Hydrological Modelling of Slope Stability

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Shallow landslide hazard

- Landslides triggered by rainfall occur in most mountainous landscapes.
- Most of them occur **suddenly** and travel **long distances** at **high speeds**.
- They can pose great threats to life and property.

Landslides in Urseren Valey, Kanton Uri, Switzerland

Typical dimensions

- **Width** $\sim$ tens of meters
- **Lenght** $\sim$ hundreds of meters.
- **Depth** $\sim$ 1-2 meters.

Factors contributing to the phenomenon

Hydrological factors

- Rainfall intensity and duration.
- Antecedent soil moisture conditions.
- Pore pressure change due to saturated and unsaturated flow of water through soil pores.

Soil properties

- Cohesion and friction angle (c,ϕ) of soil.
- Root reinforcement provided by the vegetation.
- Hydraulic conductivity and hysteretic behaviour of soil during wetting and drying cycles.
- Topography and macropores.

State of the art of models

Deterministic models

- Simplified low-dimensional models with various degrees of simplification.
- Numerical models solving the fully coupled three-dimensional variably saturated flow and stress problem using conventional numerical techniques (finite differences, finite elements).

Statistical models

- Multivariate correlation between landslides and landscape attributes and soil properties.
- Analysis of duration and intensity of rainfalls triggering landslides.

Each one of them makes **its own assumptions** on various aspects of the problem, thus **limiting its range of applicability**.

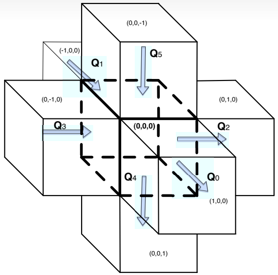
Hydrological Component I

The Cellular Automata (CA) concept is used in order to model the 3D subsurface flow.

CA: General concepts

- The domain is divided into **discrete** cells.
- Each cell has its own **state**, which describes its physical condition.
- The state of each cell evolves via simple rules based on **neighbour interactions**.
- These rules are implemented in the **transition function** which is applied to all the cells of the domain.
- **Bottom-up approach** in contrast with the *discrete to continuum to discrete* paradox exhibited by the standard numerical methods.
- CA concept is **inherently parallel**, as a collection of identical transition functions simultaneously applied to all cells.

Hydrological Component II



In the case of 3-D variably saturated flow the mass balance equation plays the role of the transition function:

$$\sum_{\alpha \in I} \overline{K}_{\alpha c} \left(\frac{h_\alpha - h_c}{l_{\alpha c}} \right) A_{\alpha c} + S_c = V_c \sigma(\psi_c) \frac{\Delta h}{\Delta t}$$

$$\sigma(\psi_c) = \begin{cases} C_c(\psi_c), & \text{for } \psi_c < 0 \\ S_s, & \text{for } \psi_c \geqslant 0 \end{cases}$$

- Each cell of the lattice communicates with its neighbours only through its faces.
- Spatial heterogeneity is tackled because every cell has its own constitutive hydraulic properties.
- The boundary conditions can be of two types: constant head (Diriclet) or constant flux (Neumann).

Hydrological Component III

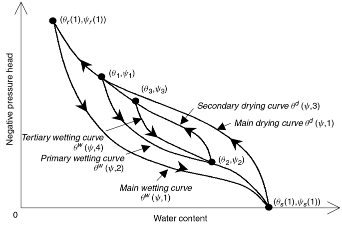
Soil Water Retention Curves

We used a modified Van Genuchten (VG) (Ippisch et al, 2006), which corrects the unrealistic conductivity values predicted by the classical VG model:

$$S_e = \begin{cases} \frac{1}{S_c}[1 + (\alpha|h|)^n]^{-m} & \text{, for } h < h_e \\ 1 & \text{, for } h \geqslant h_e \end{cases}$$

Hysteresis model

- Different curves followed during the drying and wetting processes.
- It is crucial for the continuous simulation of soil water content during storm and inter-storm periods.



Geotechnical Component

Despite their limitations, infinite slope analysis and the factor of safety concept are used due to their simplicity.

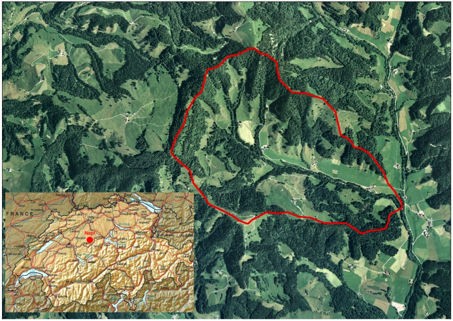
Infinite Slope analysis limitations

- Long, continuous slopes where the sliding surface is parallel to the surface.
- The thickness of the unstable material is small compared to the height of the slope.
- The end effects on the sliding block are neglected.

A factor of safety equation for both unsaturated and saturated conditions is used, which uses the concept of effective stress (Lu Ning and Godt Jonathan, WRR, 2010).

$$FOS = \frac{tan\phi}{tan\beta} + \frac{2c}{\gamma z \ sin2\beta} + S_e \frac{u_\alpha - u_w}{\gamma z}(tan\beta + cot\beta)tan\phi$$

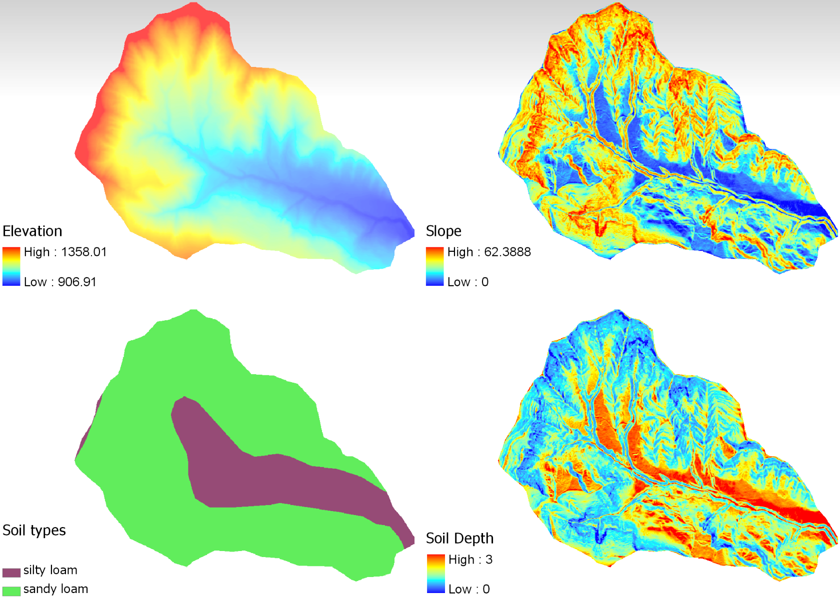
Napf catchment: Overview



- **Location:** Kanton Bern, Switzerland.
- **Area:** $2,5\ km^2$ (48 % forested).
- **Altitude:** $900\ m - 1360\ m$.
- **Triggering event:** A 3-hour precipitation event at 15-16 July 2002 caused many soil slips.

Input data

- **Surface topography:** A $3x3$ m Digital Elevation Model is used.
- **Slope:** It is calculated from the DEM using the ArcGIS routine.
- **Soil Depth:** An exponential model, which relates the soil depth to the slope is used: $d = 3.0 \cdot e^{(-\frac{1}{40} \cdot slope)}$.
- **Soil Parameters:**
  - The soil map of switzerland (Bodeneignungskarte) was used for the identification of the soil classes.
  - Representative values from the literature are used for the soil properties of each soil class.
- **Land use:** The land use map of Switzerland was used, which has a $100x100$ m resolution.
- **Precipitation:** We used the historical record of the Napf station, which is located 5 km at the north of the catchment.
- **Initial conditions:** We ran the model for a 6-month period prior to the event in order to create more realistic soil moisture conditions.


Elevation
High : 1358.01
Low : 906.91
Slope
High : 62.3888
Low : 0
Soil types
silty loam
sandy loam
Soil Depth
High : 3
Low : 0

Model Validation

The performance of the model tested against:

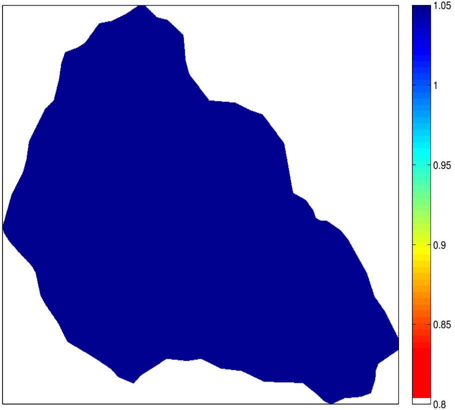
- The inventory of occurred landslides during the rainfall event of 15-16 July 2002.
- The results of a frequently used model (TRIGRS ver 2.0).

TRIGRS

- The catchment is modelled as a two dimensional array of non interacting columns.
- The water flow is considered vertical in each soil column.
- Each column consists of two zones: an unsaturated zone which is in top of the saturated zone. The two zones interact with each other through the rise of the water table.
- Infinite slope analysis is used for the computation of slope stability.

Results I: Temporal evolution

Evolution of factor of safety during the 3-hour triggering event.



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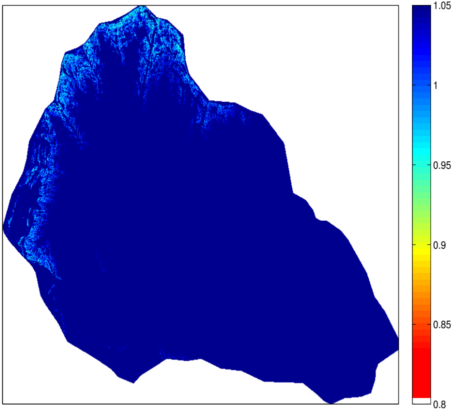

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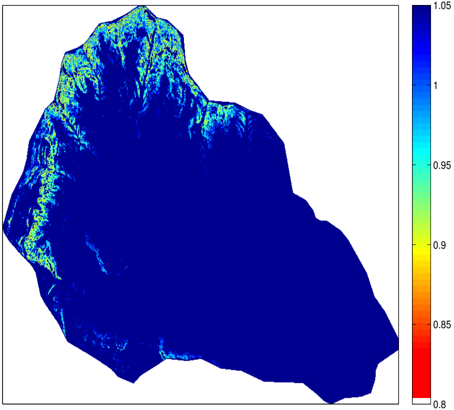

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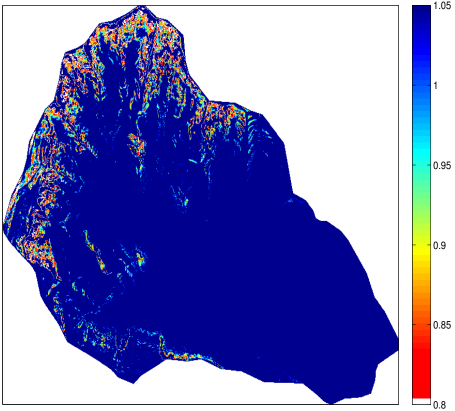
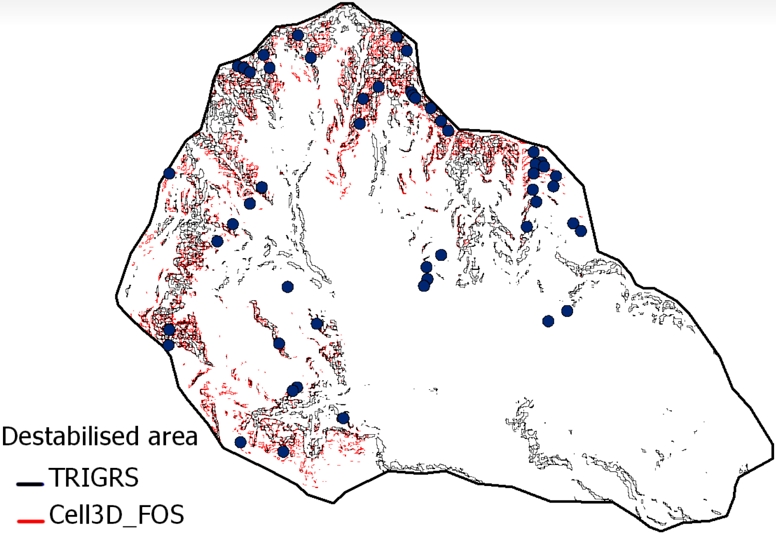
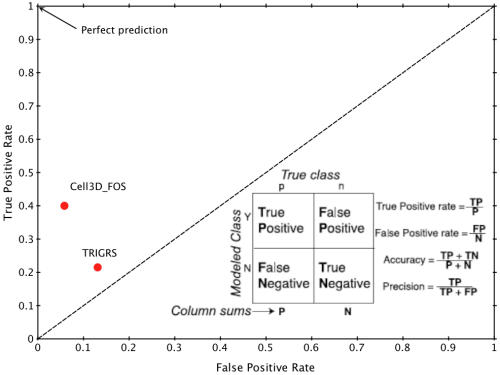


Results II: Destabilised areas



Results III: Quantitative data

	Cell3D_FOS	TRIGRS
True Positive Rate (%)	40.2	23.5
False Positive Rate (%)	6.3	11.2
Accuracy (%)	92.4	82.5
Precision (%)	14.7	4.5
Sliding Area (%)	6.5	13



Summary, conclusions and future work

1. A reduced complexity model based on Cellular Automata is used for the simulation of rainfall-induced landslides.
2. Emphasis is given on the detailed simulation of the water flow and the resulting pore water pressures.
3. A simple model for slope stability based on infinite slope analysis is coupled to the hydrological component.
4. The proposed model had a relatively good performance despite the lack of detailed hydrological and soil data.
5. An elasto-plastic model will be incorporated in order to describe better the soil behaviour due to stress and suction changes.
6. A parallel version in OpenMP and CUDA will be implemented in order to simulate bigger catchments.

Thanks for your attention!