ETH zürich

# Tsunami Modelling with BASEMENT 3.0

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HSR, Rapperswil

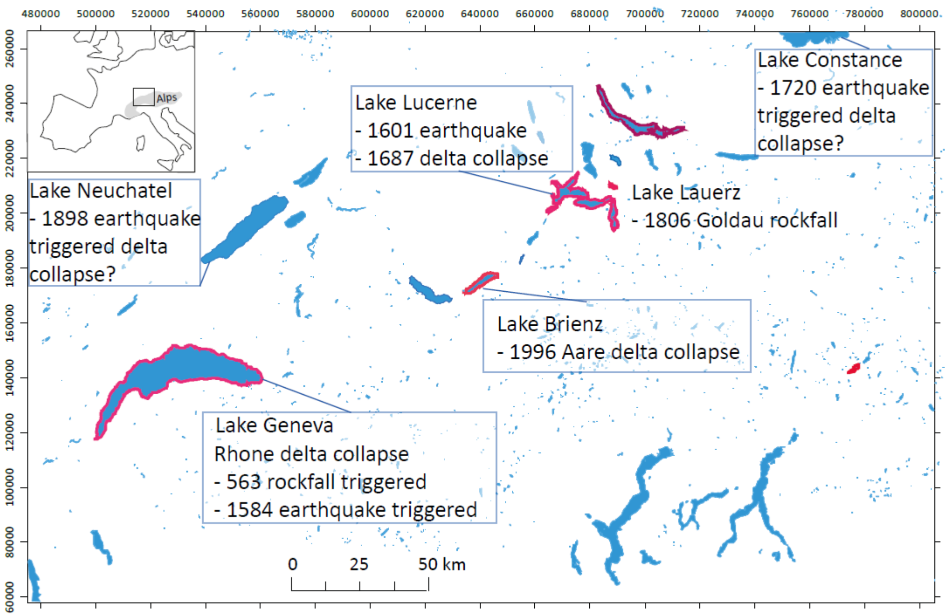
Laboratory of Hydraulics
Hydrology and Glaciology

# Motivation: Lake Tsunamis

Tsunamis do occur in every acquatic system

Hystorically:

- 563 AD Lake Geneva: - rockfall-induced delta-collapse
  - modelled wave heights up to 8m
- 1601 AD Lake Lucerne: - earthquake-triggered sublacustrine slope failure
  & rockfall in Bürgenstock
  - wave heights of 4m in Lucerne
- 1941 AD Laguna Palcacocha, Peru: - large avalanche
  - killing ~ 1,800 to 7,000 inhabitants
- climate warming tends to enhance slope instabilities




→ **Urge** for prediction of possible hazardous events

**Goal**: Understand governing mechanisms of genesis, propagation and inundation of tsunamis in lakes.

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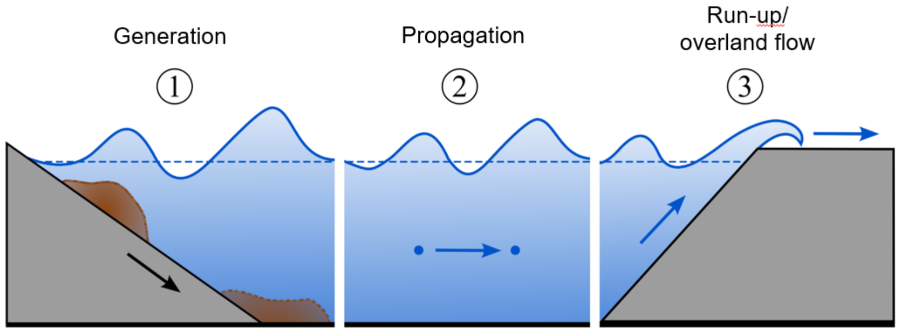
→ **Urge** for prediction of possible hazardous events

**Goal**: Understand governing mechanisms of genesis, propagation and inundation of tsunamis in lakes.

# Main key questions

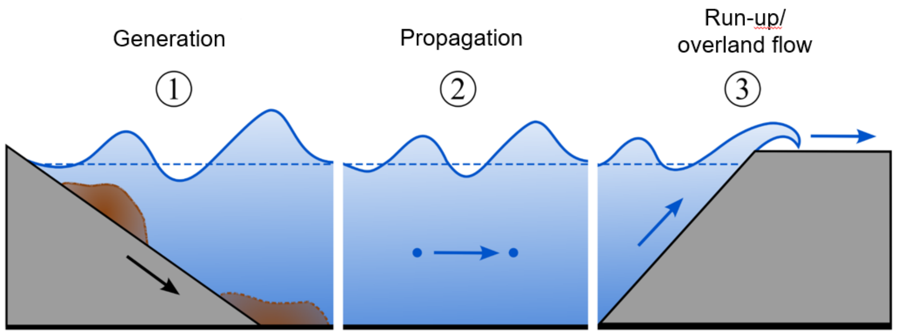
- What controls wave propagation in narrow and confined lake basins?
- Which models allow best the simulation of propagation & coastal inundations?
- Can the simulations be matched with hydraulic laboratory modeling & historic event description?




*Trigger mechanismus* → Initial slide parameters → Wave height → Wave-shore interaction → *Impact on the shoreline*

Key Properties: Lake Tsunami Modeling ⇄ **Efficient Simulation Workflow**

# Main key questions: Overview




1. Wave generation processes
2. Propagation of waves and what to consider
3. Behind the scenes of inundation
4. Proof of concept – Workflow

**BASEMENT**
A freeware simulation tool for hydro- and morphodynamic modelling

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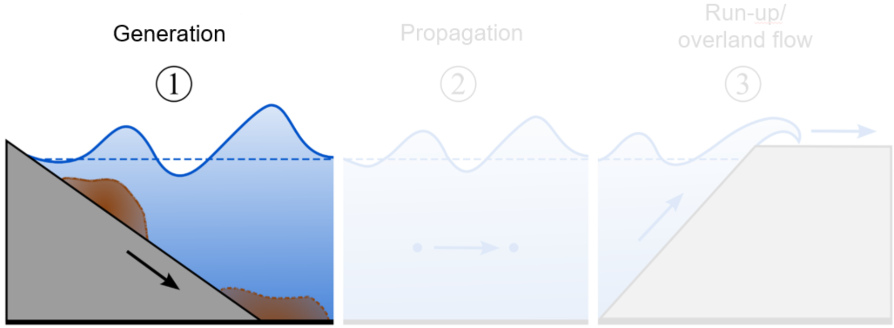


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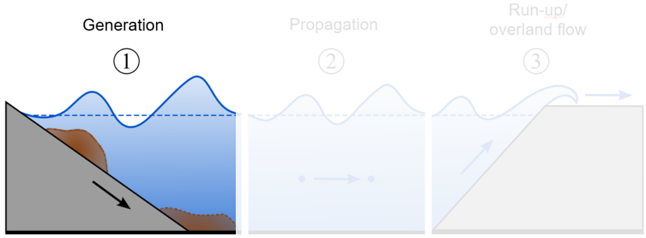
# Wave generation process

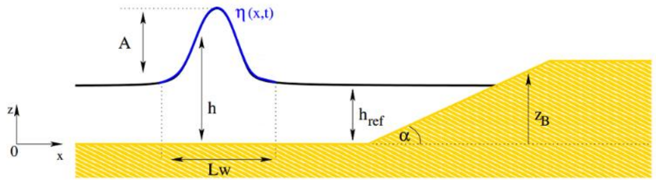


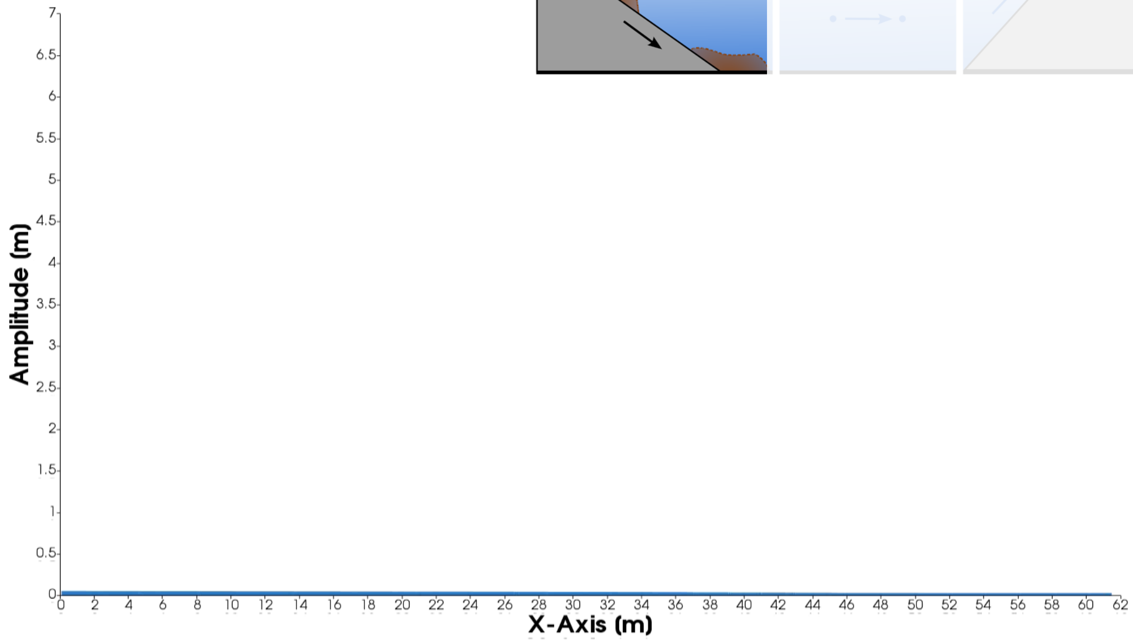

<u>Strategies for wave displacement:</u>

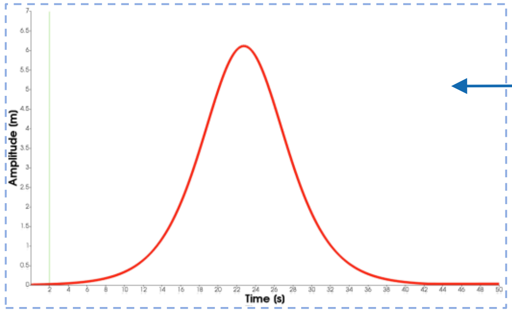
I. Boundary condition

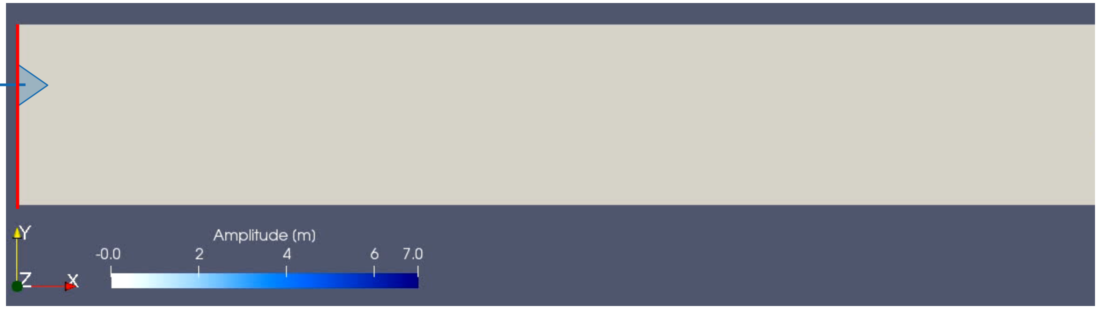
$$\eta(x,t) = A \cdot \text{sech}^2\left(\kappa\left(x - t \cdot c_s\right)\right), \text{ with } \kappa = \sqrt{\frac{3}{4}\frac{A}{h_{ref}^3}},\ c_s = \sqrt{g(A + h_{ref})}$$

$$q(x,t) = h_{ref} \cdot \eta(x,t)\sqrt{\frac{g}{h_{ref}}} \quad \text{and } L_w = \frac{2\pi}{\kappa},\ T_w = \frac{2\pi}{c_s \cdot \kappa}$$

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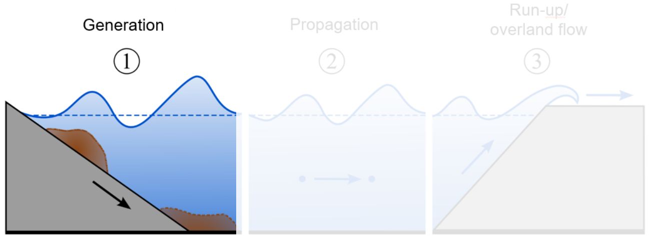
# Wave generation process




<u>Strategies for wave displacement:</u>

I. Boundary condition

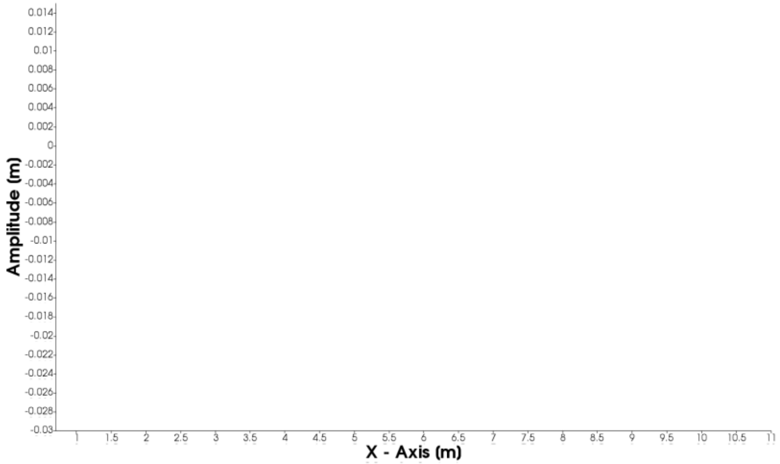
II. Bathymetry displacement

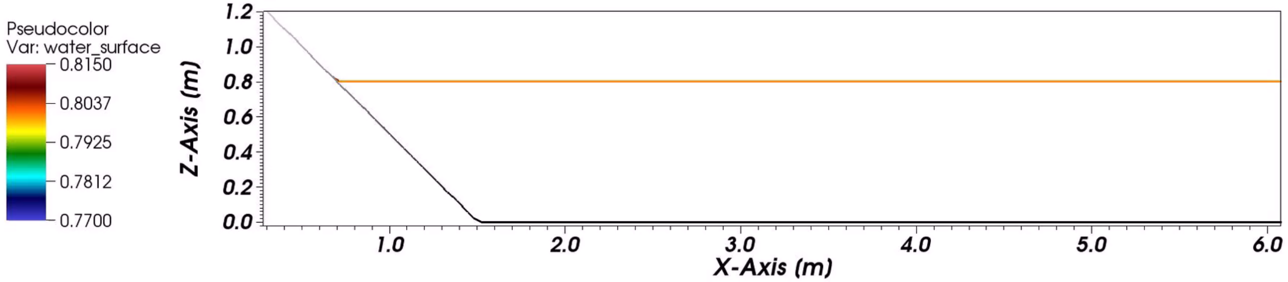
- $t = 0s$ , $h_{ref} = 0.8m$

$$z_B = \begin{cases} -1(x-1.5)m, & \text{if} \quad 0m \le x < 1.5m & \textbf{Slope} \\ 0m, & \text{if} \quad 1.5m \le x < 7.1m & \textbf{Constant} \\ 0.2(x-14.6)m, & \text{if} \quad 7.1m \le x < 14.6m & \textbf{Slope 1:5} \\ 0.4m, & \text{if} \quad 14.6m \le x \le 17m & \textbf{Dry Land} \end{cases}$$

- $t = 0.05s$, $h_{ref} = 0.8m$

$$z_B = \begin{cases} (1.5-x)m, & \text{if} \quad 0m \le x < 0.8038m & \textbf{Slope} \\ (1.405-x)m, & \text{if} \quad 0.8038m \le x < 0.97m & \textbf{Landslide} \\ (1.5-x)m, & \text{if} \quad 0.97m \le x < 1.5m & \textbf{Slope} \\ 0m, & \text{if} \quad 1.5m \le x < 7.1m & \textbf{Constant} \\ 0.2(x-14.6)m, & \text{if} \quad 7.1m \le x < 14.6m & \textbf{Slope 1:5} \\ 0.4m, & \text{if} \quad 14.6m \le x \le 17m & \textbf{Dry Land} \end{cases}$$



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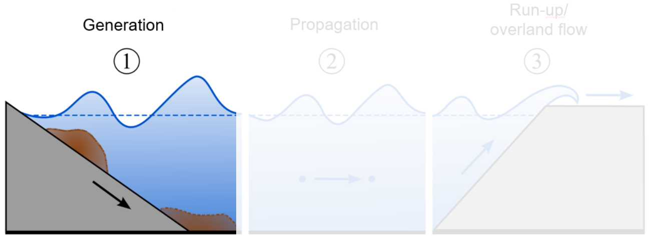


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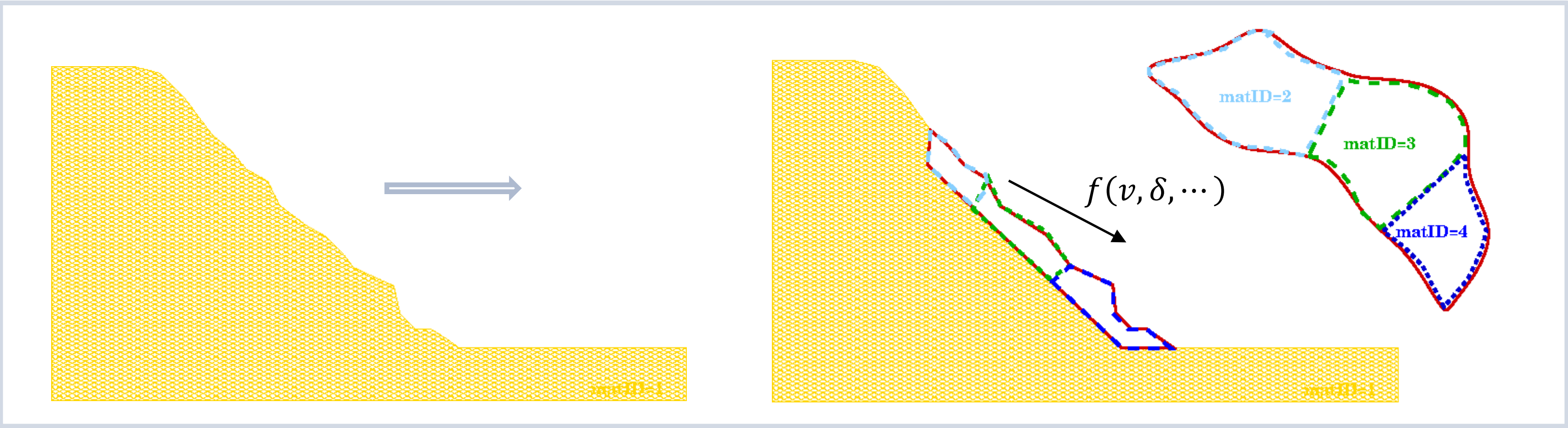
Outlook



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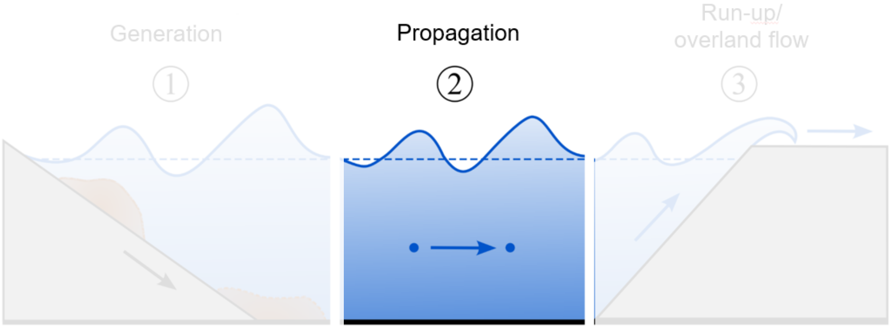


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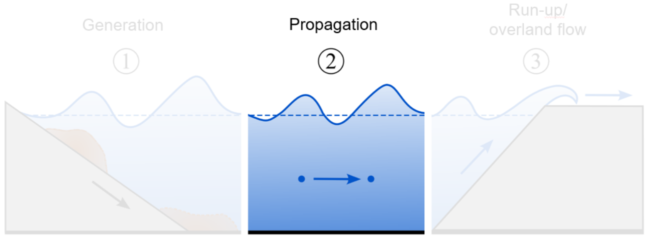
# Propagation of waves and what to consider



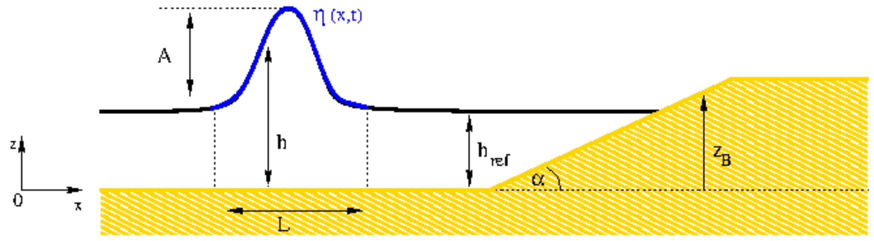

- **Tsnamis:** long waves compared to water depth

What mathematical model fits best?

- Depends on the **scales** of the physical problem
- **Shallow Water model**: no frequency dispersion ( ~ propagation time & shape of wave)
- **Frequency dispersion**: Boussinesq-type model

  ⟶ important e.g. for landslide sources (cf. Løvholt et al. 2015) & non-linear effects

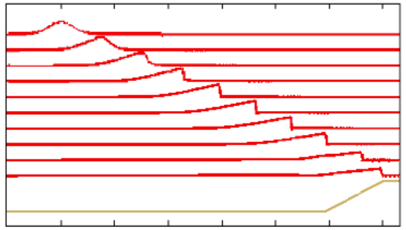
| | Deep-water | Transitional-water | Shallow-water |
| --- | --- | --- | --- |
| Relative wave length | $\frac{L}{h} < 2$ | $2 < \frac{L}{h} < 20$ | $\frac{L}{h} > 20$ |
| Wave celerity | $c = \frac{gT_w}{2\pi}$ | $c = \frac{gT_w}{2\pi} \tanh kh$ | $c = \sqrt{gh}$ |
| Group celerity | $c_{gr} = \frac{c}{2}$ | $c_{gr} = \frac{c}{2}\left[1 + \frac{2kh}{\sinh 2kh}\right]$ | $c_{gr} = c$ |
| Wave length | $L = \frac{gT_w^2}{2\pi}$ | $L = \frac{gT_w^2}{2\pi} \tanh kh$ | $L = T_w\sqrt{gh}$ |



# Propagation of waves and what to consider

- Depth-averaged 2D models based on the **Shallow Water equations**

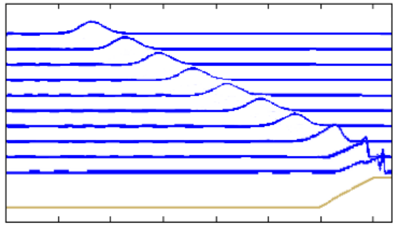
$$\begin{cases} \partial_t h + \partial_x q_x + \partial_y q_y = S_h \\ \partial_t q_x + \partial_x \left(\frac{q_x^2}{h} + 0.5 g h^2\right) + \partial_y \left(\frac{q_x q_y}{h}\right) + gh\left(\partial_x z_B + S_{f_x}\right) = 0 \\ \partial_t q_y + \partial_x \left(\frac{q_x q_y}{h}\right) + \partial_y \left(\frac{q_y^2}{h} + 0.5 g h^2\right) + gh\left(\partial_y z_B + S_{f_y}\right) = 0 \end{cases}$$



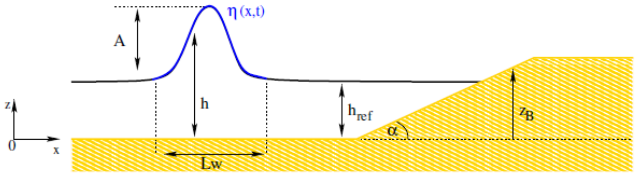
- ➢ Good for broken waves (shocks)
- ➢ Simple and efficient for run-up

- **Boussinesq-type equations** derived from Schäffer and Madsen (1995)

$$\begin{cases} \partial_t h + \partial_x q = 0 \\ (1 - D)\partial_t q + \partial_x \left(q^2 + \frac{g}{2} h^2\right) - gh\partial_x h_{ref} - B g {h_{ref}}^2 \partial_{xx}\left(h_{ref} \partial_x \eta\right) = -f_D \\ D(\omega) = \left(B + \frac{1}{2}\right) {h_{ref}}^2 \partial_{xx} \omega - \frac{1}{6} {h_{ref}}^3 \partial_{xx} \left(\frac{\omega}{h_{ref}}\right) \quad \text{and} \quad B = \frac{1}{15} \end{cases}$$



- ➢ Accurate prediction of shoaling
- ➢ No intrinsic dissipation mechanism




- $h$ : water depth
- $q_x$ : discharge, x
- $g$ : grav. acceleration
- $S_h$: lateral i/o discharge
- $S_{fx}$: friction, x
- $z_B$ : bottom elevation

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# Propagation of waves and what to consider – Insight on lake scales

- Depth-averaged 2D models based on the **Shallow Water equations**

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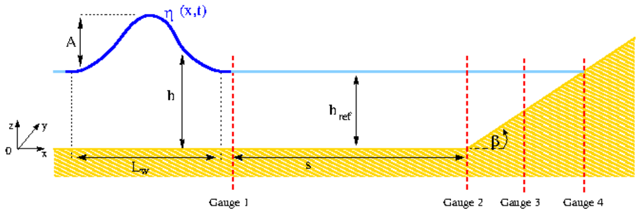
| | BASEMENT v3 | BoussClaw (GeoClaw 5.6) |
|---|---|---|
| Under developement since | 2003 | 1994 |
| Purpose of use | Teaching, research & projects | Teaching, research |
| Hyperbolic systems of PDE | **Shallow Water Eqs.** | **Boussinesq-type Eqs.** |
| Simulated dimensions | 1- & 2-D | 1- & 2-D |
| Numerical Approach | Finite Volumes | Finite Volumes |
| Computational Mesh | Unstructured | Structured |
| Multi-core CPU simulations | ✓ | ✓ |
| Support of GPGPU accelation | ✓ | ✗ |

Outlook

**Typical scales of Lakes (cf. Lake Lucerne)**

- s = [800, 1600, 3200, 6400]m,
- $h_{ref}$ = [40, 80, 120, 160, 200]m and,
- Generated wave amplitudes A=[0.1,0.2,0.3, 0.4, 1, 2, 4, 6]m.
- Relative wave height $\varepsilon = A/h_{ref}$ between 0.0005 – 0.15
- Wave length $L_w$ between 749 – 64892 m
- Ratio $(A+h_{ref})/L_w$ between 0.0031 – 0.061

Errors < +0.06%




Legend:
$\eta(x,t)$ : wave shape
A : wave amplitude
h : water column height
$h_{ref}$ : still water reference height
s : propagation distance with constant bathymetry
$\beta$ : slope angle for the run-up shoreline

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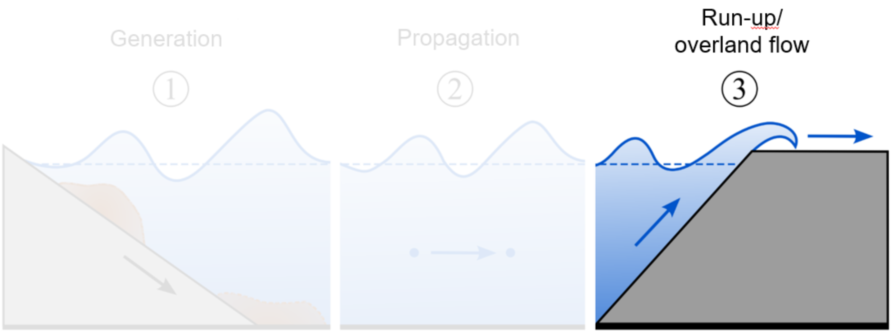
# Main key questions: Overview

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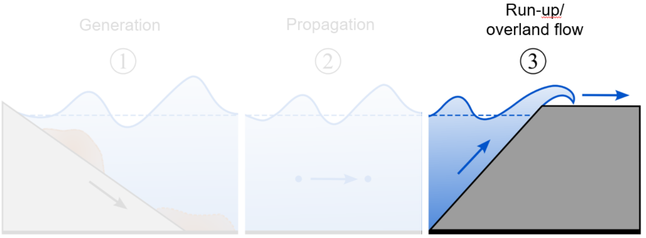
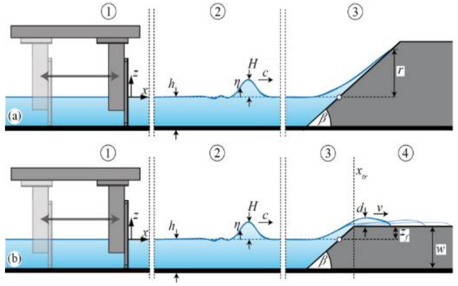
# Behind the scenes of inundation

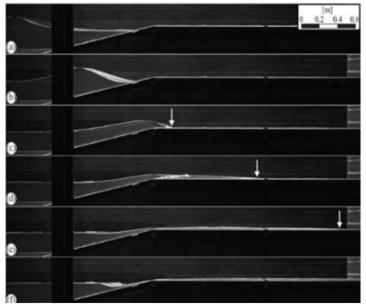


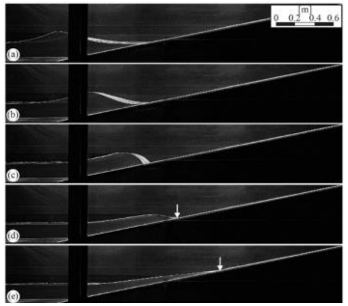

**Strong dependance from shoreline geometry**

Outlook

Validation of BASEMENT v3 against experiments of Fuchs PhD (2013)





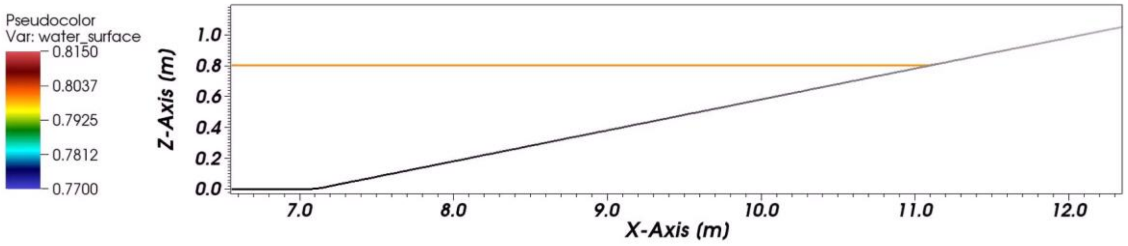


Example

Run-up of Solitary Wave on Slope 1:5 for $h_{ref}$ = 0.2m, $\varepsilon = A/h_{ref}$ = 0.1

Relative run-up height $R = r / h_{ref}$

- Numerical: BMv3, R ≈ 1.26
- Experimental: from H. Fuchs PhD (2013), R= 1.25



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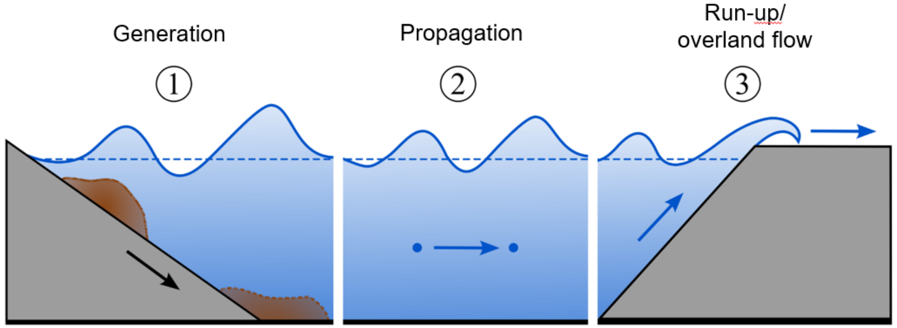


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# Proof of concept – Workflow for BASEMENT 3.0 simulation

*Workflow*

1. Case study identification

2. Elevation datasets

   e.g.: - Shoreline area, bathymetric dataset

3. Global geometry

   3.1. Shapefile of the lake
   3.2. Shapefile of potential landslide(s)*

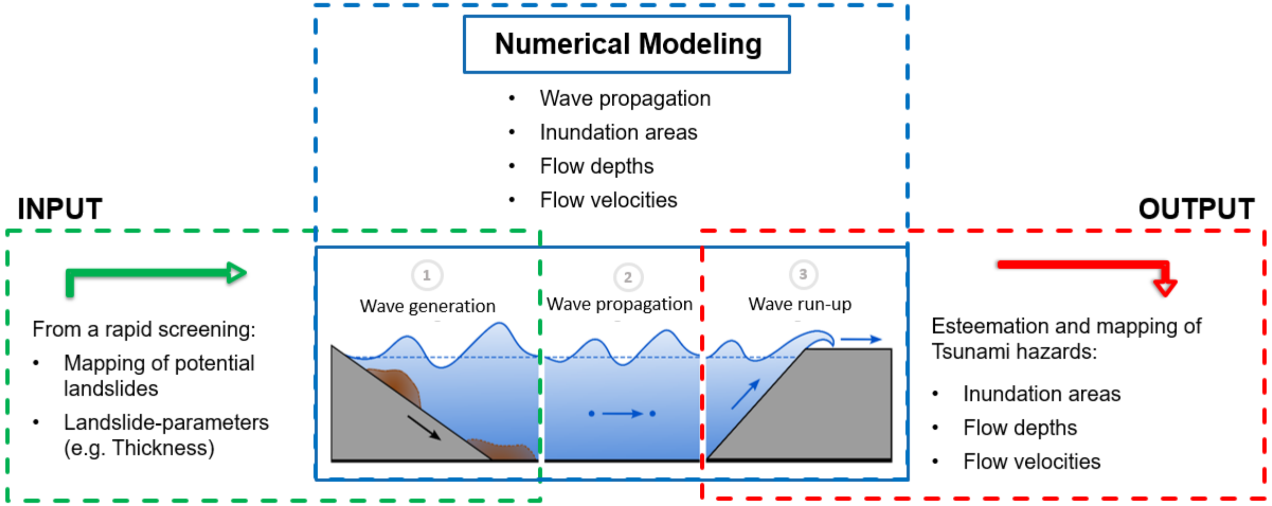
4. Scenario definition

   4.1. Volume of landslide, dynamics*
   4.2. Elevation of water at rest

5. Grid generation

   5.1 Domain definition, lake breaklines
   5.2 Assignment of properties

6. Simulation



# Proof of concept on Lake Lucerne

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Case Study

1. Orthographic view of the area of Lake Lucerne

CRS: CH1903+ (LV95)
*Source: https://map.geo.admin.ch*

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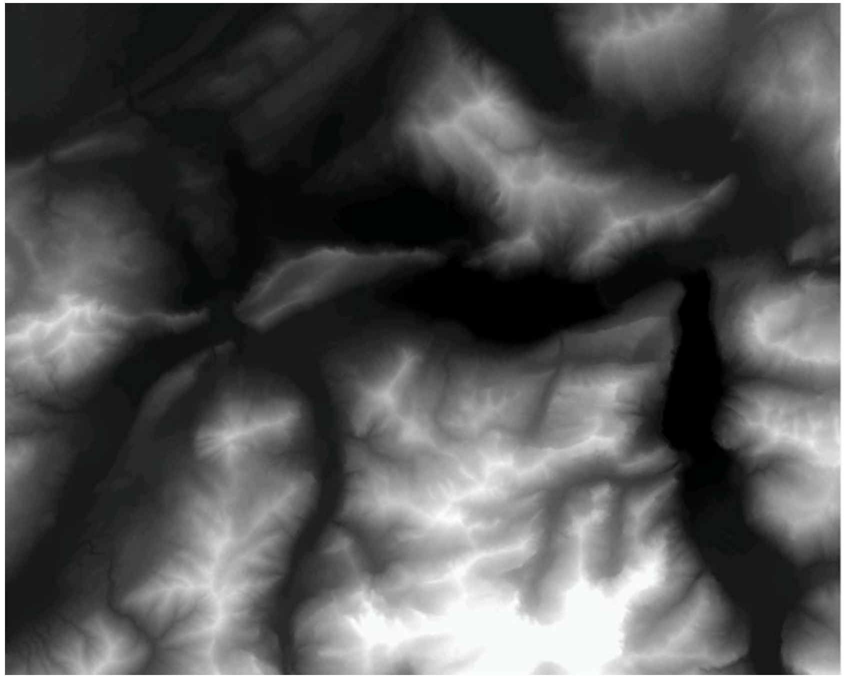
Case Study

2. Elevation dataset: Altitude of shoreline area around Lake Lucerne



CRS: CH1903+ (LV95)
[swissALTI3D]
Source: https://map.geo.admin.ch

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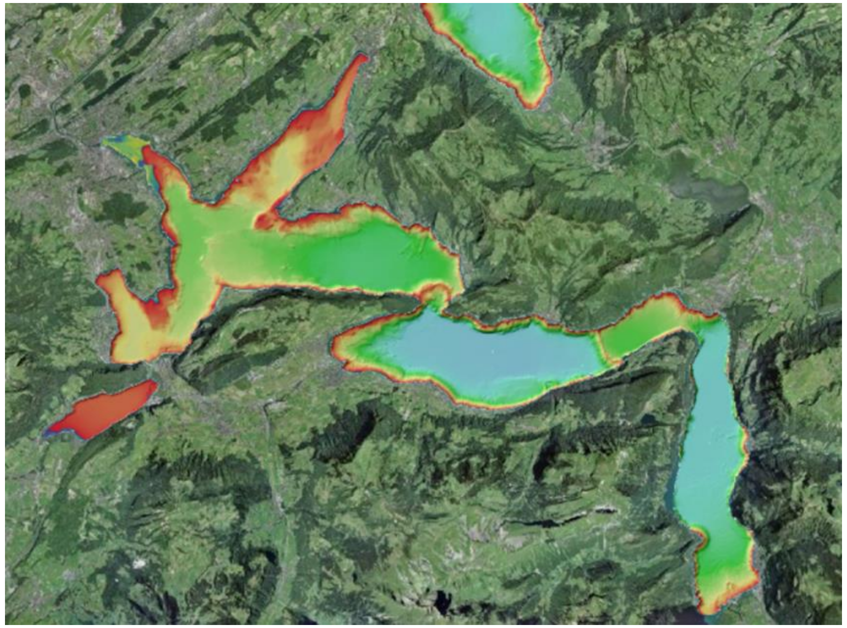
*Case Study*

2. Elevation dataset: Bathymetric dataset - high-resolution (1 m grid)



CRS: CH1903+ (LV95),
[swissBATHY3D]
*Source: https://map.geo.admin.ch*

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Case Study

3.1. Global geometry: Shapefile of Lake Lucerne

CRS: CH1903+ (LV95)

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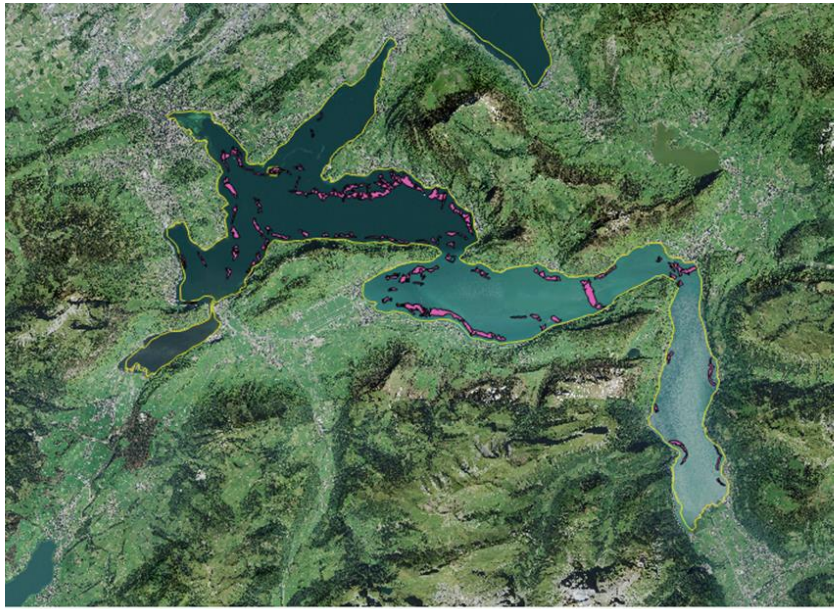
Case Study

3.2. Global geometry: Shapefile of potential landslides expected for earthquake, mean return periods of 475 years



CRS: CH1903+ (LV95)
Source: ETH SED

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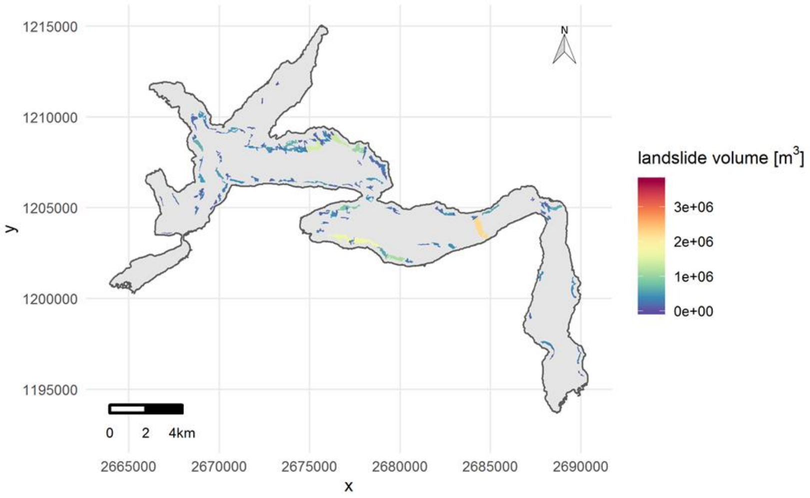
*Case Study*

3.2. Global geometry: Shapefile of potential landslides expected for earthquake, with mean return periods of 475 years




CRS: CH1903+ (LV95)
Source: ETH SED

# Proof of concept on Lake Lucerne

*Workflow*

1. Case study identification

2. Elevation datasets

   e.g.: - Shoreline area, bathymetric dataset

3. Global geometry

   3.1. Shapefile of the lake
   3.2. Shapefile of potential landslide(s)*

4. Scenario definition ←

   4.1. Volume of landslide, dynamics*
   4.2. Elevation of water at rest

5. Grid generation

   5.1 Domain definition, lake breaklines
   5.2 Assignment of properties

6. Simulation

*Case Study*

3.1. Scenario definition: Selection of two possible landslide areas (“upper” & “lower”)
- MRP=475 years

CRS: CH1903+ (LV95)
Source: ETH SED

# Proof of concept on Lake Lucerne

*Workflow*

1. Case study identification

2. Elevation datasets

   e.g.: - Shoreline area, bathymetric dataset

3. Global geometry

   3.1. Shapefile of the lake

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   4.2. Elevation of water at rest

5. Grid generation

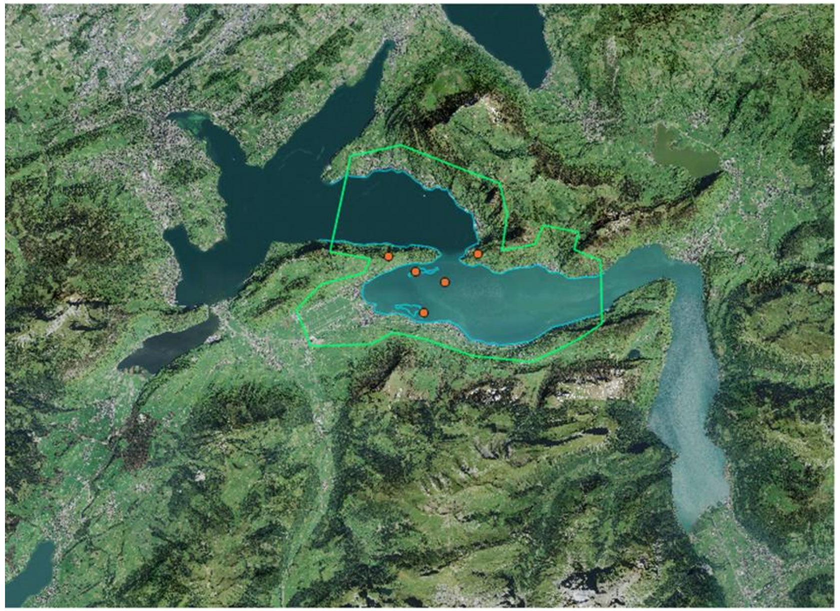
   5.1 Domain definition, lake breaklines ←

   5.2 Assignment of properties

6. Simulation

*Case Study*

5. Grid definition: Domain definition, lake breaklines and region definition for the simulation



CRS: CH1903+ (LV95)
Source: https://map.geo.admin.ch

# Proof of concept on Lake Lucerne

*Workflow*

1. Case study identification

2. Elevation datasets
   e.g.: - Shoreline area, bathymetric dataset

3. Global geometry
   3.1. Shapefile of the lake
   3.2. Shapefile of potential landslide(s)*

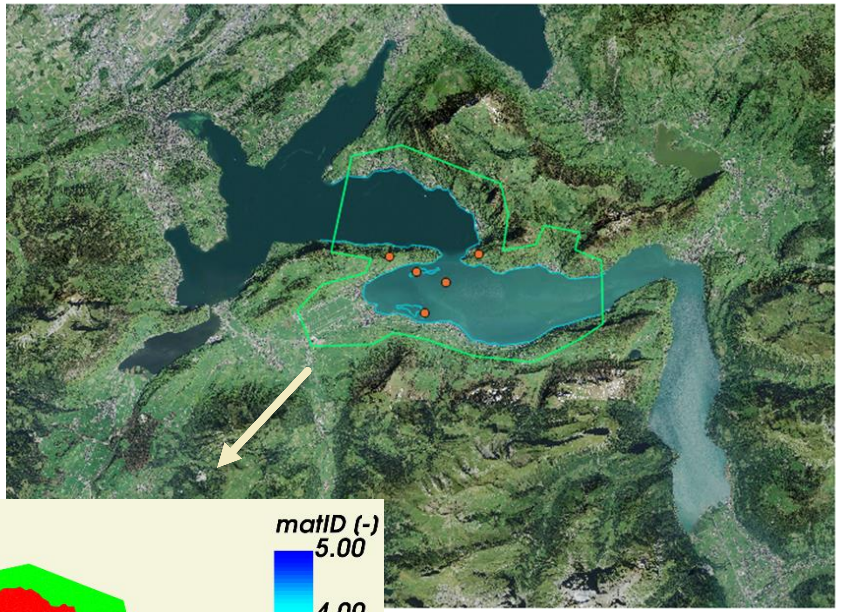
4. Scenario definition
   4.1. Volume of landslide, dynamics*
   4.2. Elevation of water at rest

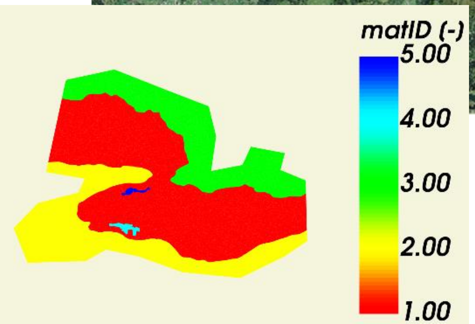
5. Grid generation
   5.1 Domain definition, lake breaklines ←
   5.2 Assignment of properties

6. Simulation

*Case Study*

5. Grid definition: Domain definition, lake breaklines and region definition for the simulation






CRS: CH1903+ (LV95)
Source: https://map.geo.admin.ch

# Proof of concept on Lake Lucerne

Workflow

1. Case study identification

2. Elevation datasets

   e.g.: - Shoreline area, bathymetric dataset

3. Global geometry

   3.1. Shapefile of the lake

   3.2. Shapefile of potential landslide(s)*

4. Scenario definition

   4.1. Volume of landslide, dynamics*

   4.2. Elevation of water at rest

5. Grid generation

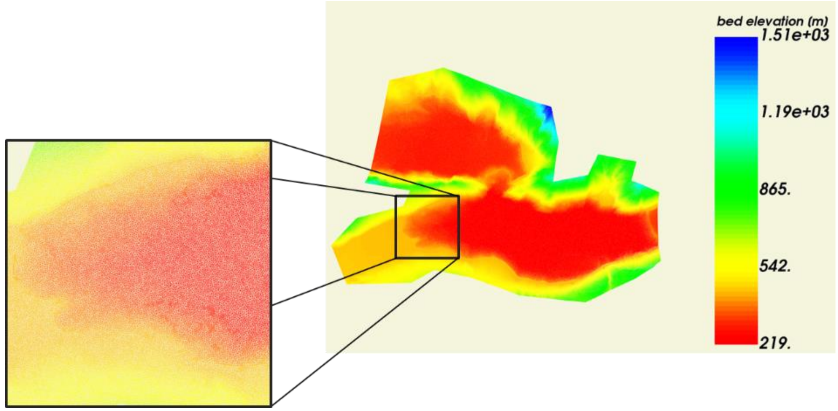
   5.1 Domain definition, lake breaklines

   5.2 Assignment of properties

6. Simulation ←

Case Study

5. Grid definition: Bed elevation information and mesh detail for the simulation



# Proof of concept on Lake Lucerne

Case Study

*Initial conditions:*

- Water surface: 434m a.s.l. [Source: https://www.hydrodaten.admin.ch/de/2207.html]
- Two submerged landslides
  – "upper" (Δ= - 5m)
  – "lower"(Δ= - 7m)

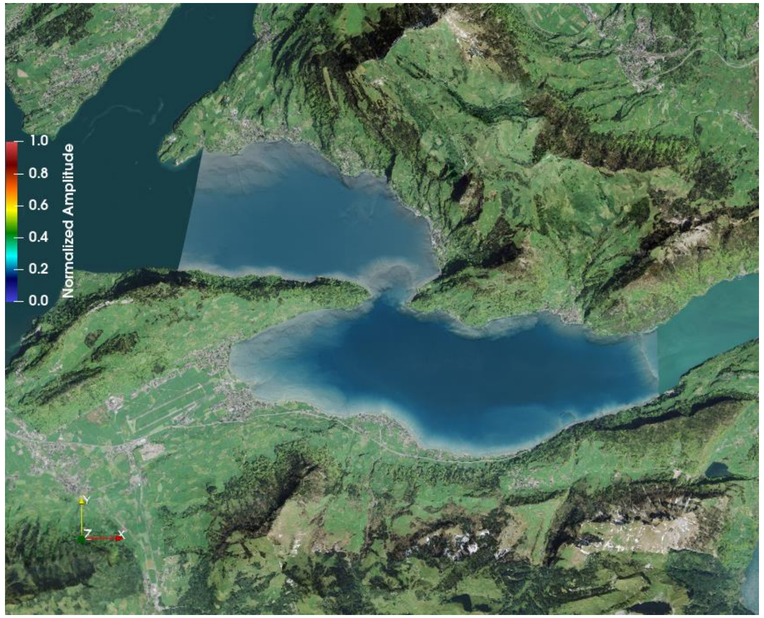
- Area of a single cell: 400m$^2$
- Simulated time since landslides: 160s

*Time needed for simulation, 324k cells*

- 1 thread (CPU): 220.1s
- 8 threads (CPU):63.5s
- GPU: 9.25s

Case Study

6. Simulation – coarse grid



# Proof of concept on Lake Lucerne

Case Study

*Initial conditions:*

- Water surface: 434m a.s.l. [Source: https://www.hydrodaten.admin.ch/de/2207.html]
- Two submerged landslides
  – "upper" (Δ= - 5m)
  – "lower"(Δ= - 7m)

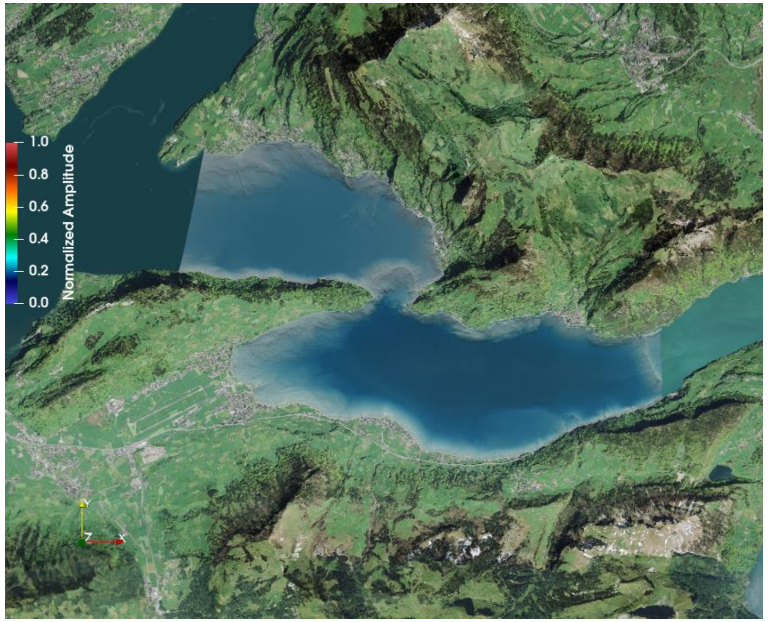
- Area of a single cell: 50m$^2$
- Simulated time since landslides: 160s

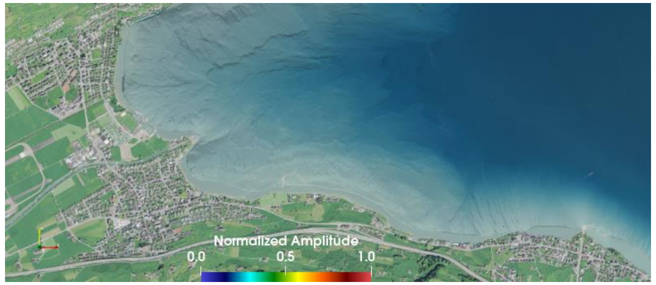
*Time needed for simulation, 2.6million cells*

- GPU: 103.3s

Case Study

6. Simulation – fine grid



# Conclusions and Outlook

## Conclusions

- ✓ BASEMENT 3.0 for tsunami modelling
- ✓ Tsunami wave can be generated via two different approaches
- ✓ Mathematical Model in BASEMENT 3.0 from first checks: suitable for the considered lake scales
- ✓ Qualitative proof of concept of wave generation, propagation & run-up on selected case study of Lake Lucerne

## Outlook

- Conclude validation for suitability of the mathematical model on the lake scales (e.g. modify parameters,..)
- Novel formulation to allow as input a function for describing the landslide dynamics
- Investigation of impact of shoreline geometries for inundation
- Validate Tsunami Modelling via BASEMENT 3.0 with historical events