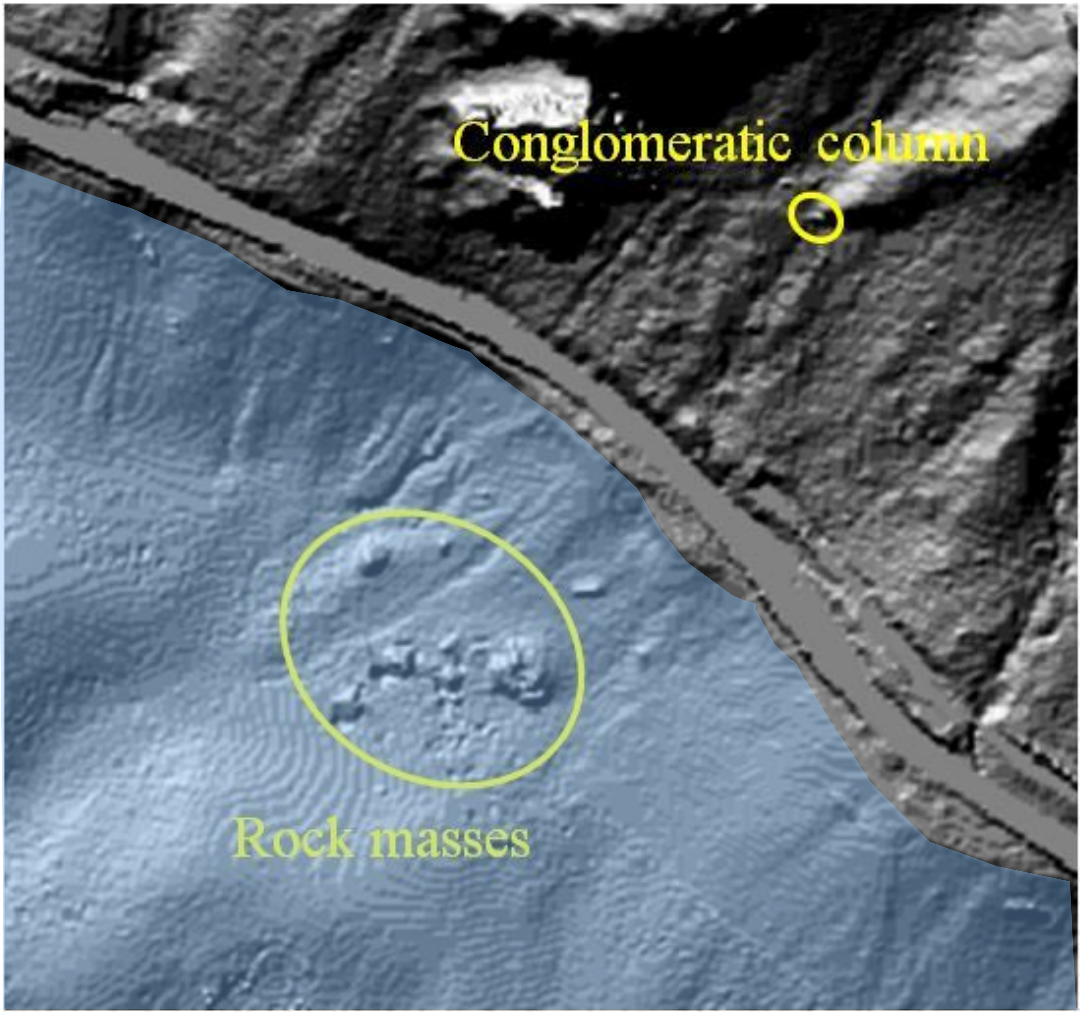
☐ Close dialog on finish

Enter parameters for 'r.impact.tsunami'

Case study

- Hazard scenario: toppling of a conglomeratic column that reaches the Como lake





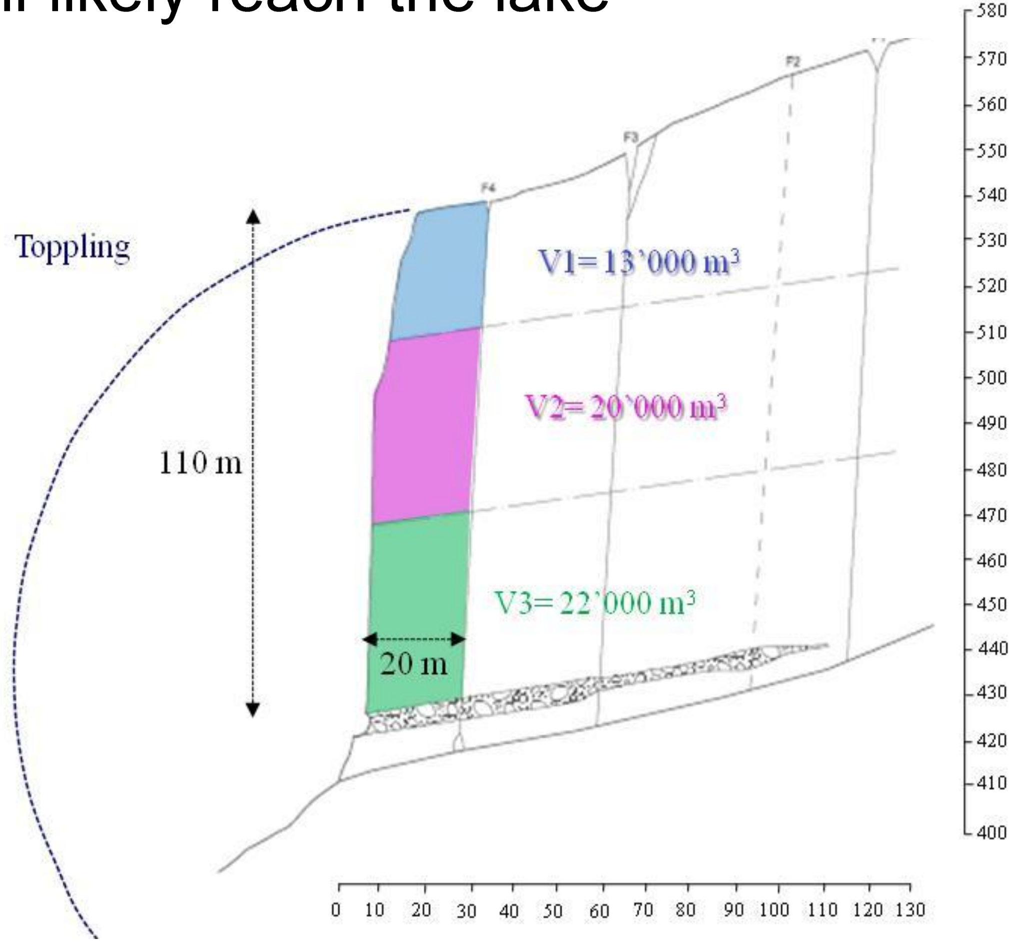
Dive inspection confirms that rock masses laid on the lake bottom have the same composition of the column: probably result of events occurred in the past

Case study

- Input parameter estimation

By field survey and rock-fall simulation with SASS model (Pamini, 2002) as described in Ambrosi et. al (2010): ropture of the column in 3 blocks, out of witch the first will likely reach the lake

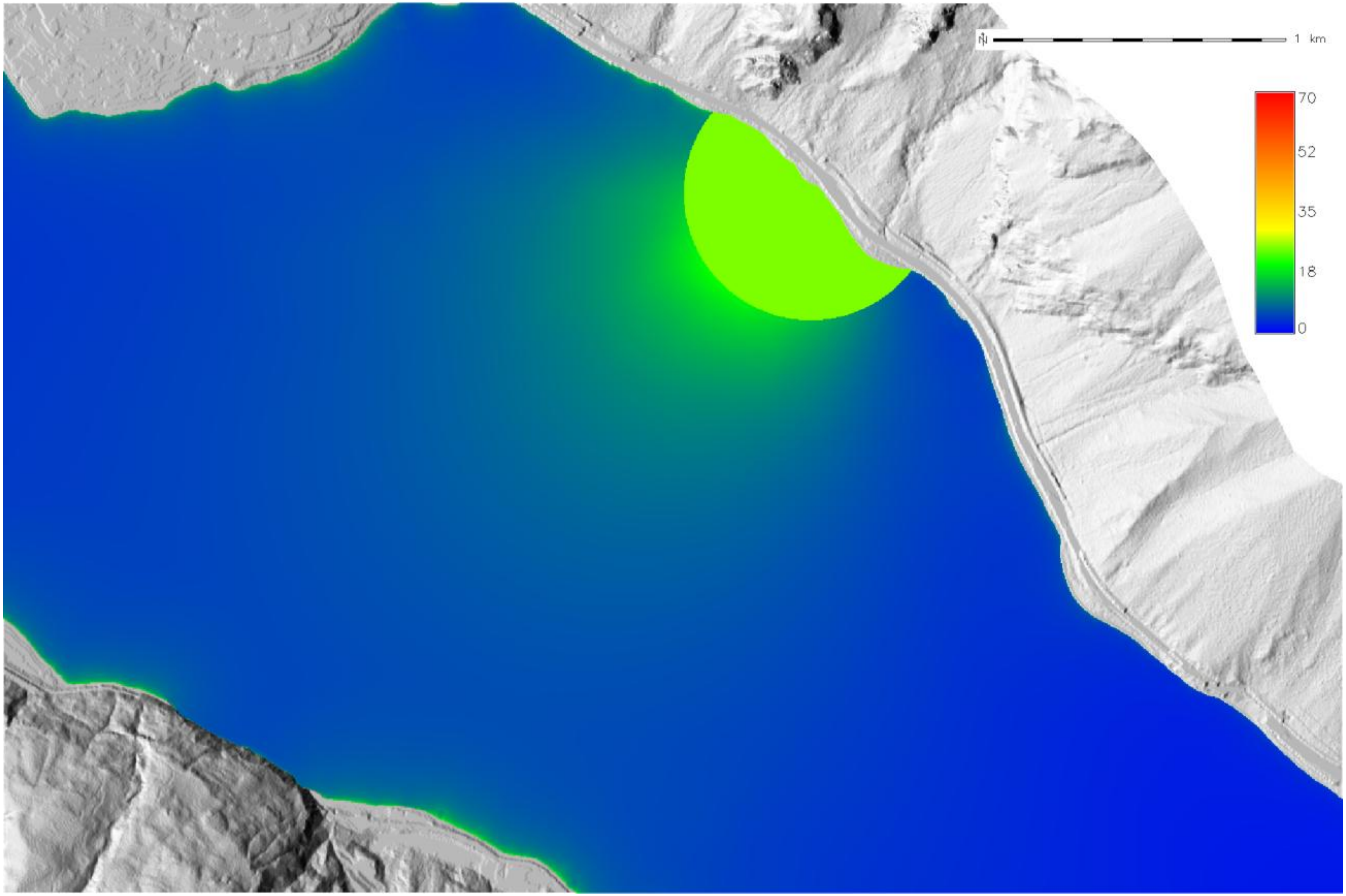
mass bulk density = 2500 [Kg/m^3],
mass bulk porosity = 0 [%]
mass volume = 13000 [m^3],
mass width = 26 [m],
mass thickness = 25 [m],
impact velocity = 35 [m/s],
impact slope angle = 35 [deg],
impact azimuth = 225 [deg],
still water depth in the impact zone = 50 [m]



Simulations

- Wave height output map

Maximum height	24.95 m
Mean height	6.84 m
Std of height	4.13 m



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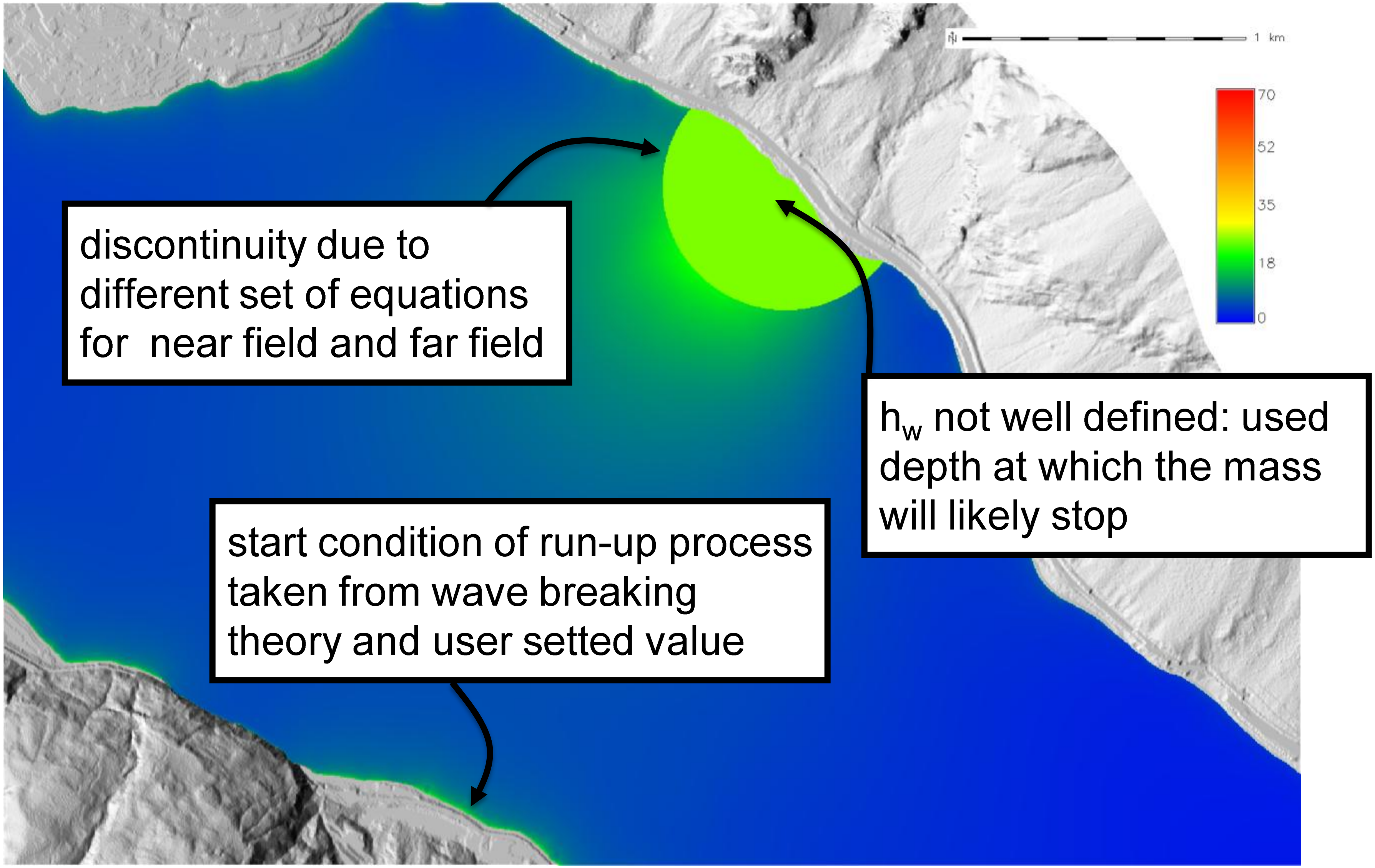


discontinuity due to different set of equations for near field and far field

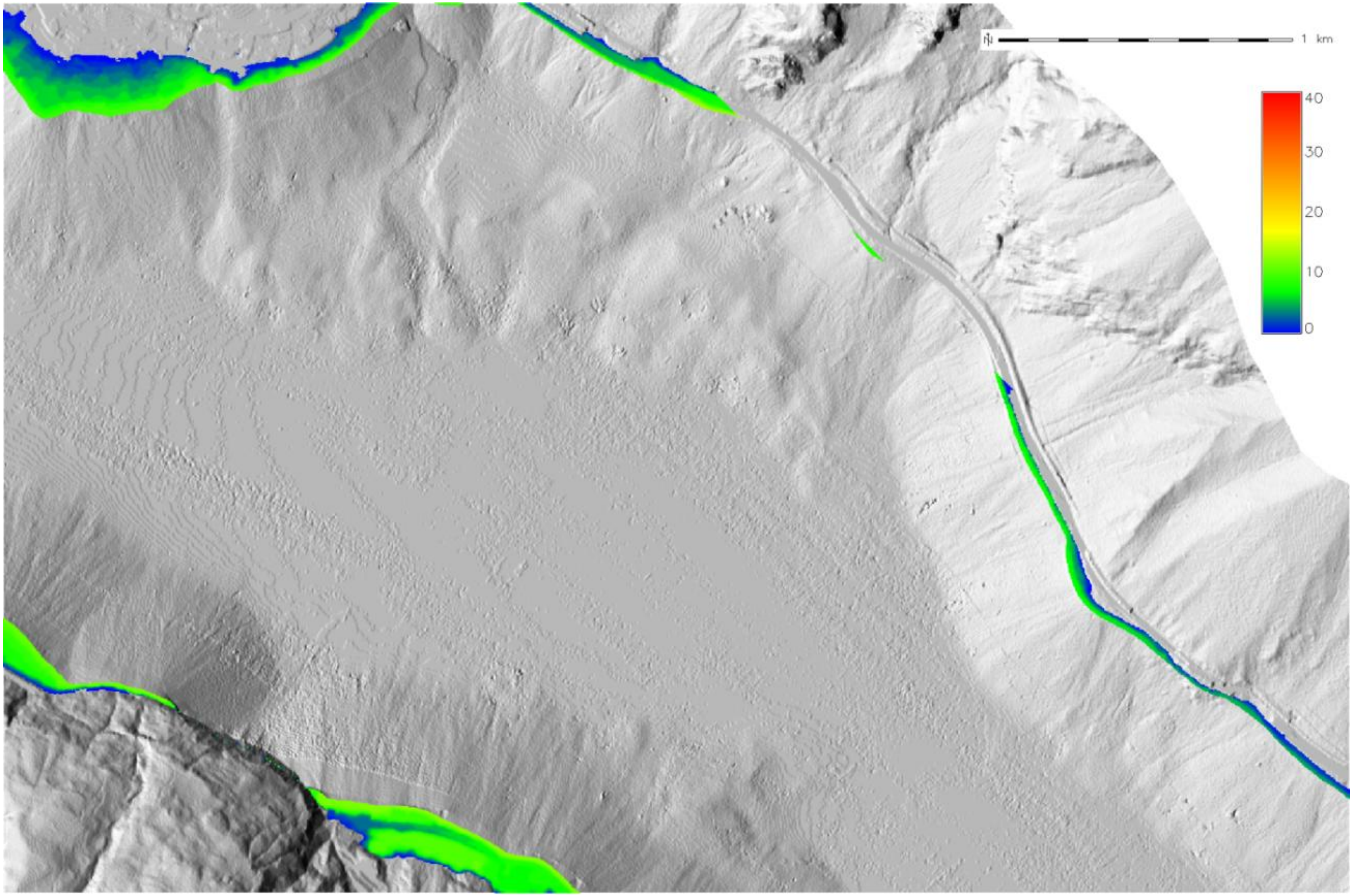
h_w not well defined: used depth at which the mass will likely stop

start condition of run-up process taken from wave breaking theory and user setted value

Simulations

- Flood height output map

Flood area	146,396 m^2
Maximum height	13.44 m
Mean height	6.06 m
Std of height	3.11 m



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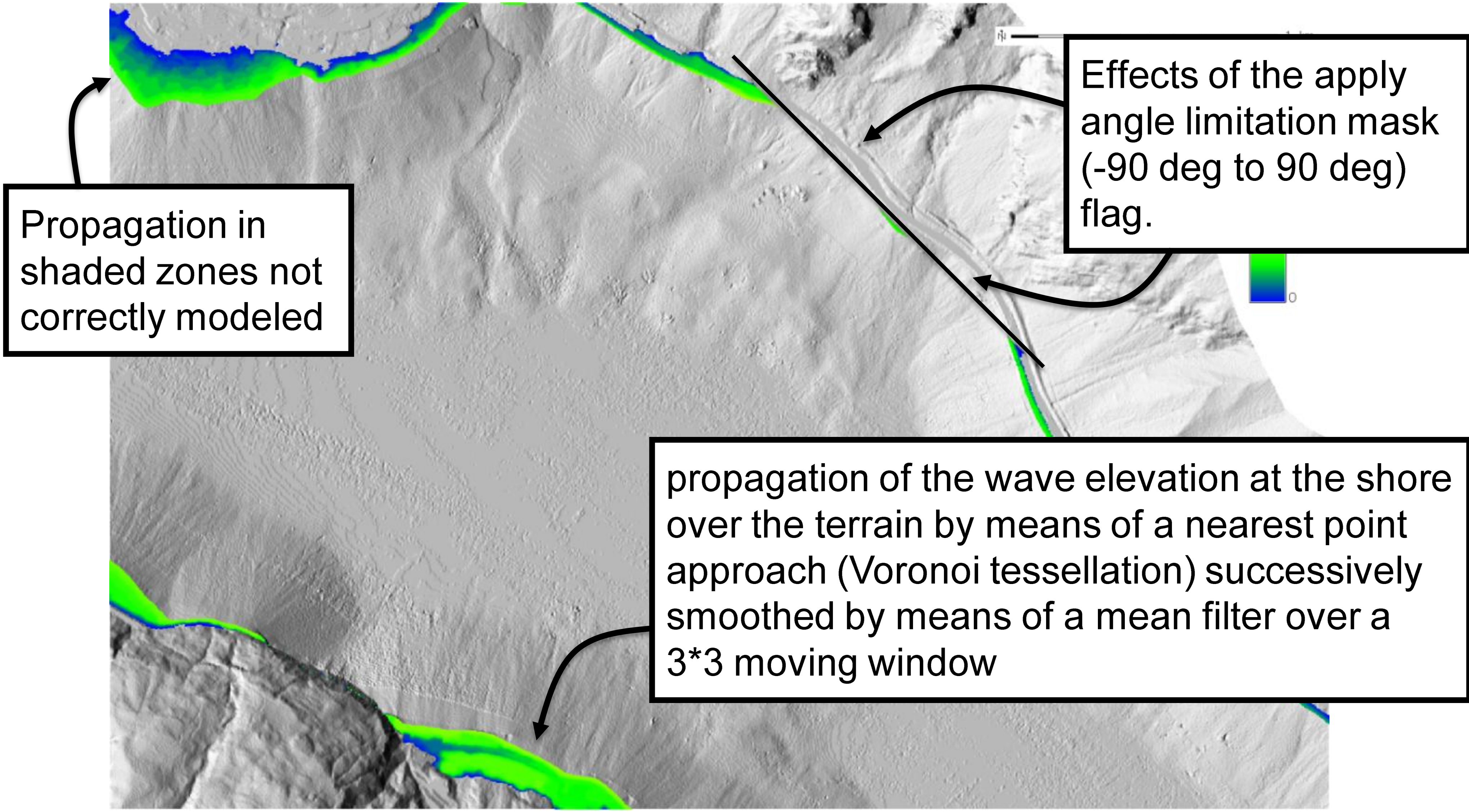
- Flood height output map



Effects of the apply angle limitation mask (-90 deg to 90 deg) flag.

Propagation in shaded zones not correctly modeled

propagation of the wave elevation at the shore over the terrain by means of a nearest point approach (Voronoi tessellation) successively smoothed by means of a mean filter over a 3*3 moving window

Module reports

- Respecting of validity_limits and maximum wave parameters

```
==========   MAXIMUM WAVE HEIGHT   ========
HM = 24.9545600723
TM = 19.0053090237
LM = 497.819032673
a = 19.9636480579
c = 26.1936826206
rM = 257.181932638
==========   LIMITING CONDITIONS REPORT   ========
Slide Froude number limitation (0.86<= F <= 6.83): value=1.58060264513 – respected=True
Relative slide thickness (0.09<= S <= 1.64): value=0.5 – respected=True
Relative slide mass (0.11<= M <= 10.02): value=0.5 – respected=True
Relative slide density (0.59<= D <= 1.72): value=2.5 – respected=False
Relative granulate density (0.96<= Dg <= 2.75): value=0.001 – respected=False
Relative slide volume (0.05<= V <= 5.94): value=0.8 – respected=True
Relative slide width (0.74<= B <= 3.33): value=1.04 – respected=True
Bulk slide porosity (30.7<= por <= 43.3): value=0.0 – respected=False
Slide impact angle (30deg<= beta <= 90deg): value=35.0 – respected=True
Impulse product parameter (0.17<= P <= 8.13): value=0.874612184799 – respected=True
```

Sources of uncertainties

- Basin shape and mass type influences

Bathymetry variation	-h ~ +H
Diffraction	shaded zones reached.
Constriction	lateral constriction ~ + H
Reflection	reflected wave has - H.
Refraction	perpendicular waves
Solid mass	solid mass ~ + H
Validity limits	limits are not respected ~ ?

EXPECTED IMPACT

HIGH MED LOW UNKNOWN

Uncertanties estimation

▪ Basin shape effects

- Bathymetry variation ▪ wave height automatically corrected in r.impact.tsunami with Shoaling equation

- Solid mass type ▪ according to Zweifel (2004) experiments higher maximum wave are expected.

$$\frac{(a_{Ms}/h_w)-(a_M/h_w)}{a_{Ms}/h_w} = 1 - 0.26 \cdot F$$

In the case study an increase of maximum wave height of a factor of 2.43 is estimated.

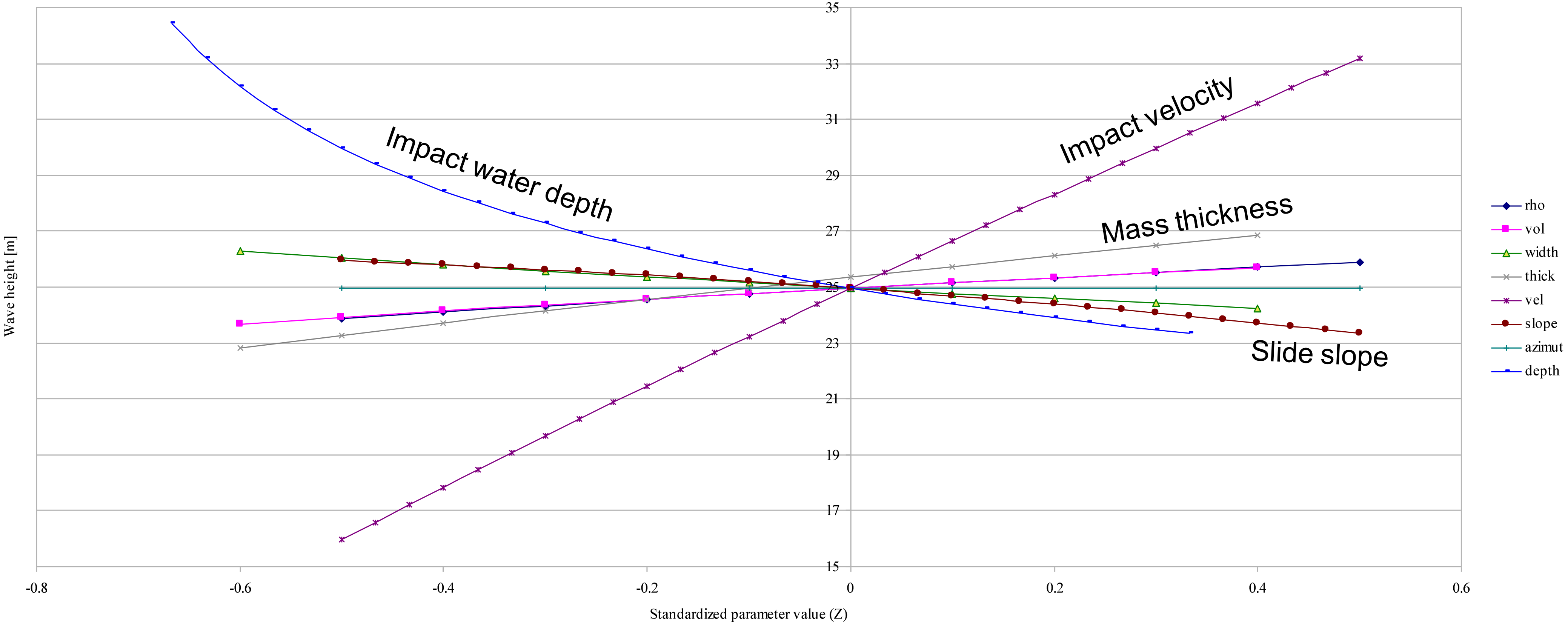
Model sensitivity

- Effects of input parameter variation

Parameter	Acronym	Range	Variation
Mass bulk density [Kg/m^3]	rho	2,000 – 3,000	100
Mass volume [m^3]	vol	10,000 – 15,000	500
Mass width [m]	width	20 – 30	1
Mass thickness [m]	thick	20 – 30	1
Impact velocity [m/s]	vel	20 – 50	1
Impact slope angle [deg]	slope	20 – 50	1
Impact azimuth	azimuth	200 – 251	10
Still water depth in the impact zone	depth	10 – 70	2

Sensitivity of wave height

- Effects of input parameter variation

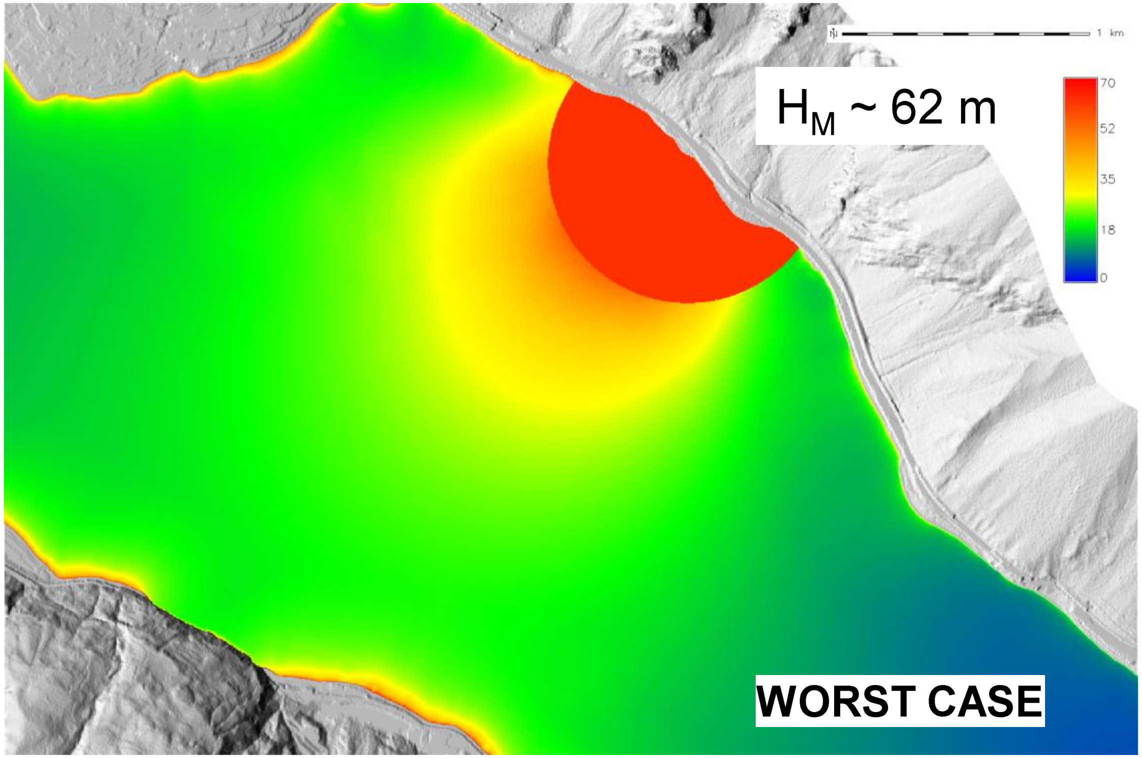


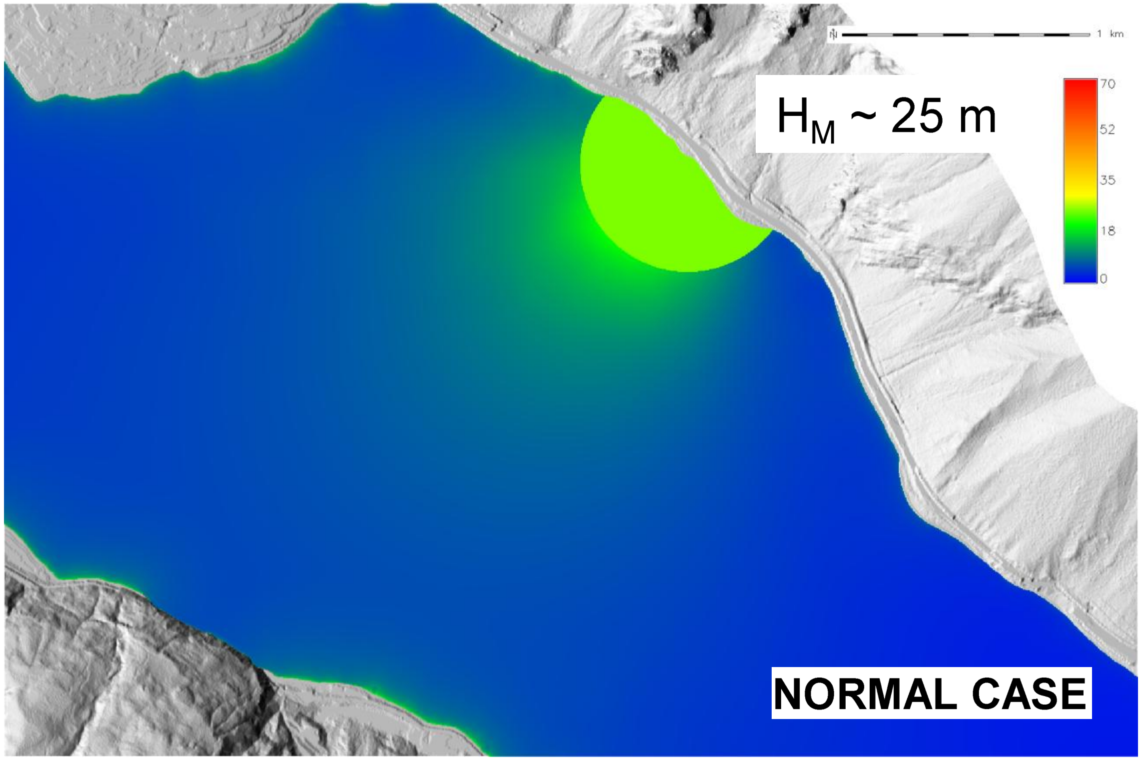
Water height and mass velocity at the impact are the parameters most affecting the results: their determination has a certain level of uncertainty due to no definition of “impact point” and estimation of “impact velocity”

Worst case scenario

- Considering uncertainties

- r.impact.tsunami is run with:
  - Applying Shoaling correction for bathymetry variation
  - Applying mass type correction for solid body
  - Using upper bound values of parameter variability range





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- Considering uncertanties

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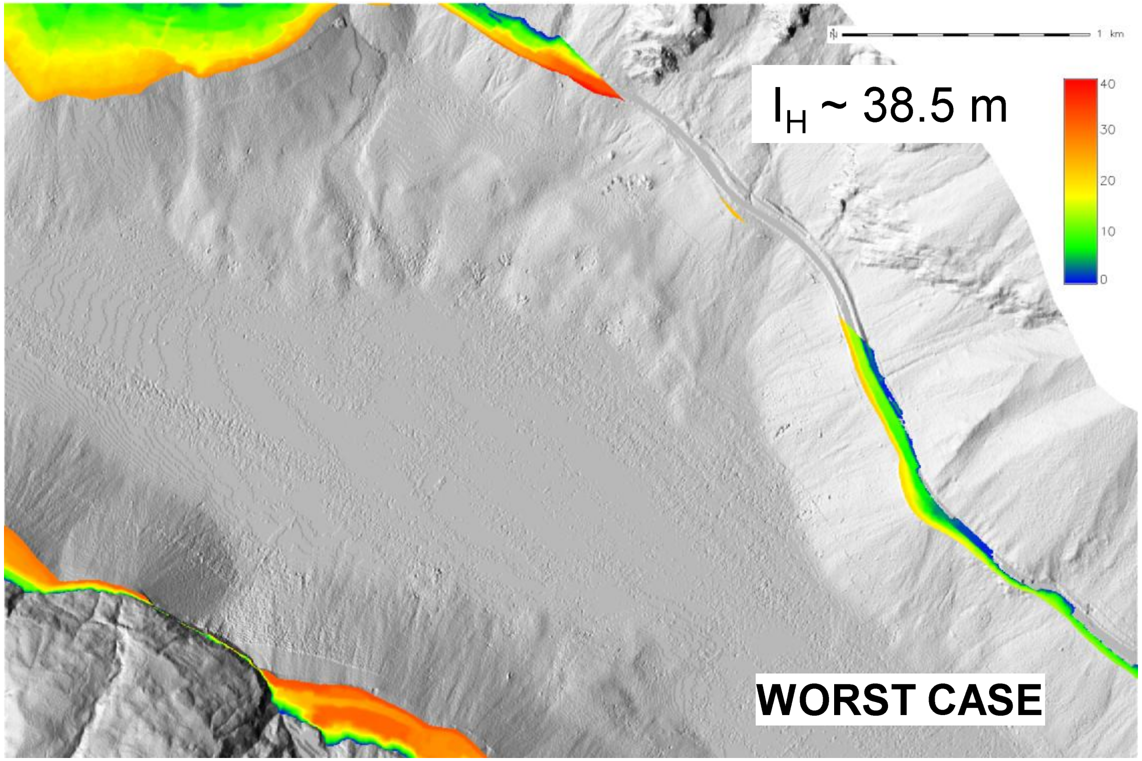
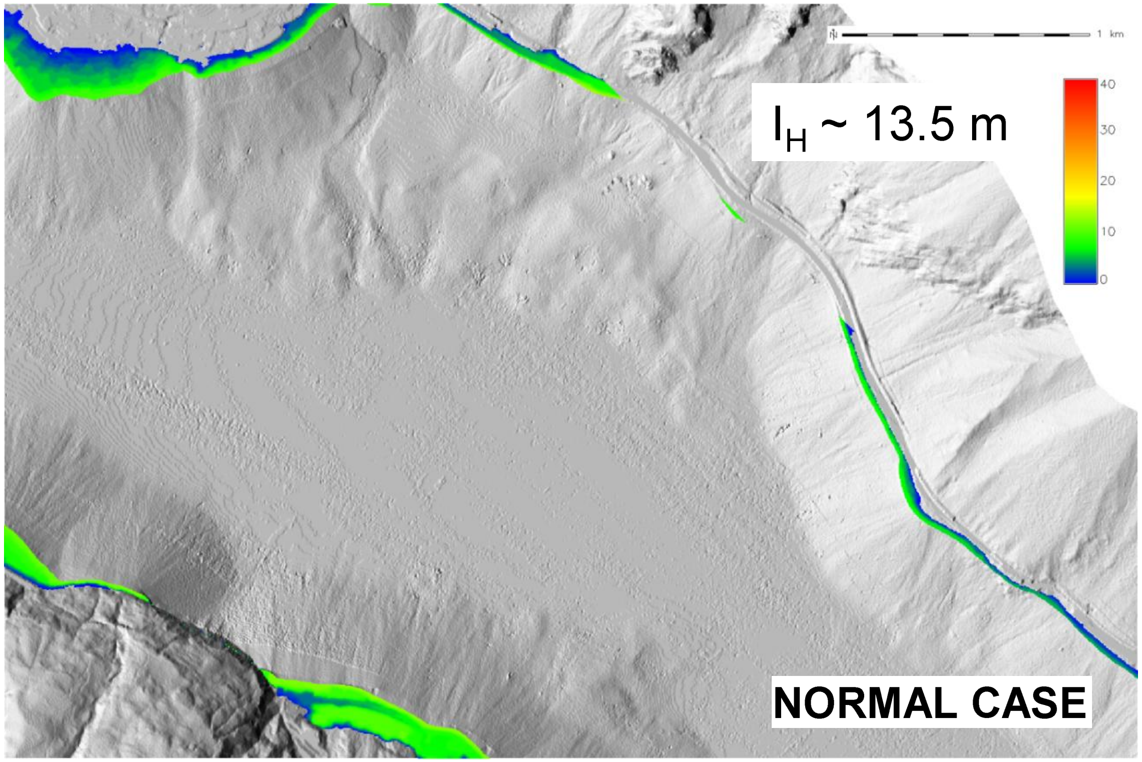
  - Applying Shoaling correction for bathymetry variation
  - Applying mass type correction for solid body
  - Using upper bound values of parameter variability range

Maximum inundation area is estimated to be **268,384 m²**, that is **121,988 m²** more than the inundation area estimated with base values.

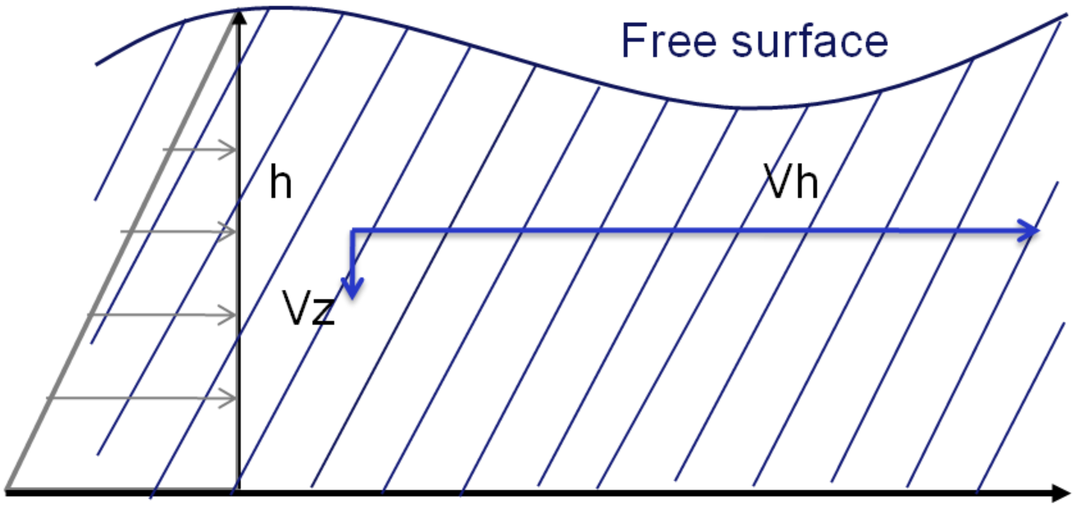




Shallow water equation approach (SWE)

- To model wave propagation and run-up processes

- SWE method applies the shallow water equations (Kinmark, 1985) to simulate the wave propagation and the resulting run-up: with this approach the two phenomena can be simulated with a single model even though since the SWE treats the wave breaking only as a propagation wave, the details of the wave breaking process cannot be obtained (Li & Raichlen, 2002).



1) component of velocities along the vertical direction is negligible if compared to the horizontal ones
2) the pressure distribution over the flow depth is nearly hydrostatic

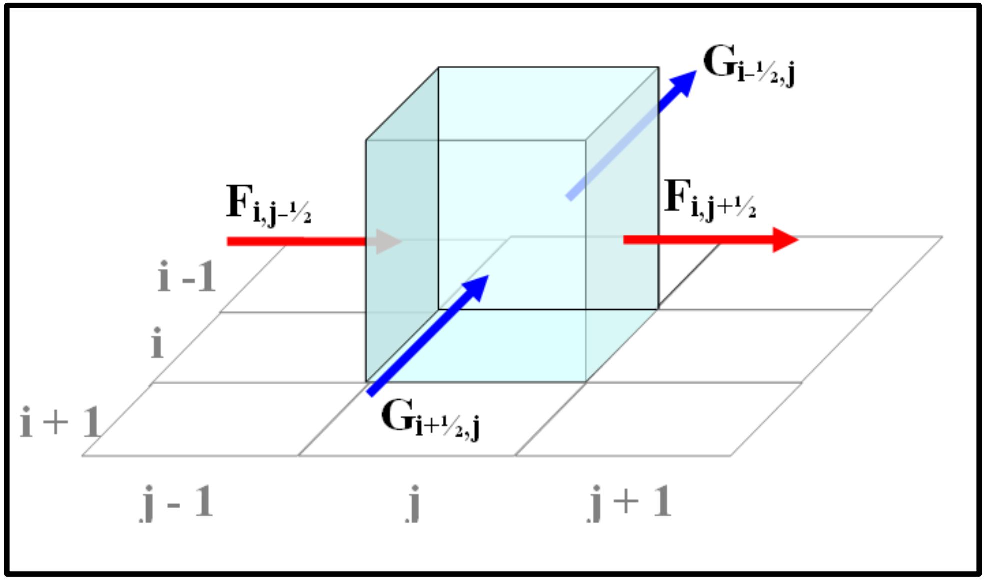
Shallow water equations solution

applying the Upwind Conservative Scheme by Ying et al. (2004) we get the solution

$$\boxed{\mathbf{U}_{ij}^{n+1} = \mathbf{U}_{ij} - \Delta t \left(\frac{\left(\mathbf{F}_{i,j+1/2} - \mathbf{F}_{i,j-1/2}\right)}{ewres} + \frac{\left(\mathbf{G}_{i-1/2,j} - \mathbf{G}_{i+1/2,j}\right)}{nsres} - \mathbf{S}_{ij} \right)}$$

With the one-sided upwind method we solves explicitly this equation in two separate steps:

1. the continuity equation is evaluated deriving the <u>water depth at time *t+1*</u>,
2. these values are used to solve the momentum equations that provide the <u>flow velocities at time *t+1*</u>



r.swe

- C ANSI developed module that solves the swe with advanced numerical scheme (Cannata and Marzocchi, 2011) for each cell and timestep estimating locally water height and velocity.
- Included stability analysis to automatically adjust optimal resolution time step

Input options

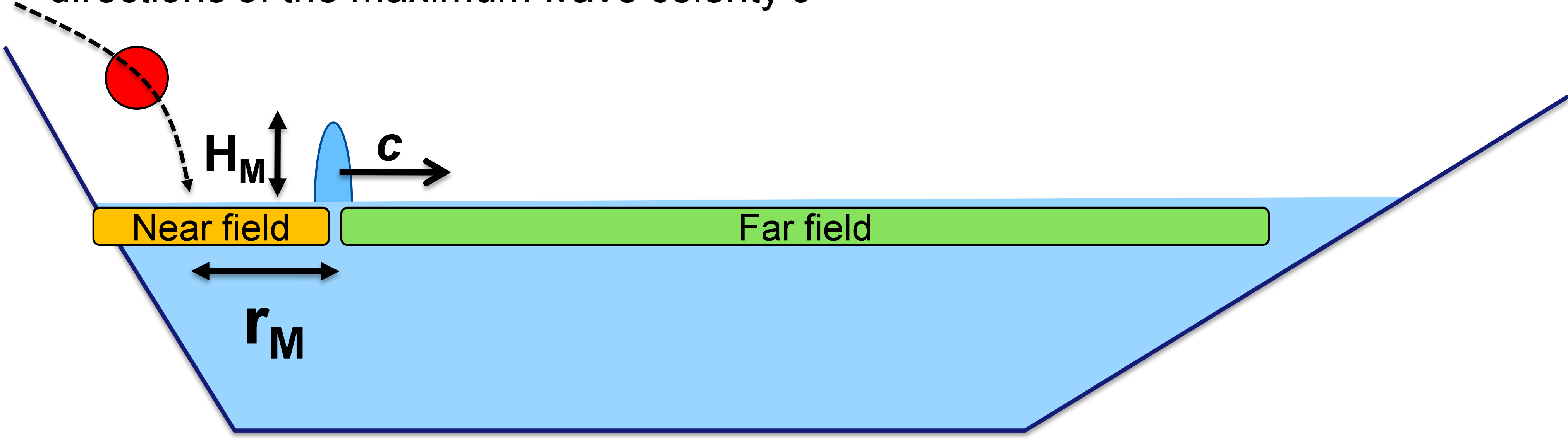
- elevation raster map accounting for bathymetry
- lake water depth raster map
- Initial velocity in east and north directions raster maps (derived with r.impact.tsunami)
- manning's roughness coefficient raster map;
- simulation time length.
- simulation timestep

Output options

- time-lag for outputs generation;
- additional instants for output map generation;
- prefix for water depth output series raster maps;
- prefix for water velocity output series raster maps;
- maximum water depth and relative time output raster map;
- maximum water velocity and relative time output raster map;
- maximum intensity output and relative time raster map.

Case study application

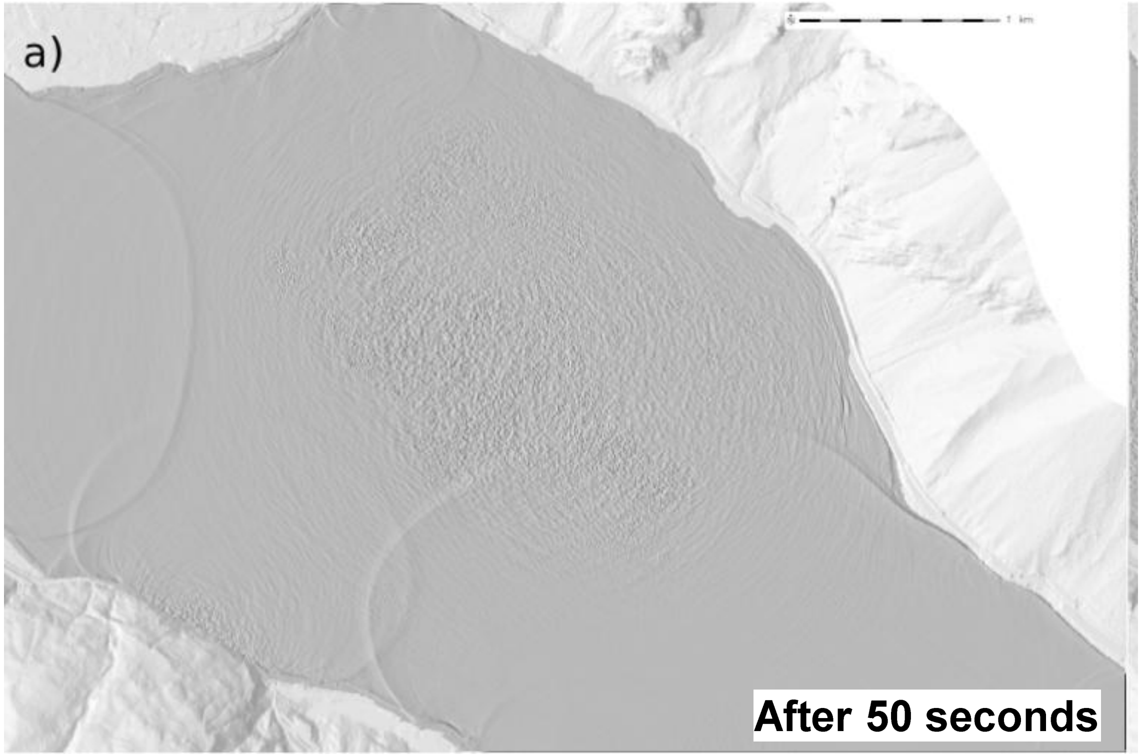
- The same computational region used in H2009 simulation was applied. In particular the initial water depth corresponds almost everywhere to the initial lake depth, while in correspondence of the distance r_M from the impact point the maximum wave height H_M is assumed. In the same manner the initial velocities u_0 and v_0 respectively along the East and North directions are considered null everywhere with exception of the r_M distance from the impact point ehere the velocities are assumed to be the components along the East and North directions of the maximum wave celerity c



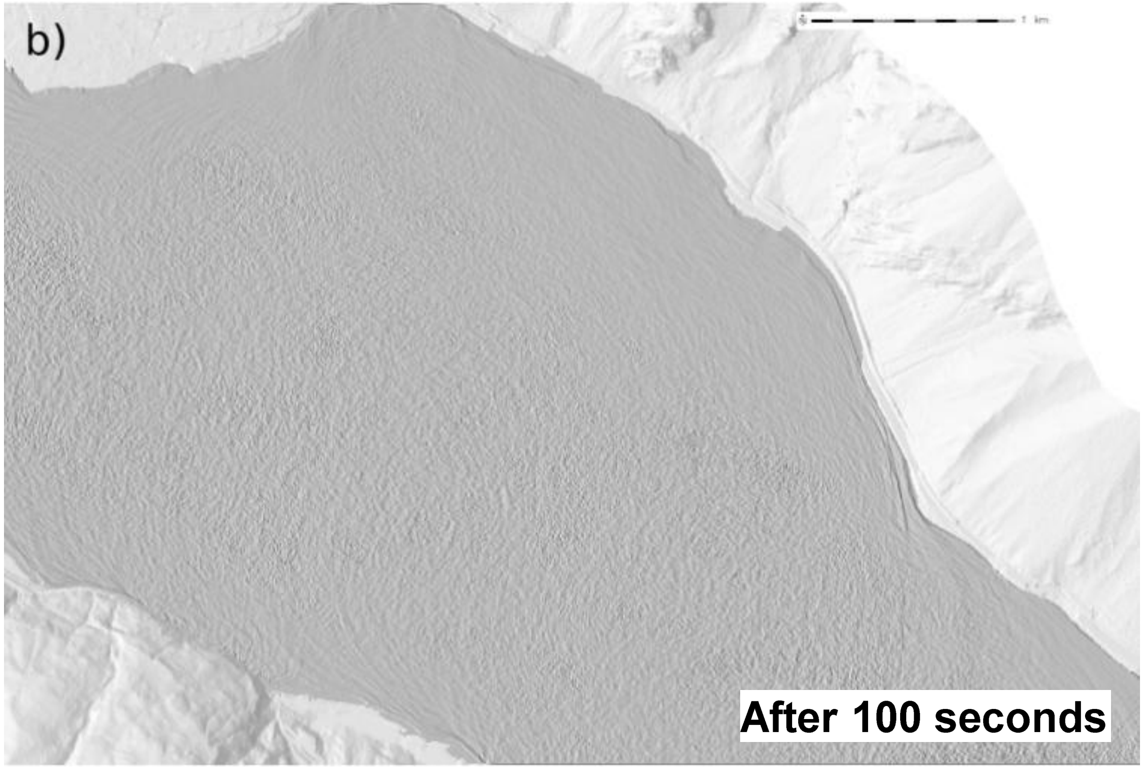
Case study

- Considering uncertanties

- r.swe:
  - Is not affected by basin shape effects (already considered in wave propagation)
  - Is affected by mass type because the impact wave estimation depends on H2009



After 50 seconds

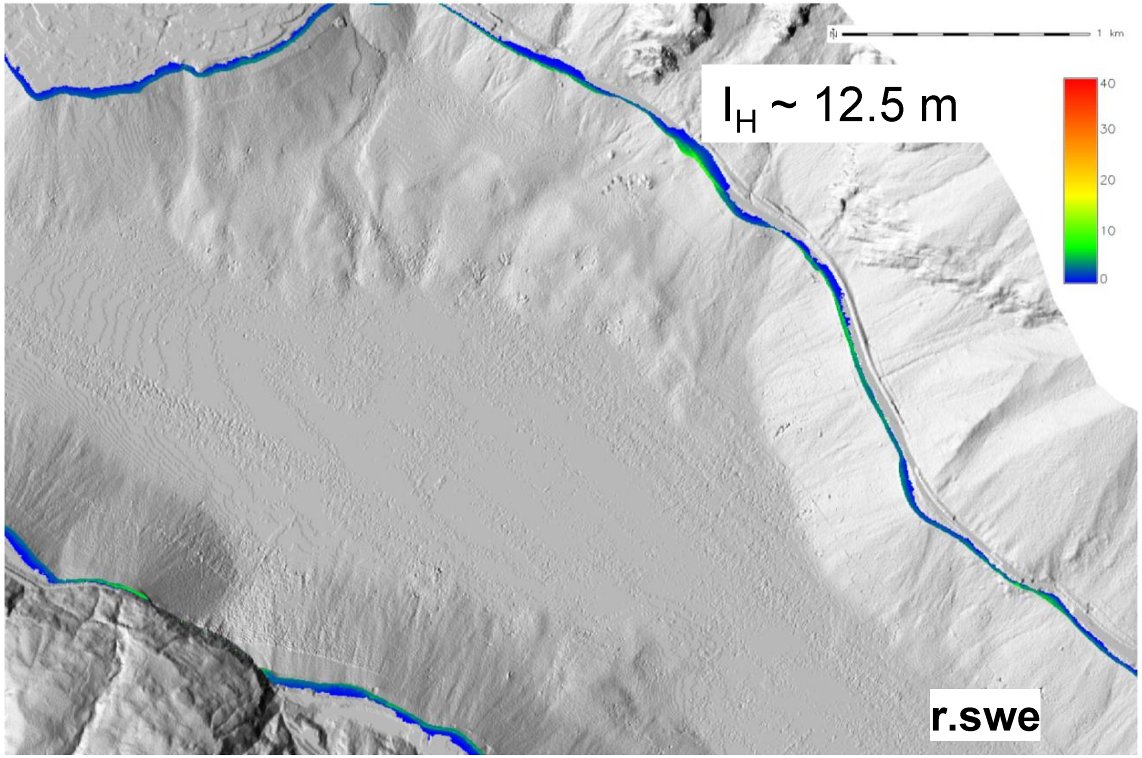


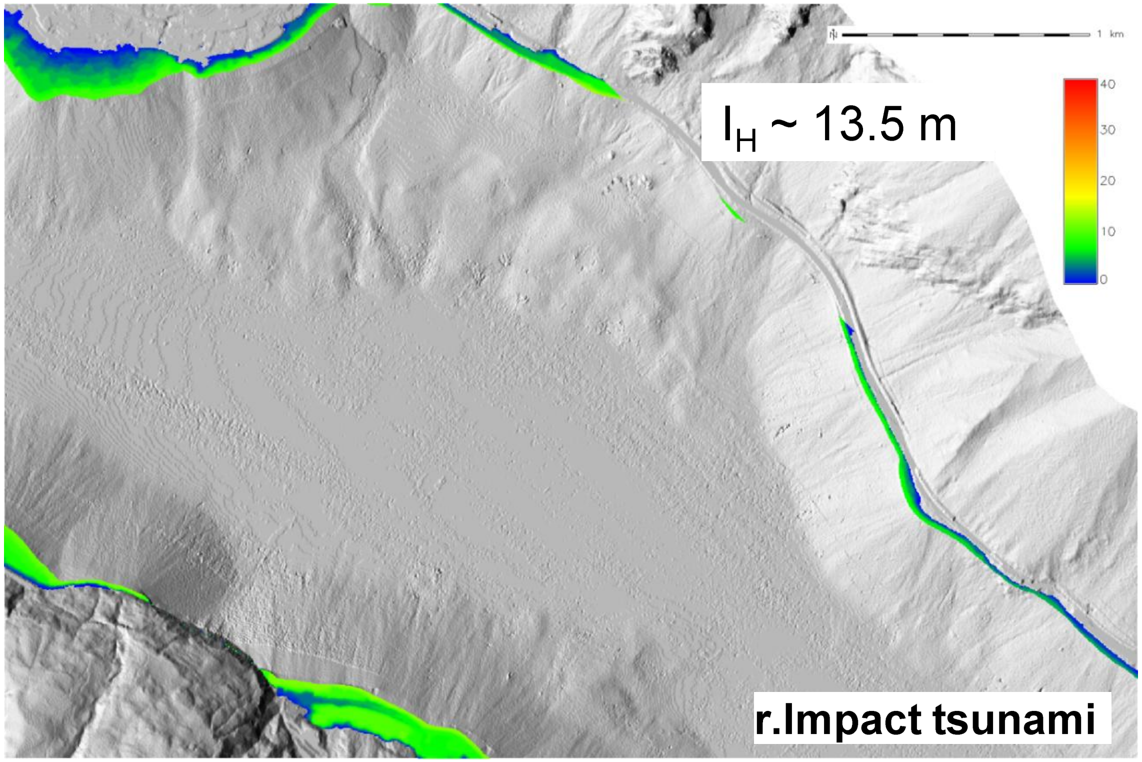
After 100 seconds

Methods comparison

▪ Considering uncertanties

- SWE evaluate lower maximum inundation height and thus less flooding area



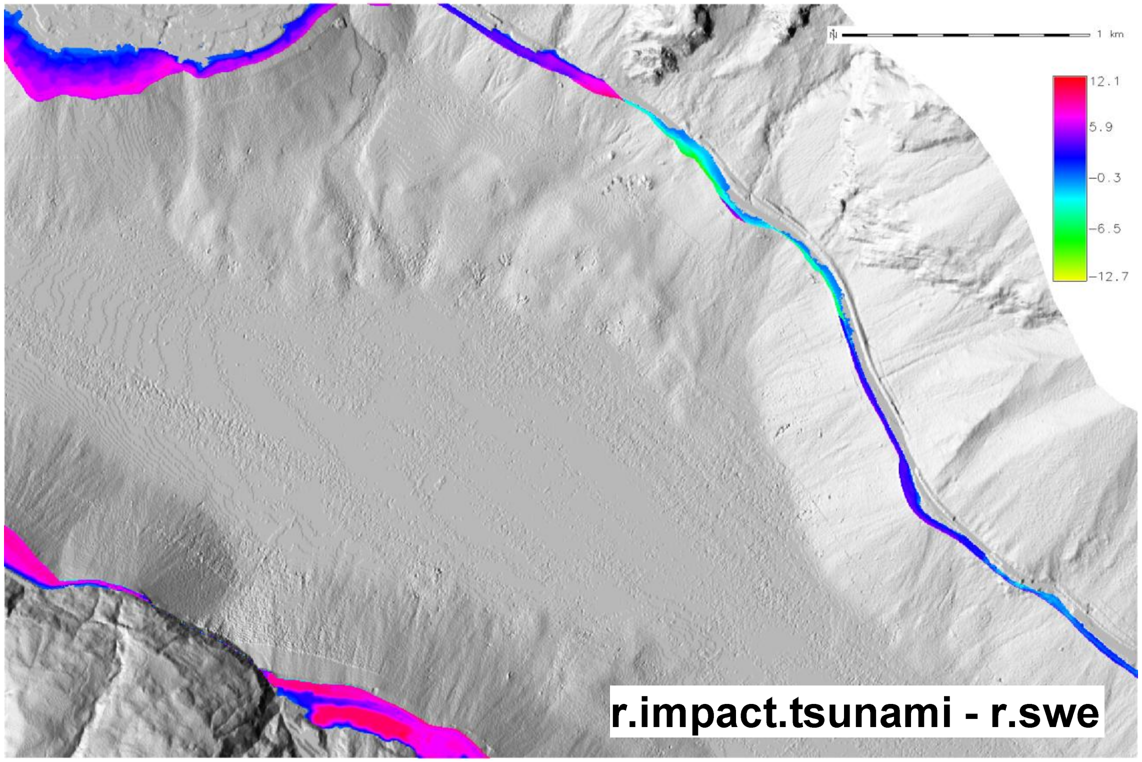


Methods comparison

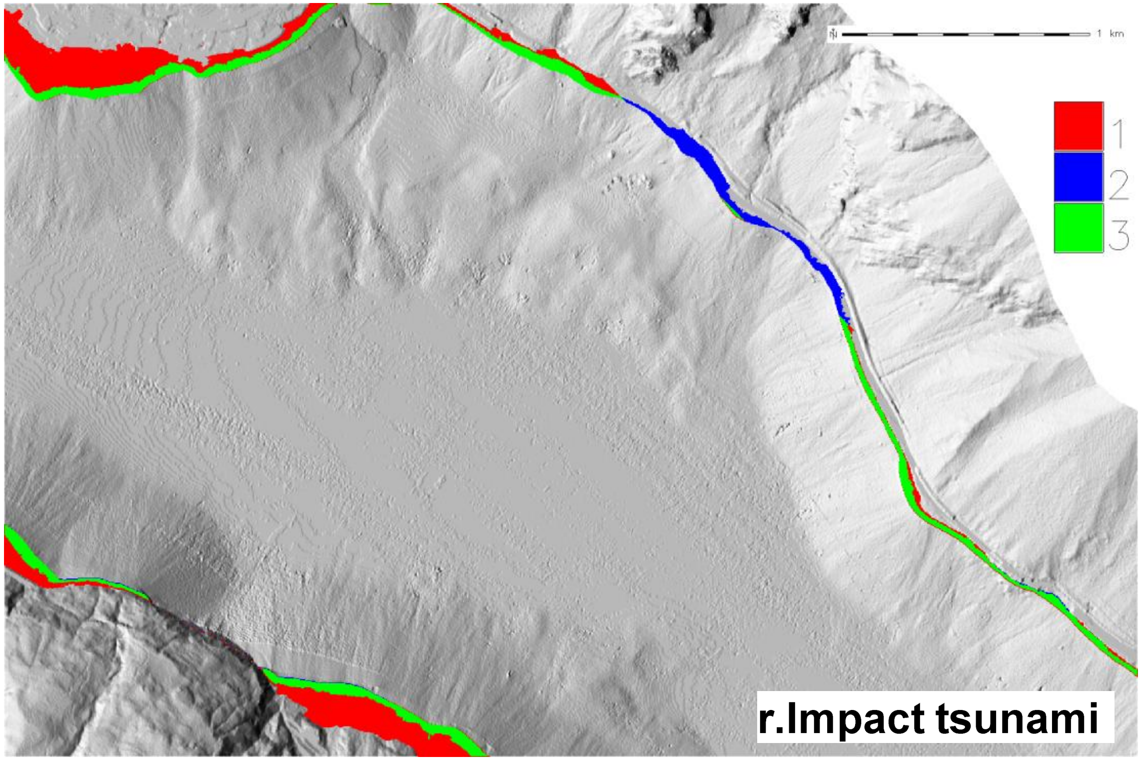
- H2009 - SWE

- difference type 1: inundation area estimated by the H2009 method and not by the SWE
- difference type 2: inundation area estimated by the SWE method and not by the H2009
- difference type 3: inundation area considered by both methods

Maximum difference	12.11 m
Mean difference	4.41 m
Std of differences	3.58 m
difference type 1: area	89,960 m^2
difference type 2: area	16,542 m^2
difference type 3: area	56,416 m^2



r.impact.tsunami - r.swe



r.Impact tsunami

Conclusions

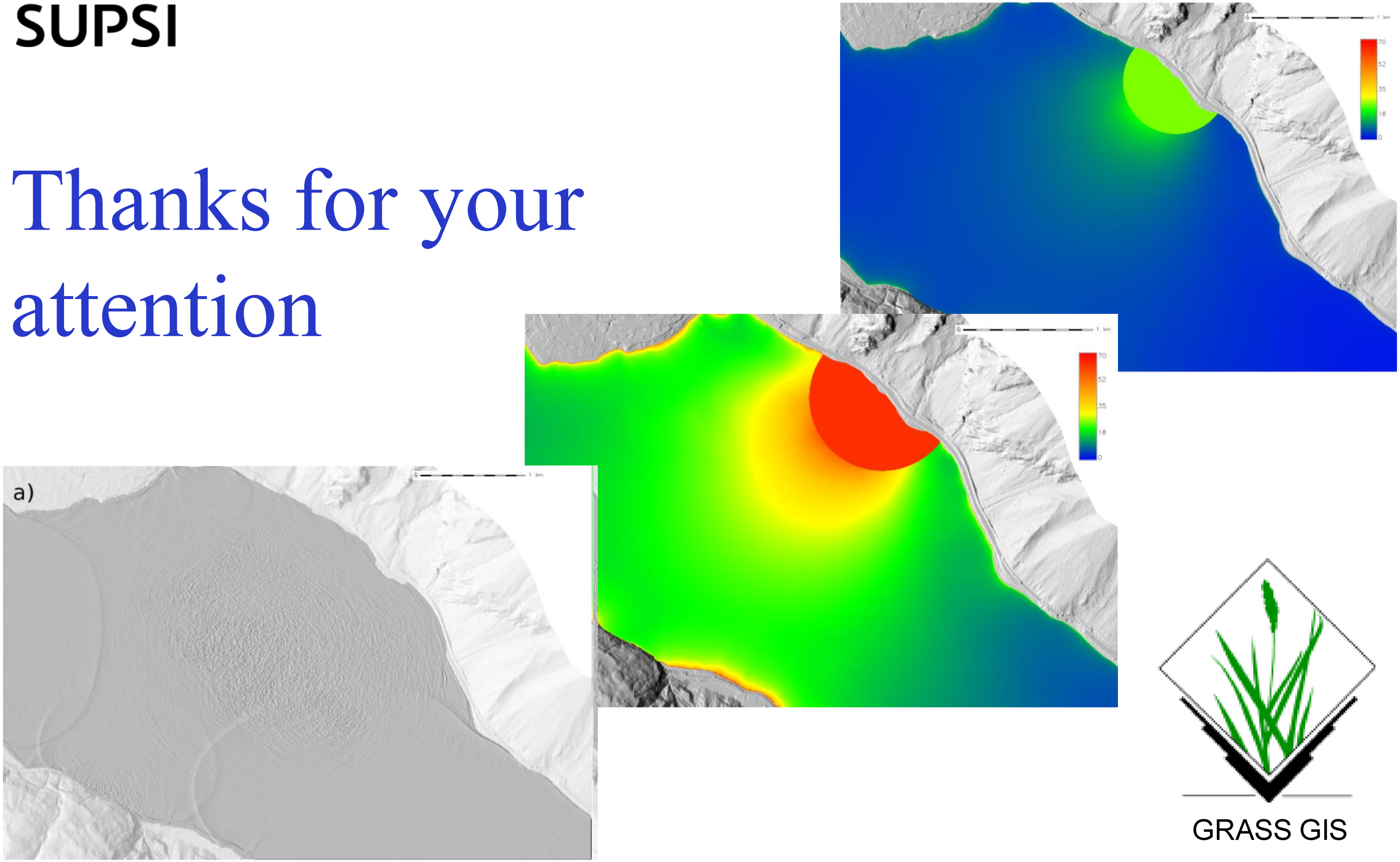
- The H2009 method has been implemented in GRASS (r.impact.tsunami)
- High uncertainty is given by bathymetry variation and in particular by mass type
- Predominant parameters are still water depth in the impact zone and the mass impact velocity
- The SWE method has been implemented in GRASS (r.swe)
- H2009 estimates higher inundation respect to SWE

Conclusions

- Both methods can be used to estimate landslide-generated tsunamis
  - *r.impact.tsunami* has the advantage to be fast and requires low computational resources
  - *r.swe* has the advantage to account for basin shape effects

- **No data for validation + High uncertainties = methods provide only indications for analysis and therefore should be used with consciousness !!!**

Thanks for your attention



GRASS GIS