Introduction to modelling natural hazards

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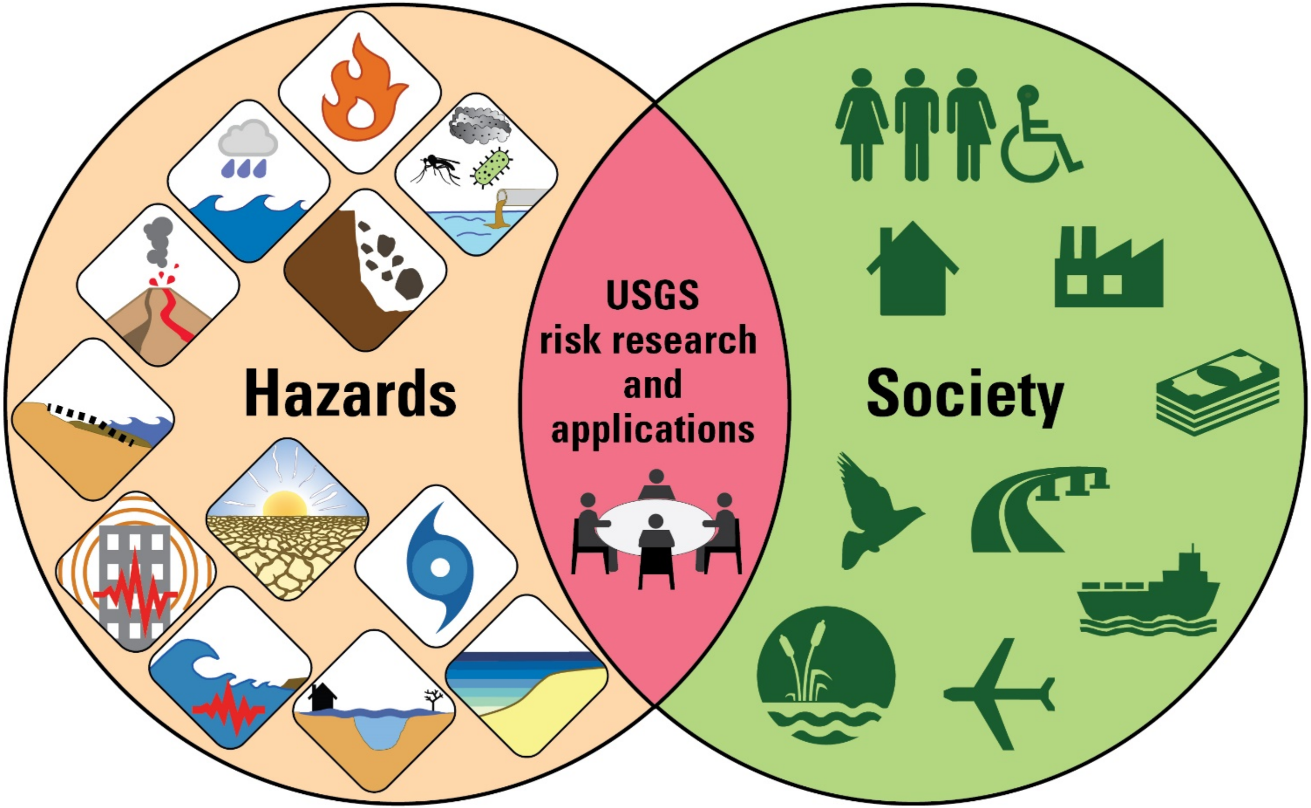
Learning objectives

After this lecture you will be able to …

- Distinguish the term landslide susceptibility from hazard and risk
- Classify natural hazard modelling methods
- Describe the importance of …
    - Input data (inventory, explanatory variables)
    - State of the art sampling designs within and outside of landslides
    - Modeling method (geo-statistical)

  for the model result (map and performance measures)
- List model performance assessment methods
- Report the range of model uncertainty
- Design a geostatistical landslide susceptibility model (theoretically & practically after the workshop)

Natural hazards



https://www.usgs.gov/media/images/venn-diagram-hazards-and-society

Background

Every year naturally or anthropogenically triggered landslides cause damage on houses, linear infrastructure (roads, train tracks) or farmland

→ worldwide but also in Austria (St. Lorenzen 2012; Feldbach & Lower Austria 2009; Gasen/Haslau 2005)
→ not isolated events but spatially abundant

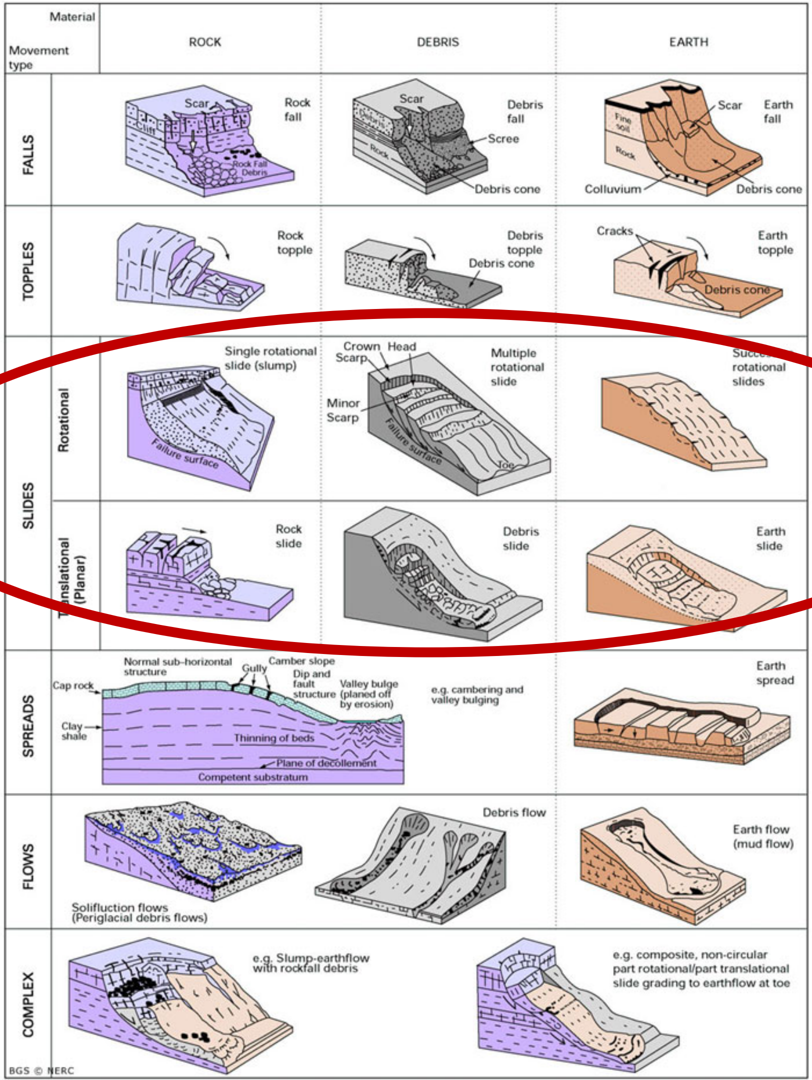


Motivation

- Gain knowledge on the **past** occurrence and distribution of **landslides**
- Detect possible **future affected areas/slopes** where more detailed analysis of the slope stability is necessary
- **Landslide susceptibility maps** as basis for well informed decisions of a municipality

  →Instead of reaction to events **avoidance of damage** & better **preparedness** to possible landslide events

Landslide types



Cruden & Varnes 1996

http://www.bgs.ac.uk/research/engineeringGeology/images/landslip_types_large.jpg

What is a landslide?

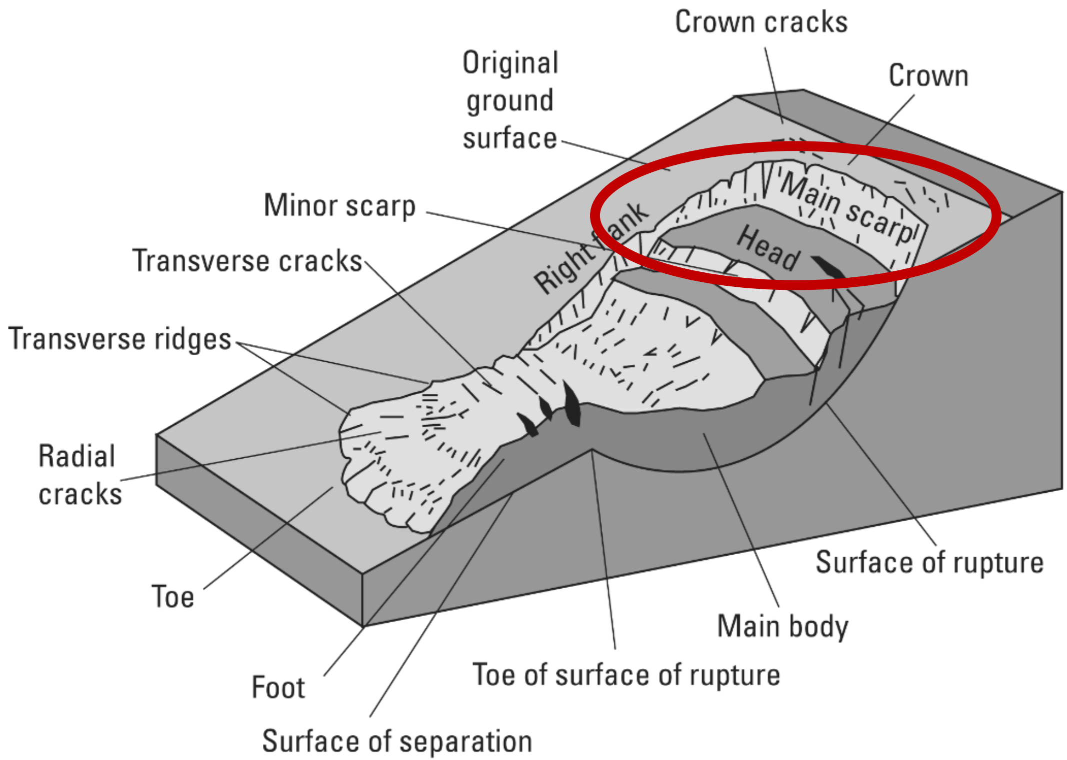


Figure 2. A simple illustration of a rotational landslide that has evolved into an earthflow. Image illustrates commonly used labels for the parts of a landslide (from Varnes, 1978, Reference 43).

USGS Landslide Handbook, Highland and Bobrowsky 2008, after Varnes 1978)

Natural hazard maps

Inventory (Points, Polygons)

Susceptibility map

Hazard map

Exposure map or elements at risk

Risk map $R = f(H_I, V_I)$

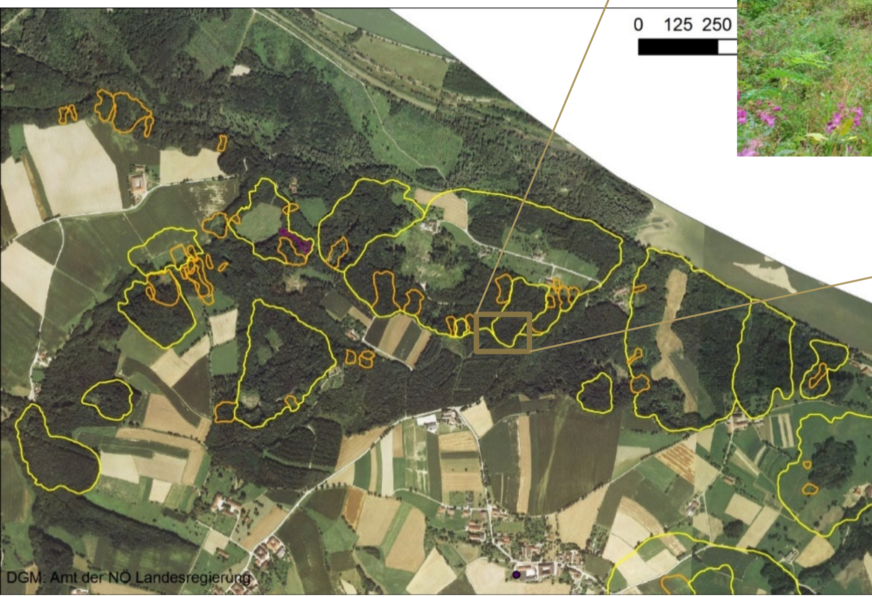
Glade, T., Anderson, M.G., Crozier, M.J. (Eds.), 2005. Landslide Hazard and Risk. John Wiley & Sons, Ltd, Chichester, England.
Promper, C., Gassner, C., Glade, T., 2015. Spatiotemporal patterns of landslide exposure – a step within future landslide risk analysis on a regional scale applied in Waidhofen/Ybbs Austria. International Journal of Disaster Risk Reduction 25–33.

Landslide inventories

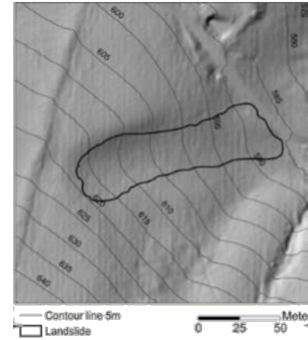
- The most important data
- WHERE have landslides occurred historically
- Ideally complete inventory – NEVER the case
  → at least representative inventories necessary
- Different mapping methods: (Guzzetti et al. 2012)
  - Mapping in the field: topographic map, GPS, Laser-distancemeasurements combined with GPS
  - Desktop mapping: orthophotos, satellite imagery, stereoscopic interpretation of satellite imagery, high resolution DTMs

Ardizzone, F., M. Cardinali, A. Carrara, F. Guzzetti, and P. Reichenbach (2002), Impact of mapping errors on the reliability of landslide hazard maps, Natural Hazards and Earth System Sciences, 2, 3–14. **Guzzetti, F., A. Mondini, M. Cardinali, F. Fiorucci, M. Santangelo, and K.-T. Chang** (2012), Landslide inventory maps: New tools for an old problem, Earth-Science Reviews, 112(1-2), 42–66.
Malamud, B. D., D. L. Turcotte, F. Guzzetti, and P. Reichenbach (2004), Landslide inventories and their statistical properties, Earth Surface Processes and Landforms, 29(6), 687–711.

Landslide inventories
LiDAR DTM based



Bias in input data and modelling results

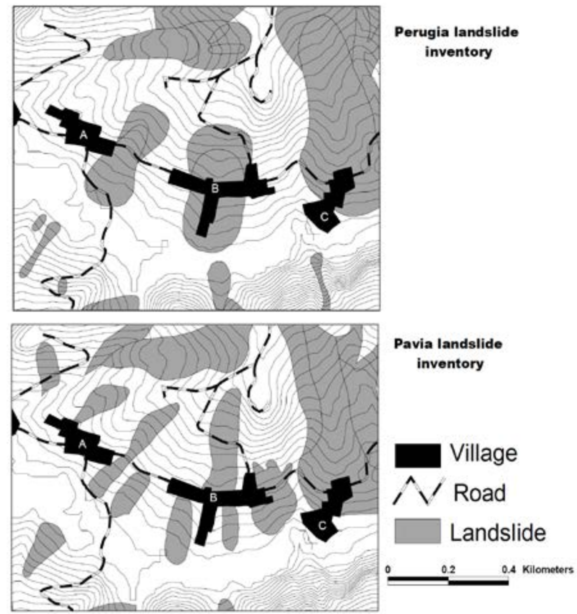


Inventory:

→ Completeness of the landslide inventory varies depending on

→ source: archive, search of news reports, mapping on LiDAR DTM, mapping on orthophotos

→ Mapping team

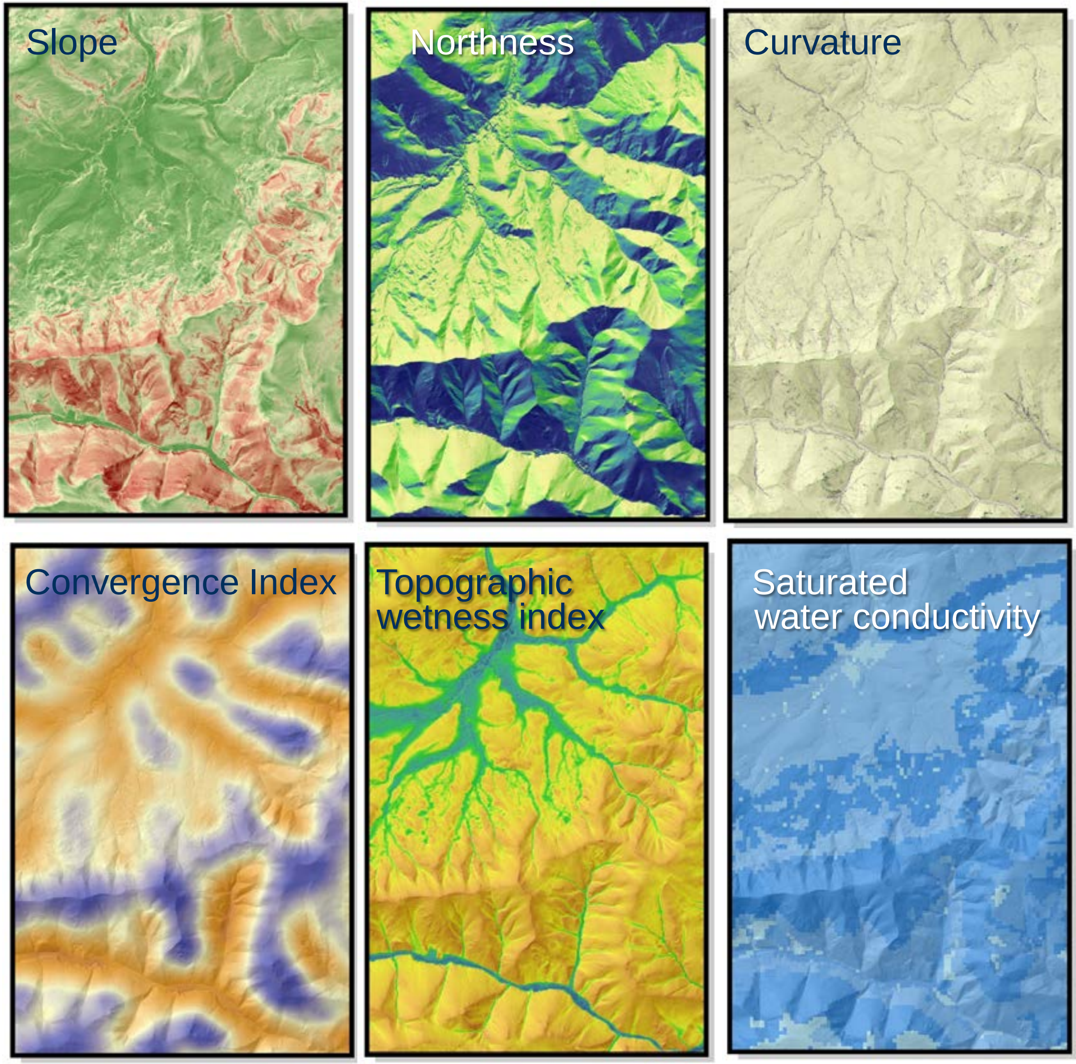


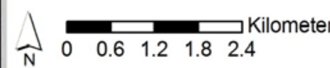
Explanatory variables:

→ Match of landslide occurrence conditions with explanatory variables (e.g. landuse)

Ardizzone, F., Cardinali, M., Carrara, A., Guzzetti, F., Reichenbach, P., 2002. Impact of mapping errors on the reliability of landslide hazard maps. Natural Hazards and Earth System Sciences 2, 3–14
Steger S, Brenning A, Bell R, Glade T (2017) The influence of systematically incomplete shallow landslide inventories on statistical susceptibility models and suggestions for improvements. Landslides. doi: 10.1007/s10346-017-0820-0
Schmaltz EM, Steger S, Glade T (2017) The influence of forest cover on landslide occurrence explored with spatio-temporal information. Geomorphology 290:250–264. doi: 10.1016/j.geomorph.2017.04.024

Explanatory Variables (examples)





Landslide susceptibility …

"[…] is the likelihood of a landslide occurring in an area on the basis of local terrain conditions" (Brabb, 1984)

"[…] is the probability of spatial occurrence of slope failures, given a set of geo-environmental conditions." (Guzzetti, 2005)

→ **Frequency and magnitude** of the landslides remain **unknown**!

Landslide susceptibility maps (LSM) can be implemented in **spatial planning**.

Brabb, E.E. (1984) Innovative approaches to landslide hazard mapping. Proceedings 4th International Symposium on Landslides, Toronto, 1: 307-324.
Guzzetti, F. (2005), Landslide hazard and risk assessment, Dissertation, Rheinischen Friedrich-Wilhelms-Universität Bonn, Bonn.

Theoretical background Susceptibility modelling

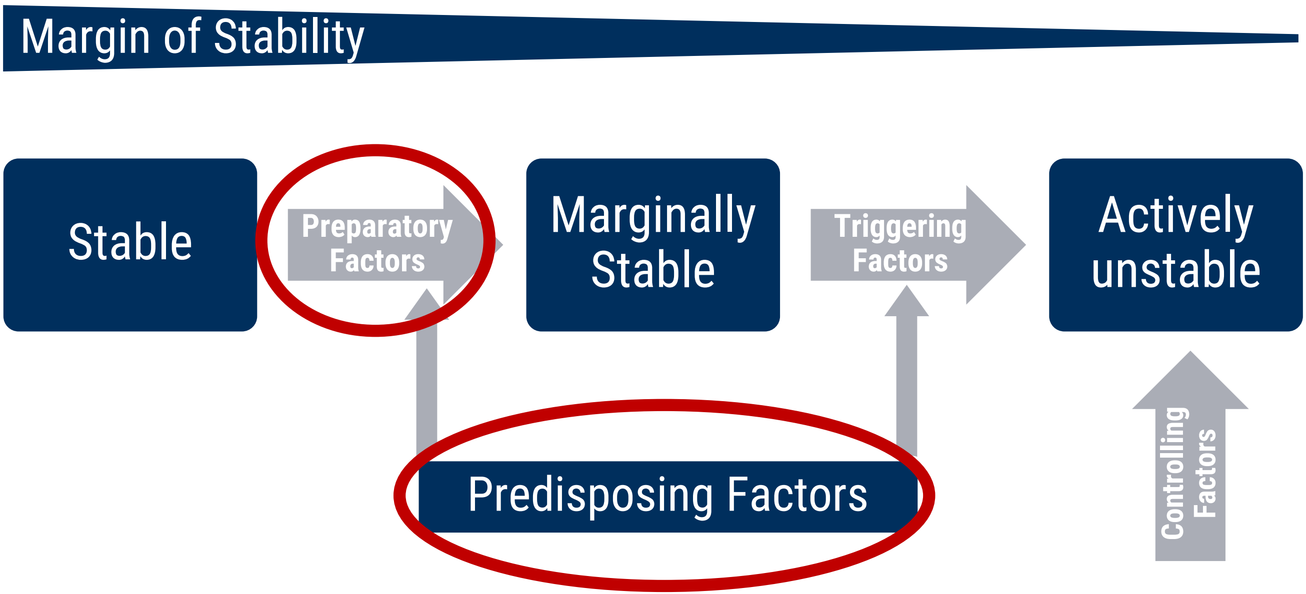
Uniformitarianism:
"The past is the key to the future" (Hutton, Lyell)
→ used in statistical modelling methods:
Past location of landslides used to predict
future location

Principles of slope instability:
Shear stress/shear strength (Coloumb, Terzaghi)
Stability states and destabilizing factors (Crozier, 1986)
→ gives basic concept for identification of "geomorphologically relevant" variables

Crozier, M. J. (1986), Landslides: causes, consequences & environment, Croom Helm, London; Sydney; Dover, New Hampshire.
Orme, A. R. (2002), Shifting paradigms in geomorphology: the fate of research ideas in an educational context, Geomorphology, 47(2–4), 325–342.

Theoretical background Susceptibility modelling

Mass Movement Theory –
Stability states and destabilizing factors (based on Crozier, 1986)



Crozier, M. J. (1986), Landslides: causes, consequences & environment, Croom Helm, London; Sydney; Dover, New Hampshire.
Glade, T., and M. J. Crozier (2005), The nature of landslide hazard impact, in: Glade T., Anderson M., and Crozier, M.J. (Eds.), Landslide Hazard and Risk, John Wiley & Sons, Ltd, Chichester, England, pp. 43–74.

Statistical landslide susceptibility modelling

"All models are wrong, but some are useful..." (Box, 1979)

- Heuristic methods
  - Expert opinion (weighting of variables), Index method
- Geo-statistical methods of spatial modelling
  - **representative** knowledge on the location of landslides and the extent of landslide free areas in the past necessary

Regional *(country, province, municipality) to local (slope) Global?*

- Physically-based methods
  - Soil mechanics, hydrological properties of the subsurface need to be determined to calculate shear stress/strength of the material under different conditions

Local (slope) *to Regional*

Modelling steps – your way to a susceptibility map

Data collection, landslide mapping (response variable), **Datenaufbereitung** (explanatory variables)

Sample (Point(s) in landslide (value 1) and points outside landslides (value 0) wiht a 1:1 ratio); extract values of explanatory variables to points

Generalised additive **modell** to predict where landslides are 0 – 100 % probable

Model performance assessment (spatial cross validation)

Transfer of the prediction to all raster cells; Classification in **landslide susceptibility classes for the landslide susceptibilit map**

Statistical landslide susceptibility modelling

- Weights of Evidence
- Logistic Regression

Traditional methods

- Generalised Additive Models

Mix providing non-linearity

- Artificial Neuronal Networks
- Support Vector Machines
- Regression trees or random forest

Machine learning methods

(Brenning 2005, 2008)

Brenning, A. (2005), Spatial prediction models for landslide hazards: review, comparison and evaluation, Natural Hazards and Earth System Sciences, 5(6), 853–862. **Brenning, A.** (2008), Statistical Geocomputing combining R and SAGA: The Example of Landslide susceptibility Analysis with generalized additive Models, SAGA—Seconds Out, 19, 23–32.

Statistical landslide susceptibility modelling

- Linear logistic regression (response variable y = (0|1))

$$\log \frac{p(y_i|x_{i1}, \ldots x_{ip})}{1 - p(y_i|x_{i1}, \ldots x_{ip})} = \beta_0 + x_{i1}\beta_1 + \ldots x_{ip}\beta_p$$

- Generalised additive modell (response variable y=(0|1))

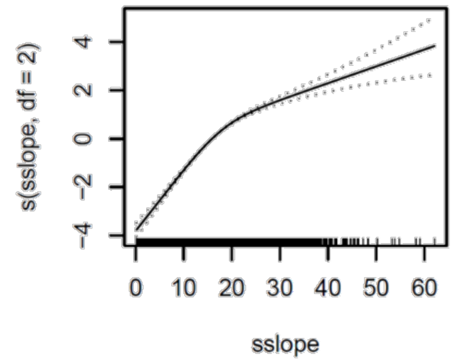
$$\log \frac{p(y_i|x_{i1}, \ldots x_{ip})}{1 - p(y_i|x_{i1}, \ldots x_{ip})} = \beta_0 + f_1(x_{i1}) + \ldots f_p(x_{ip})$$

Statistical landslide susceptibility modelling

Generalized additive models (GAM)
(Hastie & Tibshirani 1990, Brenning 2008, Goetz 2011)

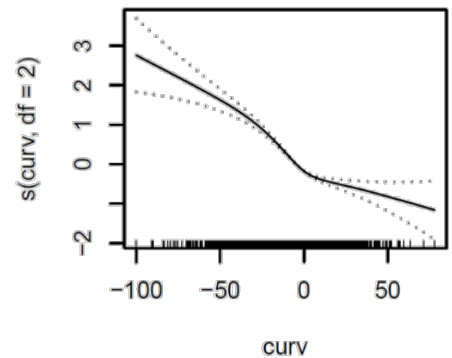
Comparable to logistic regression

BUT: GAM includes nonlinearities in the relationship between explanatory and response variable



Model design:

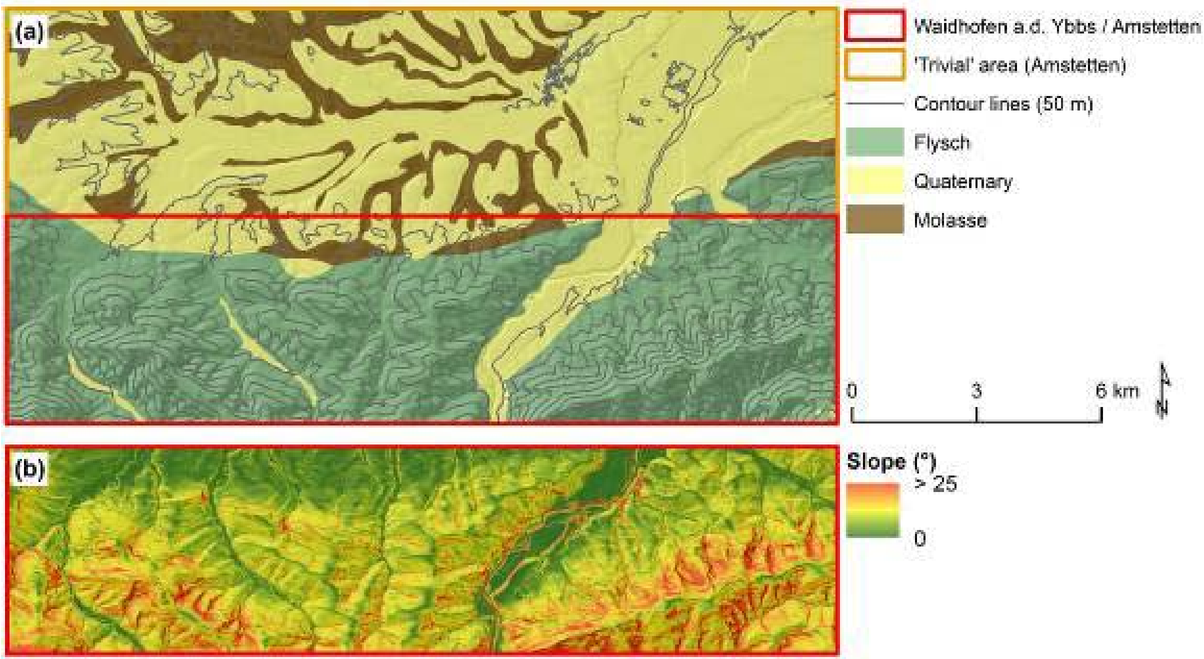
- Random sampling of points within and outside of landslides (1:1)
- Stepwise variable selection
- Cell size 10 m x 10 m



Hastie, T., and R. Tibshirani (1990) Generalized additive models, Chapman & Hall/CRC, London.
Brenning, A. (2008) Statistical Geocomputing combining R and SAGA: The Example of Landslide susceptibility Analysis with generalized additive Models, SAGA—Seconds Out, 19, 23–32.
Goetz, J. N., R. H. Guthrie, and A. Brenning (2011) Integrating physical and empirical landslide susceptibility models using generalized additive models, Geomorphology.

Sampling design stable areas (outside of landslides)

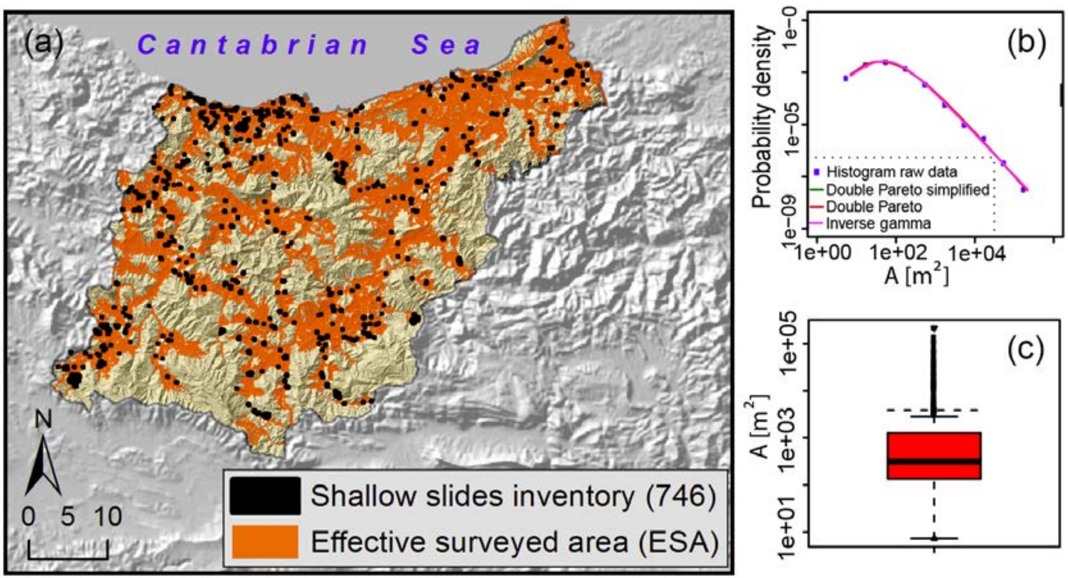
- Avoid sampling in “trivial areas” (Steger et al. 2017)



Steger S, Glade T (2017) The Challenge of “Trivial Areas” in Statistical Landslide Susceptibility Modelling. In: Mikos M, Tiwari B, Yin Y, Sassa K (eds) Advancing Culture of Living with Landslides. Springer International Publishing, Cham, pp 803–808

Sampling design stable areas (outside of landslides)

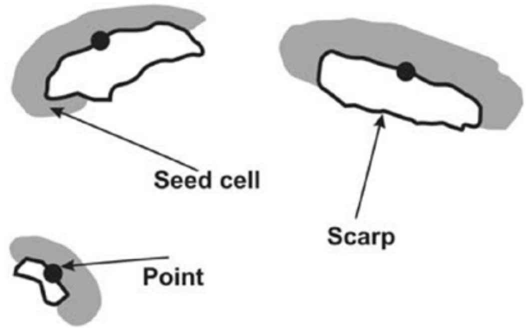
- Know where landslides where mapped (and where not; e.g. definition of visible area from the mapped landslides after Bornaetxea et al. 2018)

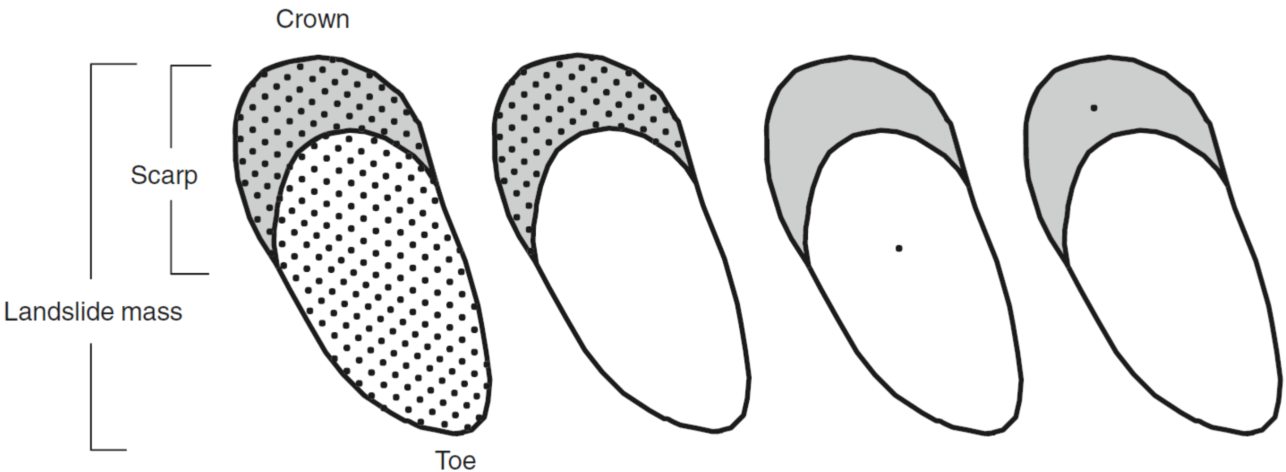


Bornaetxea T, Rossi M, Marchesini I, Alvioli M (2018) Effective surveyed area and its role in statistical landslide susceptibility assessments. Nat Hazards Earth Syst Sci 18:2455–2469.

Sampling design within landslides

- Scarp, body, entire polygon, seed cell
- One point, multiple points per area
- Centroid or center of mass, highest point random point(s)





Regmi NR, Giardino JR, McDonald EV, Vitek JD (2014) A comparison of logistic regression-based models of susceptibility to landslides in western Colorado, USA. Landslides 11:247–262
Yilmaz I (2010) The effect of the sampling strategies on the landslide susceptibility mapping by conditional probability and artificial neural networks. Environ Earth Sci 60:505–519.
Hussin HY, Zumpano V, Reichenbach P, et al (2016) Different landslide sampling strategies in a grid-based bi-variate statistical susceptibility model. Geomorphology 253:508–523

Assessment of the quality of susceptibility maps

(Spatial) transferability of model…

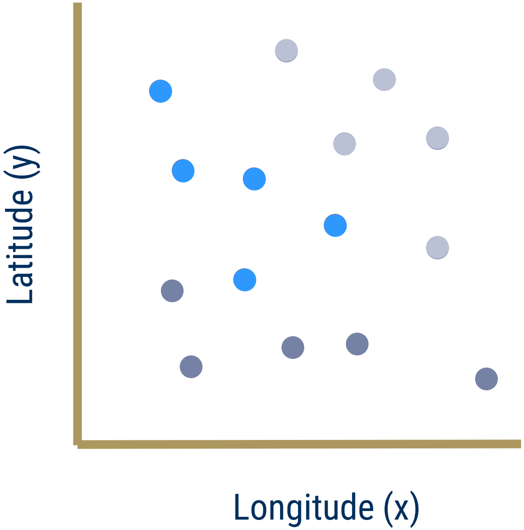
… is the ability to fit a model in one training area /point sample and apply it to a test area / point sample which has comparable geo-environmental conditions

How good does my model fit to "new" landslides?
→ *k*-fold cross-validation

Why do we need to validate?

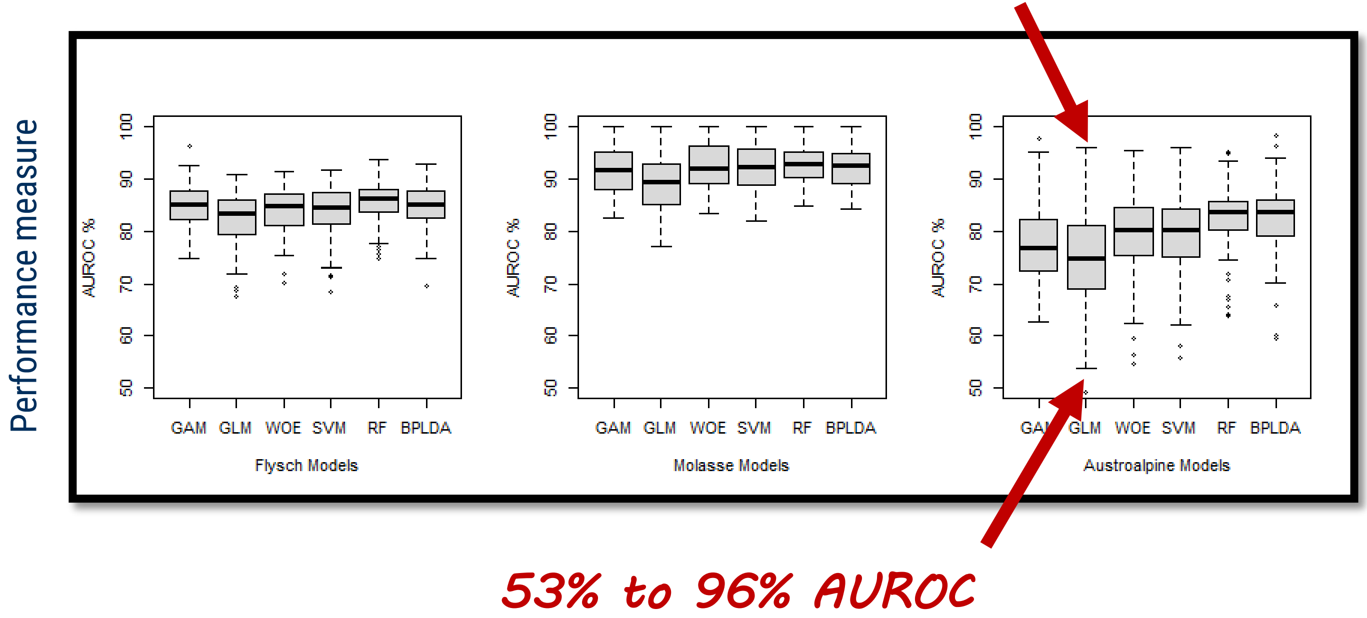
Common approach

- Holdout method
- *k*-fold cross-validation



Do you feel lucky?

Is your model really good, or is it just by chance?

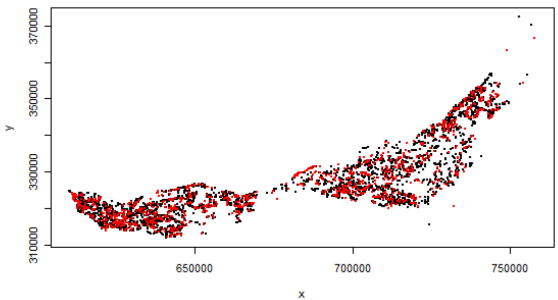


Repeated *k*-fold cross-validation

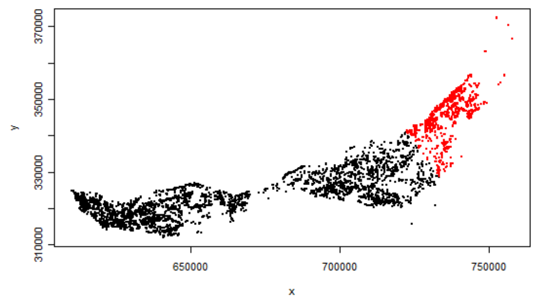
Calculation and comparison of area under the receiver operating characteristic curve (AUROC) values (0-1)

5-fold validation: *k*-1 folds to train the model, 1 fold to test the model

Random partitioning



Spatial partitioning



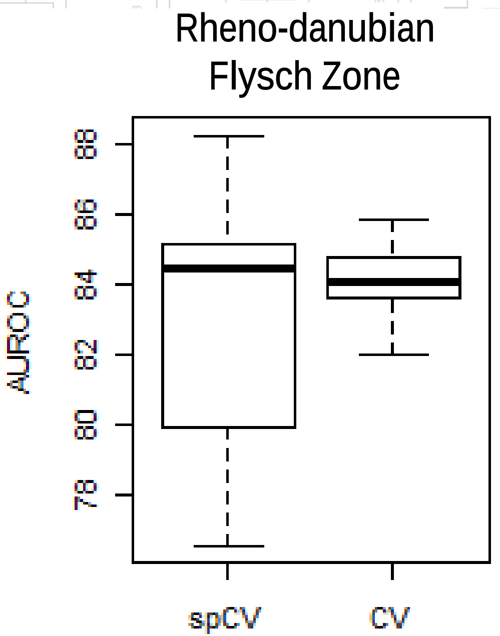
20 repetitions = 100 model (GAM) runs

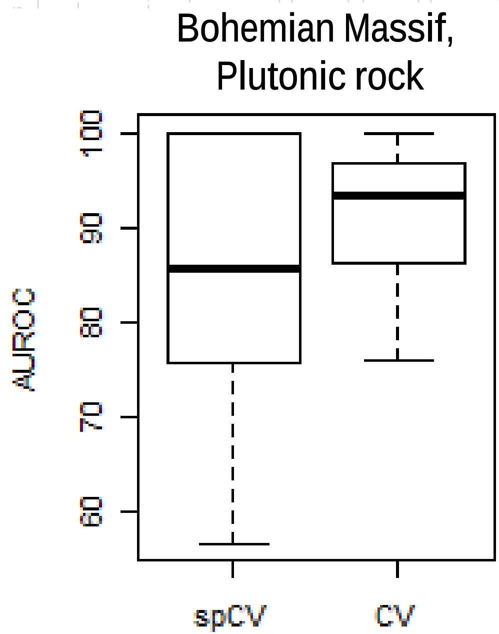
(Brenning 2005, Brenning 2012)

Brenning, A. (2005), Spatial prediction models for landslide hazards: review, comparison and evaluation, Natural Hazards and Earth System Sciences, 5(6), 853–862.

Brenning, A. (2012), Spatial cross-validation and bootstrap for the assessment of prediction rules in remote sensing: the R package 'sperrorest'. IEEE International Symposium on Geoscience and Remote Sensing IGARSS, in press.

(Spatial) transferability





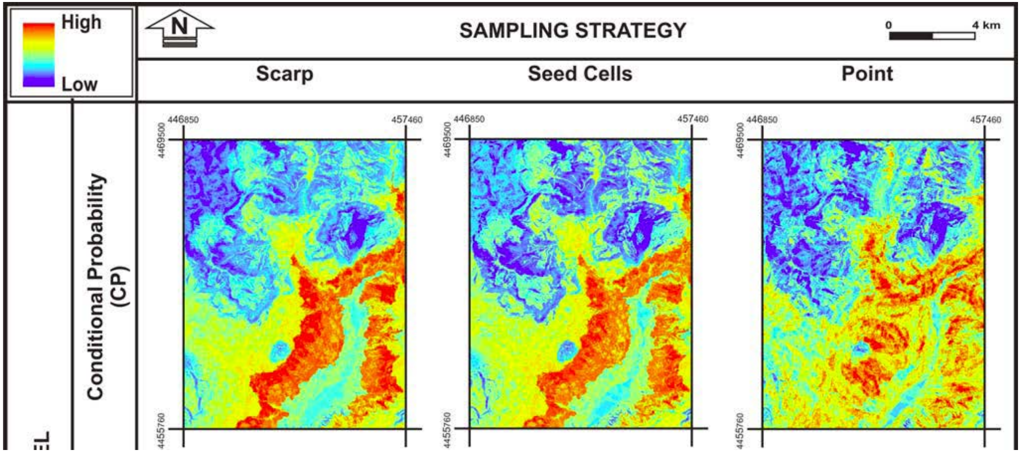
spCV = spatial *k*-fold cross-validation
CV = *k*-fold cross-validation with random sampling
AUROC = statistical quality measure (>50)

Petschko, H., A. Brenning, R. Bell, J. Goetz and T. Glade (2014) Assessing the quality of landslide susceptibility maps for Lower Austria. NHESS.

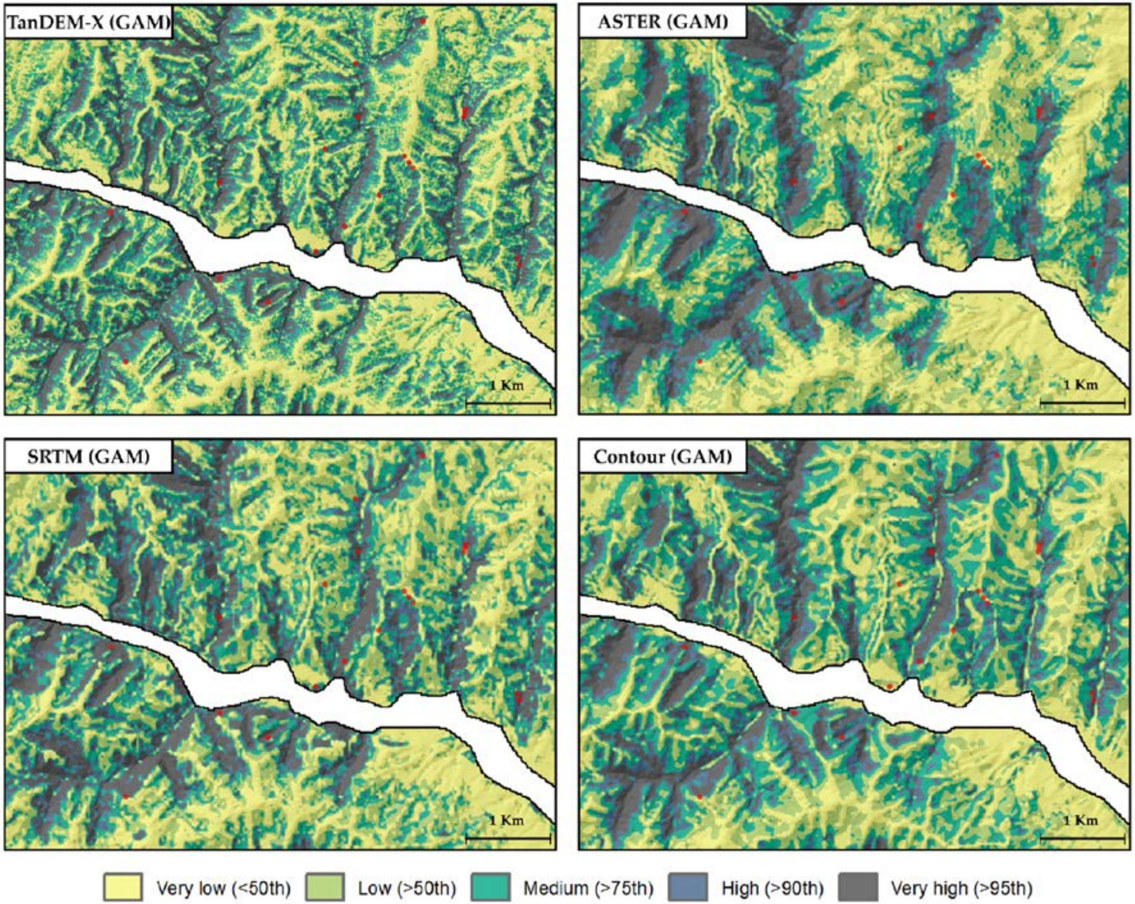
Bias in input data and **modelling results**

Artefacts due to

- bias in input data (inventory, explanatory variables) → geomorphic plausibility
- Sampling design (within and outside of landslide samples)
- Modelling method

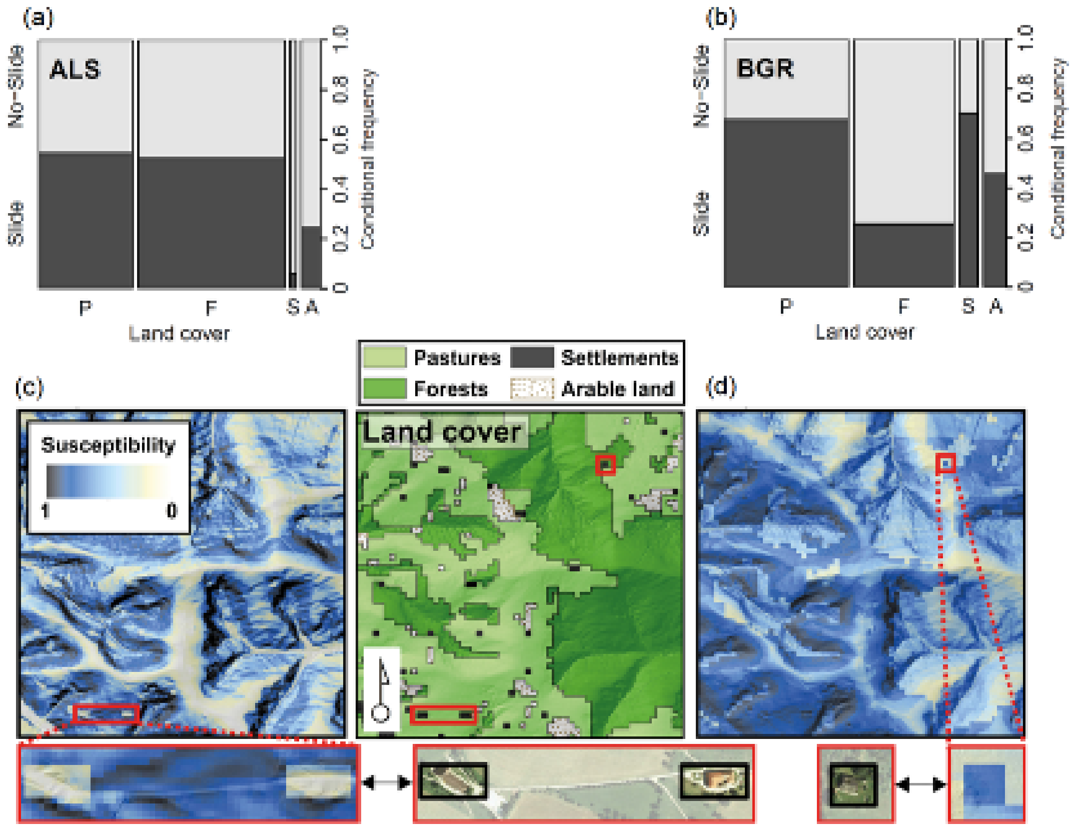


Firgure from Yilmaz I (2010) The effect of the sampling strategies on the landslide susceptibility mapping by conditional probability and artificial neural networks. Environ Earth Sci 60:505–519

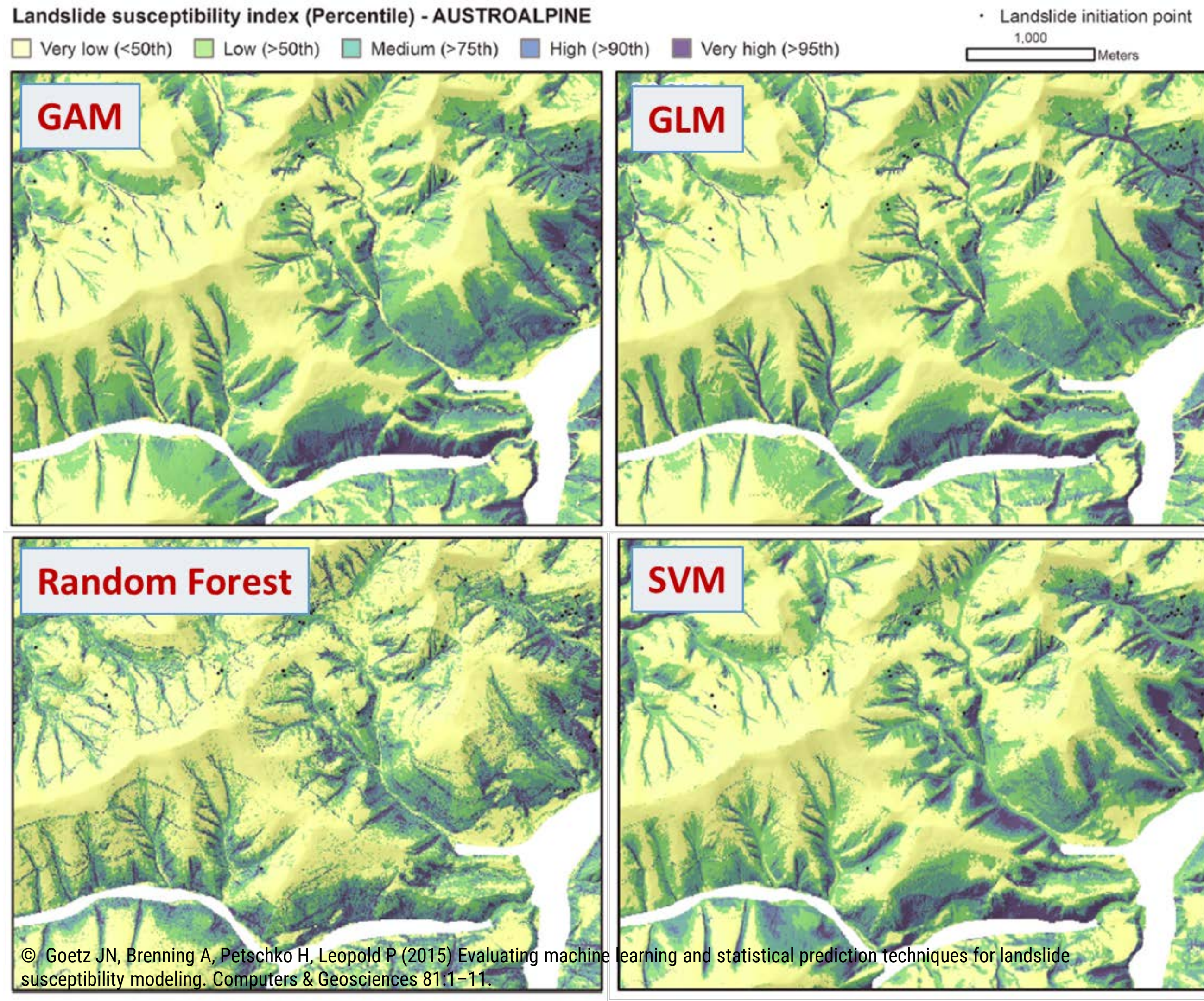


.: Classified landslide susceptibility maps at slope scale for each DEM, generated through GLM and GAM. Red points indicate previous landslides.

Geomorphic plausibility of resulting map



Steger S, Brenning A, Bell R, et al (2016) Exploring discrepancies between quantitative validation results and the geomorphic plausibility of statistical landslide susceptibility maps. Geomorphology 262:8–23.


Landslide susceptibility index (Percentile) - AUSTROALPINE
Very low (<50th)
Low (>50th)
Medium (>75th)
High (>90th)
Very high (>95th)
Landslide initiation point
1,000
Meters
GAM
GLM
Random Forest
SVM

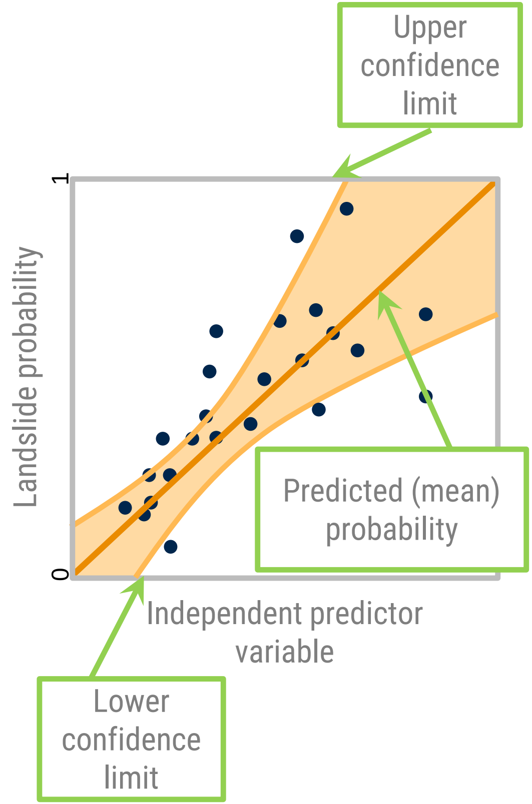
Model uncertainty and its influence on classified susceptibility maps

Estimate approximate 95% confidence limits

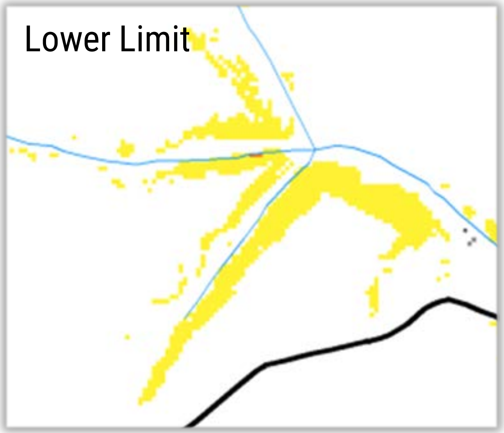
→ Standard error of the prediction for each raster cell

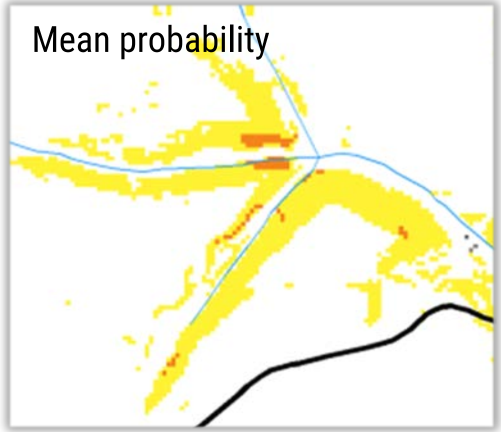
→ Calculated estimated 95% upper and lower confidence limits using the standard error

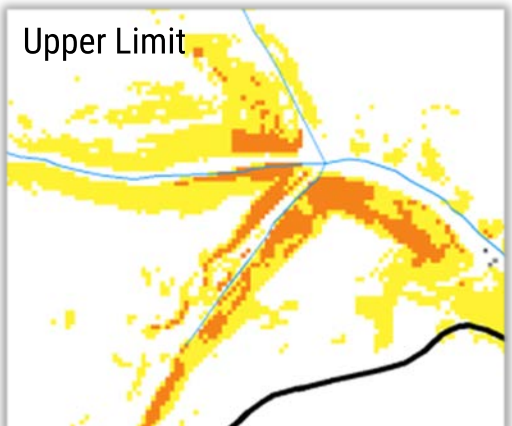
→ Classified landslide susceptibility map using probability threshold values from “original” predicted (mean) probability map
  → three landslide susceptibility maps



Model uncertainty and its influence on classified susceptibility maps







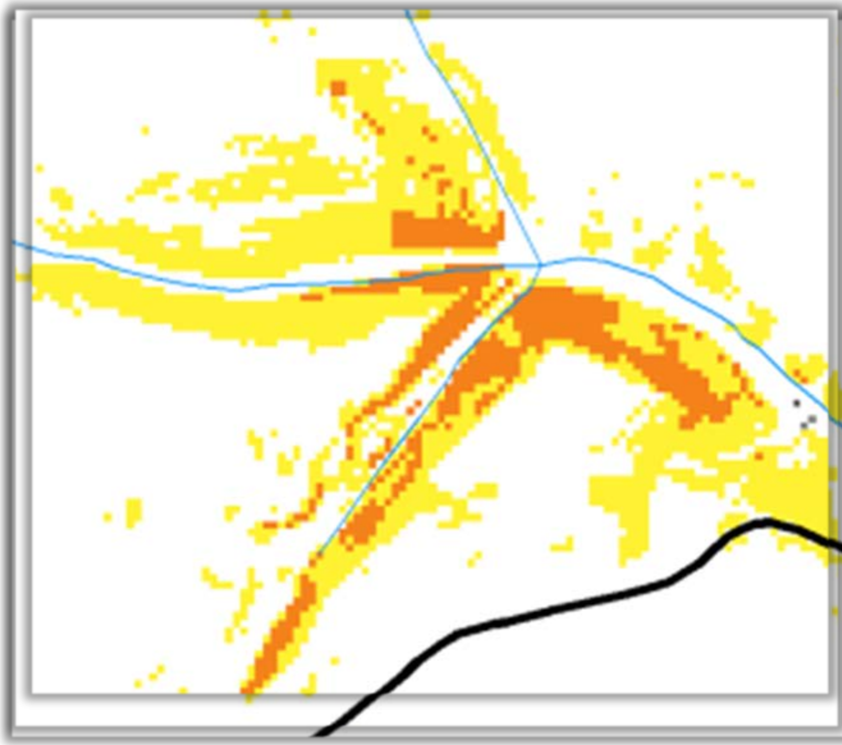
95% Confidence intervall

White = Low landslide probability
Yellow = medium landslide prob.
Orange = high landslide prob.

1 Pixel = 10m

Petschko, H., Brenning, A., Bell, R., Goetz, J., & T. Glade (2014) Assessing the quality of landslide susceptibility maps – case study Lower Austria, Nat. Hazards Earth Syst. Sci., 14, 95-118

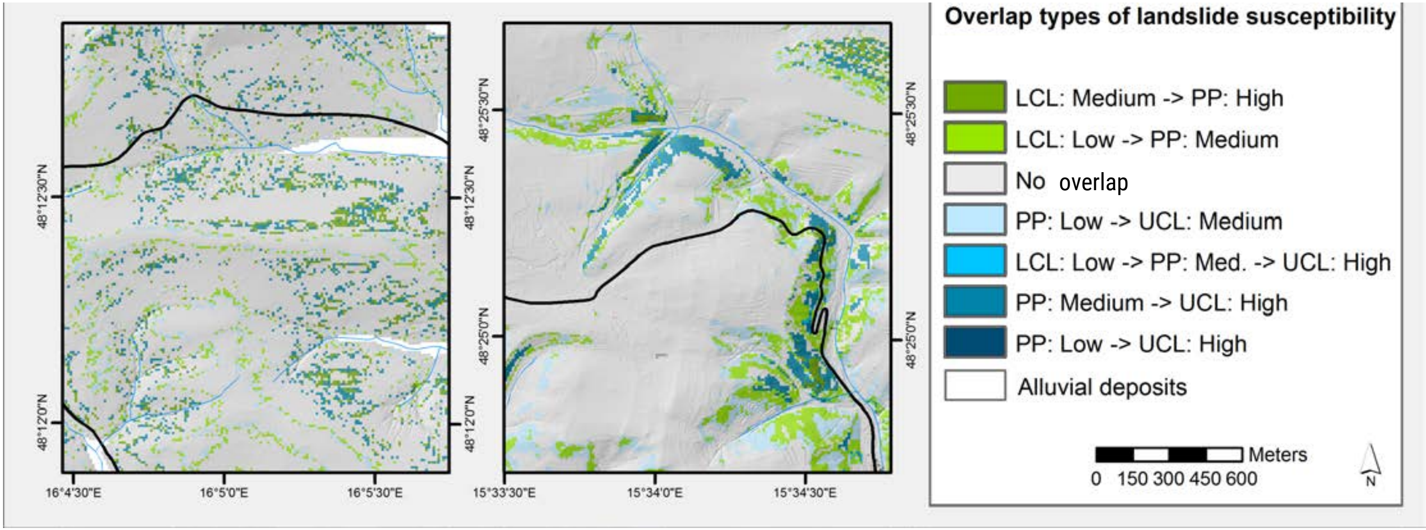
Model uncertainty and its influence on classified susceptibility maps



1 Pixel = 10m

Petschko, H., Brenning, A., Bell, R., Goetz, J., & T. Glade (2014) Assessing the quality of landslide susceptibility maps – case study Lower Austria, Nat. Hazards Earth Syst. Sci., 14, 95-118

Model uncertainty and its influence on classified susceptibility maps



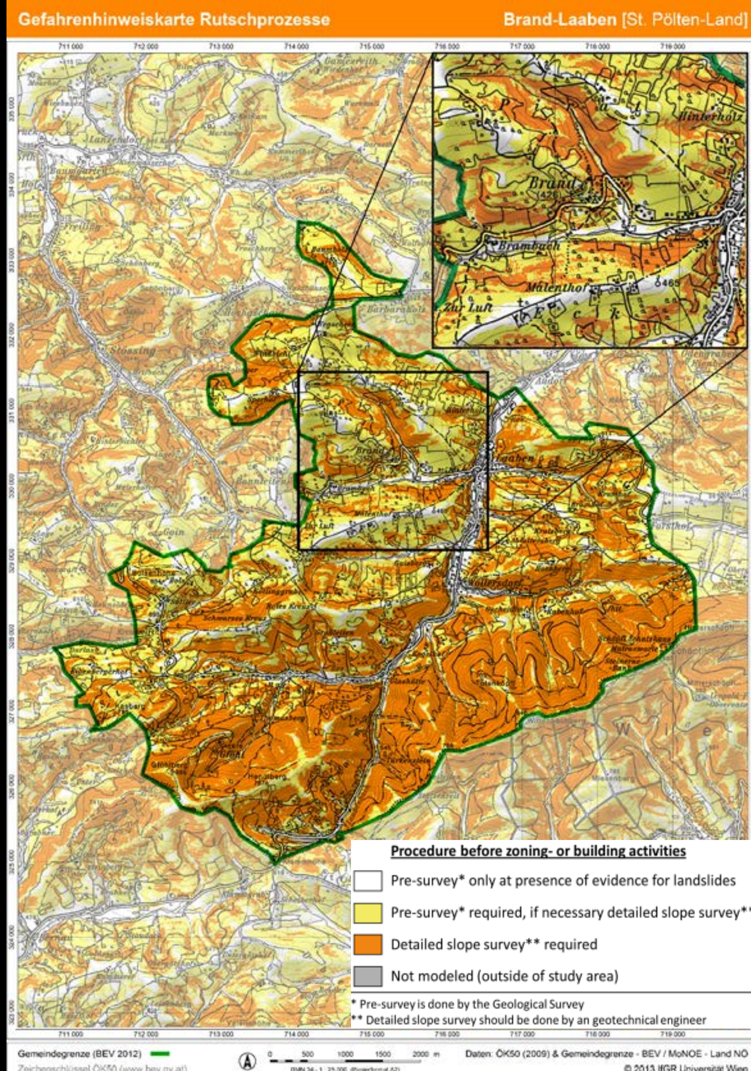
LCL: Lower confidence interval limit
PP: Predicted mean probability
UCL: Upper confidence interval limit

Petschko, H., Brenning, A., Bell, R., Goetz, J., & T. Glade (2014) Assessing the quality of landslide susceptibility maps – case study Lower Austria, Nat. Hazards Earth Syst. Sci., 14, 95-118

Model uncertainty and its influence on classified susceptibility maps

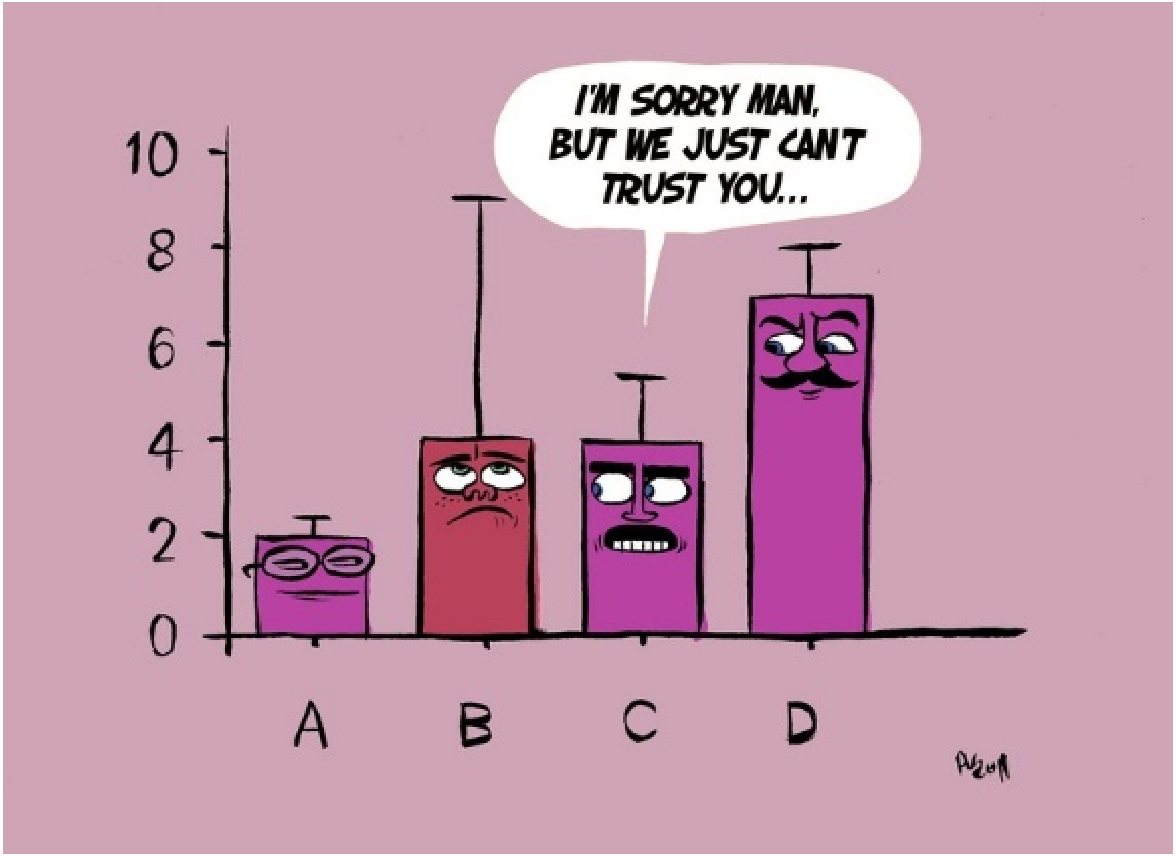
	Percent of raster cells
LCL: Low → PP: High	0.02
LCL: Medium → PP: High	2.00
LCL: Low → PP: Medium	5.00
No change	85.00
PP: Low → UCL: Medium	6.00
LCL: Low → PP: Medium → UCL: High	0.40
PP: Medium → UCL: High	2.00
PP: Low → UCL: High	0.03

Petschko, H., Brenning, A., Bell, R., Goetz, J., & T. Glade (2014) Assessing the quality of landslide susceptibility maps – case study Lower Austria, Nat. Hazards Earth Syst. Sci., 14, 95-118



Gefahrenhinweiskarte Rutschprozesse
Brand-Laaben [St. Pölten-Land]
Procedure before zoning- or building activities
Pre-survey* only at presence of evidence for landslides
Pre-survey* required, if necessary detailed slope survey**
Detailed slope survey** required
Not modeled (outside of study area)
* Pre-survey is done by the Geological Survey
** Detailed slope survey should be done by an geotechnical engineer
Gemeindegrenze (BEV 2012)
Zeichenschlüssel ÖK50 (www.bev.gv.at)
Daten: ÖK50 (2009) & Gemeindegrenze - BEV / MoNOE - Land NÖ
© 2013 IfGR Universität Wien

Lessons Learnt



https://scienceandglobalpolitics.files.wordpress.com/2014/12/errorbars.jpg

Thank you!

Helene (Petschko) Goetz
GIScience Jena
helene.petschko@uni-jena.de

Materials:
daad_summerschool/2_day/4_ps/nat_haz/

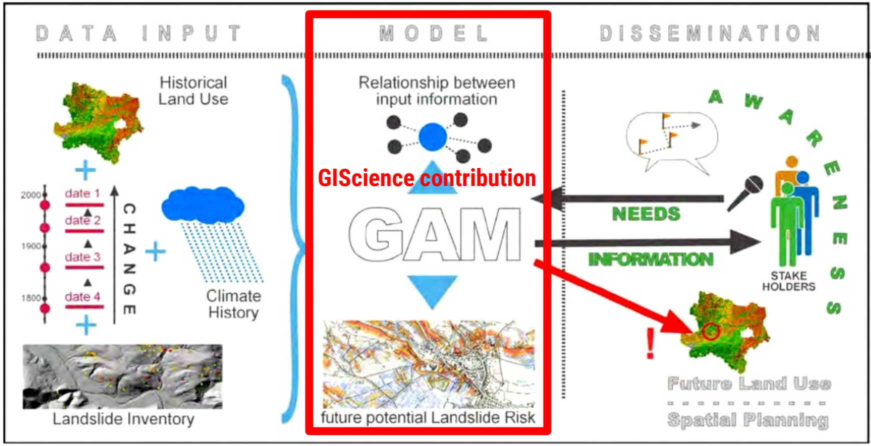
Landslide research @ GIScience

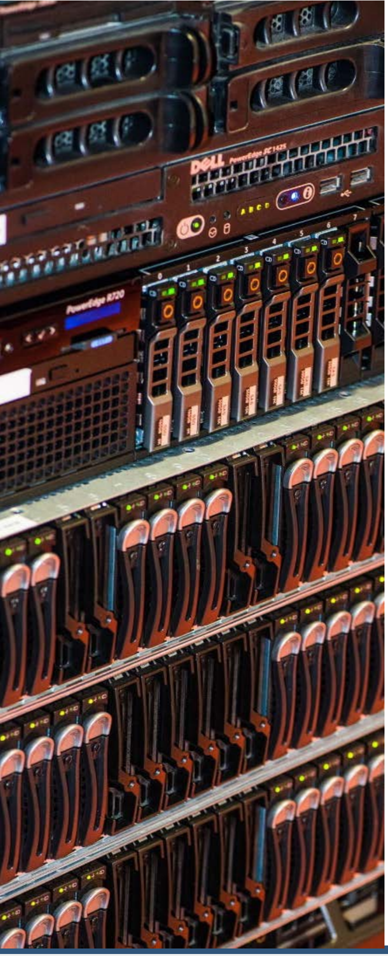
Topics

- **Predictive geostatistical landslide susceptibility modelling** to create landslide susceptibility maps for spatial planning purposes
- **Estimating the importance of predisposing and triggering factors** of landslides (distance to highways, climate change, land use change, topography,…) with geostatistical models
- Improving model comparisons using **advanced model performance assessments**
- Increasing the **understanding of model uncertainties** of statistical landslide susceptibility models

Current Projects

- **LaCCiLUC „Network for Environmental Modeling of Earth Surface Processes: Landslide Hazards in the Context of Climate and Land Use Change“**
  BMBF (03/2017 – 02/2019).
  PI: GIScience FSU Jena
  Partner: codematix GmbH, Institute of Geography der Romanian Academy and Department of Geography, University of Vienna.
- **EASICLIM „Eastern Alpine Slope Instabilities under Climate Change”**
  Austrian Climate Research Programme – ACRP (04/2017 – 03/2019).
  PI: Wegener Center for Climate and Global Change, University Graz
  Partner: JOANNEUM RESEARCH, AIT, GIScience FSU Jena
- **ILLAS „Integrating Land use Legacies in Landslide Risk Assessment to support Spatial Panning“**
  ACRP (04/2017 – 03/2020).
  PI: AIT Austrian Institute of Technology
  Partner: JOANNEUM RESEARCH, GIScience FSU Jena, Institute of Social Ecology (SEC) BOKU





Methods and Geocomputation in R

- Spatial Statistical Modelling (Generalized Linear Model (logistic regression), Generalized Additive Models)
- Machine Learning (Boosting, Random Forest, Support Vector Machine)
- Model performance assessment: **spatial k-fold cross validation** (implementation of R software extension sperrorest)
- Developed R packages
  - *RSAGA* (using SAGA GIS within R)
  - *RQGIS* (using QGIS within R)
  - Parallelized spatial error estimation and variable importance assessment (*sperrorest*)
  - odds ratio calculation (*oddsratio*)

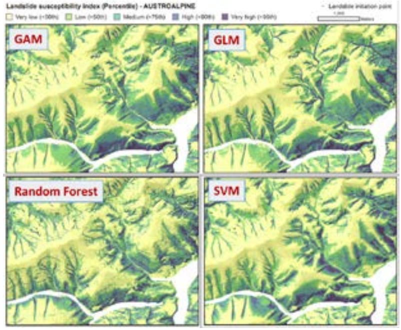
Study areas

- Vancouver Island (Canada)
- Southern Ecuador
- Lower Austria
- Paldau (Styria, Austria)
- Romanian sub-Carpathians

Recent Publications

Landslide susceptibility modelling

- Steger S, **Brenning A**, Bell R, Glade T (2017) **The influence of systematically incomplete shallow landslide inventories on statistical susceptibility models and suggestions for improvements**. Landslides
- Steger S, **Brenning A**, Bell R, **Petschko H**, Glade T (2016) **Exploring discrepancies between quantitative validation results and the geomorphic plausibility of statistical landslide susceptibility maps.** Geomorphology 262:8–23.
- **Brenning A**, Schwinn M, Ruiz-Páez AP, **Muenchow J** (2015) **Landslide susceptibility near highways is increased by 1 order of magnitude in the Andes of southern Ecuador, Loja province.** Nat Hazards Earth Syst Sci 15:45–57.
- **Goetz JN**, Guthrie RH, Brenning A (2015a) **Forest harvesting is associated with increased landslide activity during an extreme rainstorm on Vancouver Island, Canada**. Nat Hazards Earth Syst Sci 15:1311–1330.
- **Goetz JN, Brenning A, Petschko H**, Leopold P (2015b) **Evaluating machine learning and statistical prediction techniques for landslide susceptibility modeling**. Computers & Geosciences 81:1–11.
- **Petschko H, Brenning A**, Bell R, **Goetz JN**, Glade T (2014) **Assessing the quality of landslide susceptibility maps – case study Lower Austria.** Nat Hazards Earth Syst Sci 14:95–118.
- **Goetz JN**, Guthrie RH, **Brenning A** (2011) **Integrating physical and empirical landslide susceptibility models using generalized additive models.** Geomorphology 129:376–386



Geocomputation in R

- **Muenchow J, Schratz P, Brenning A** (2017) **RQGIS: Integrating R with QGIS for Statistical Geocomputing.** The R Journal 9:20
- **Brenning A** (2008) **Statistical Geocomputing combining R and SAGA: The example of landslide susceptibility analysis with generalized additive models.** SAGA—Seconds Out 19:23–32