Simulating the effect of check dams on landscape evolution at centennial time scales

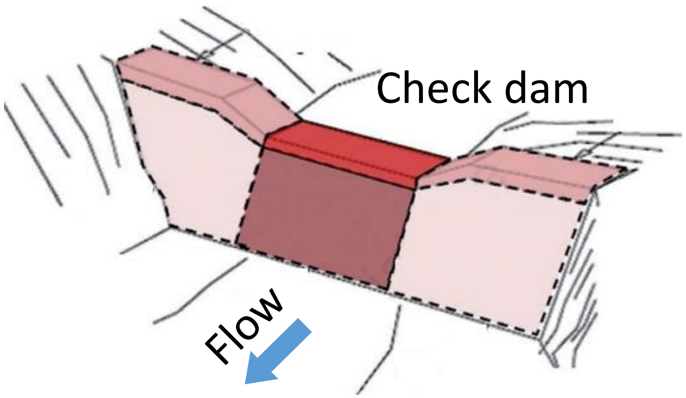
Jorge Alberto Ramirez, Mirjam Mertin, Markus Zimmermann, Margreth Keiler

UNIVERSITÄT BERN

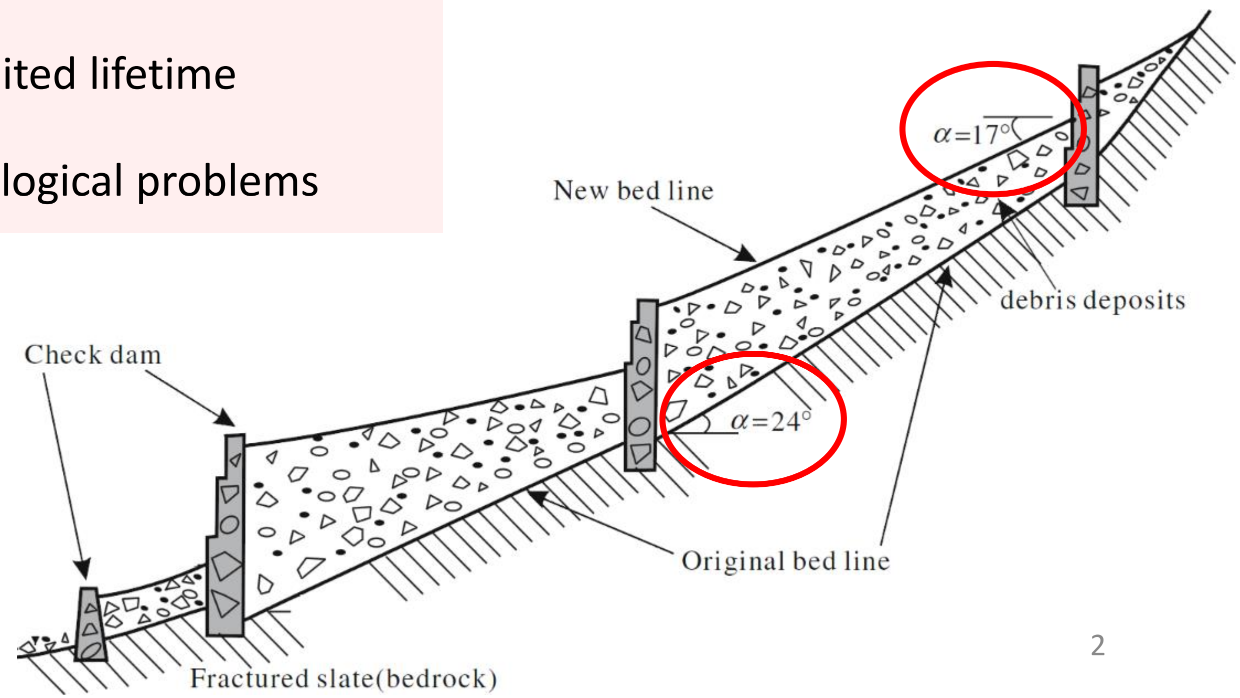
Pros and cons of check dams

UNIVERSITÄT BERN

A **check dam** is a small dam constructed across a river to counteract erosion by reducing water flow velocity

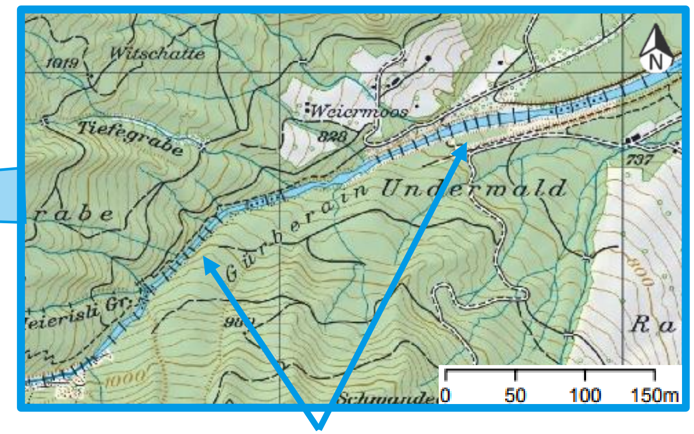


Pros	Cons
Reduction of slope gradient	Expensive investment and maintenance
Less channel erosion	Limited lifetime
Increase bank stability	Ecological problems



Study site: Guerbe river

- Guerbe river is located in the Swiss preAlps
- Catchment area of 12 km^2
- River contains 120 check dams, first built in 1860
- Average river slope is 9°



check dams in the Guerbe

Guerbe check dams

UNIVERSITÄT BERN

- Maintenance cost of check dams and protective system is 2 million USD/year
- In 1990, after a major flood event renovation costs were 40 million USD
- Most expensive river in Switzerland, but many other rivers are similar




Bachmann (2009)

Research question

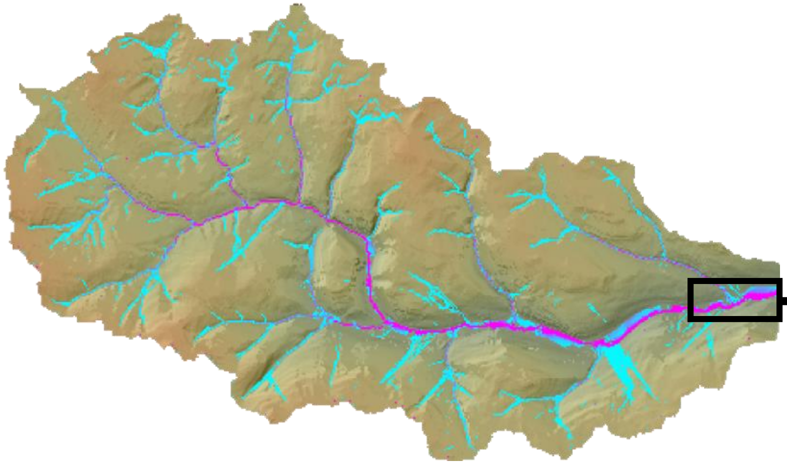
UNIVERSITÄT BERN

What would happen **geo-morphologically** if check dams were **no longer maintained** and allowed to structurally deteriorate?

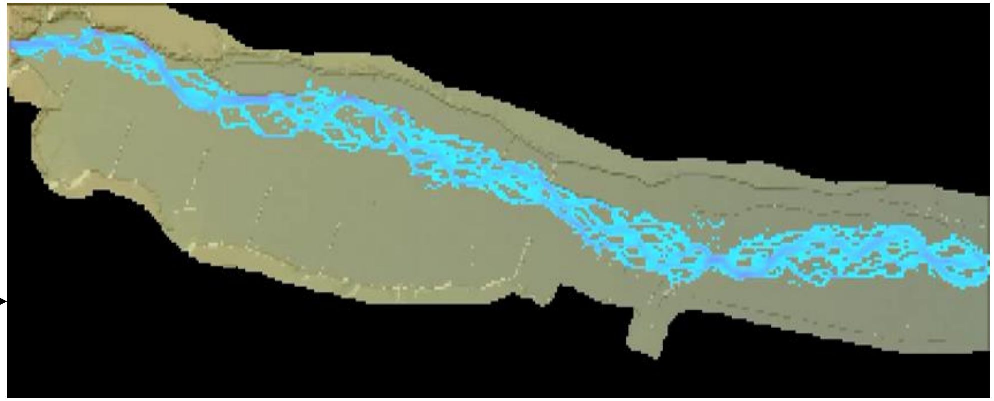
Modelling approach: CAESAR-Lisflood

- Catchment or reach based cellular model
- Models morphological change
- Hydrological model is TOPMODEL (surface runoff)
- Hydraulic model is Lisflood-FP (flow depths and velocities)
- Sediment transport
  - Bedload, 9 fractions using Wilcock & Crowe equation
- Slope processes include landslides and soil creep

Catchment scale

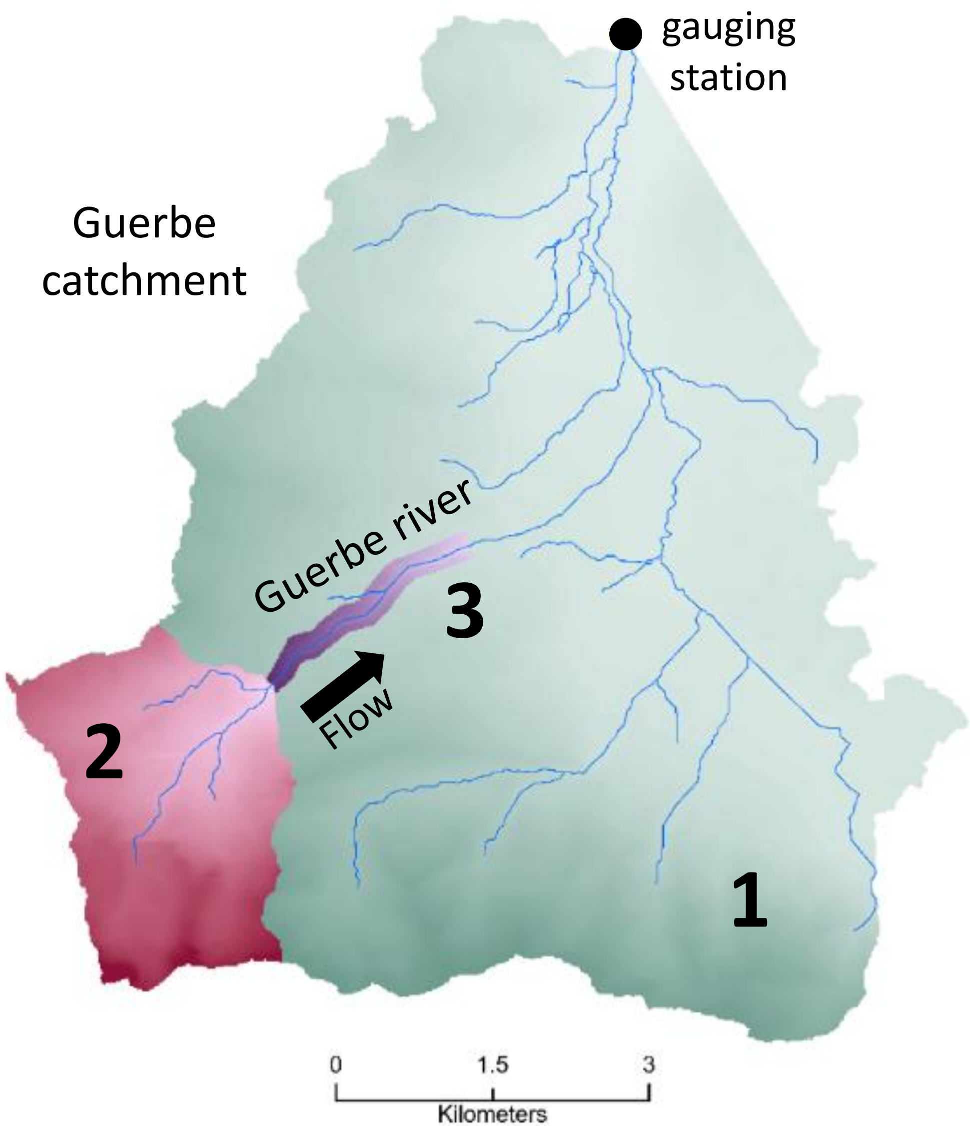


Reach scale



Model setup

UNIVERSITÄT BERN



3 step process

1. Calibrate hydrological model on **large catchment** using observed discharge and simulated rainfall

2. Apply calibrated parameters to **sub-catchment** and use simulated rainfall to generate water and sediment flux

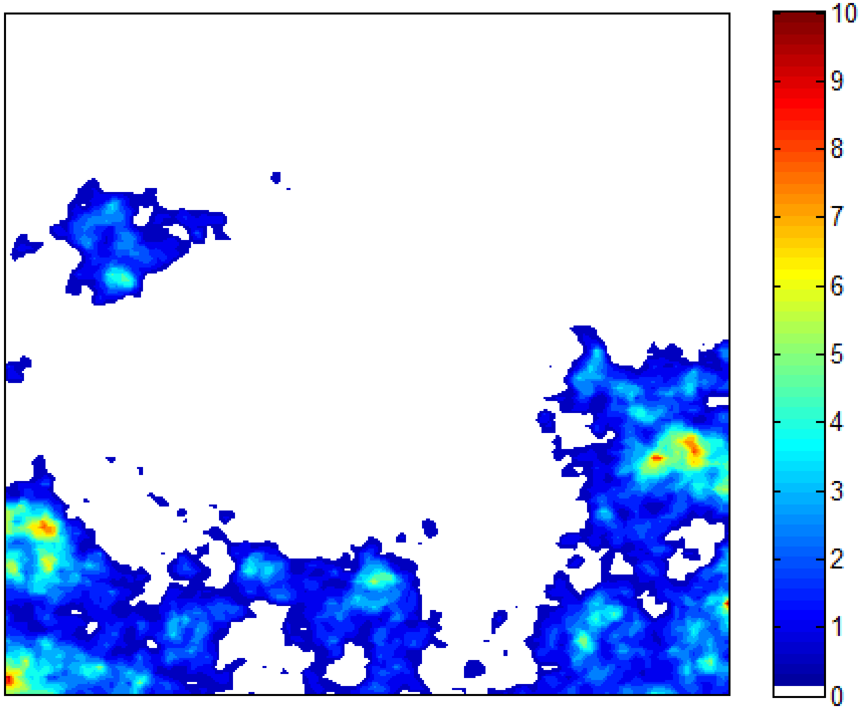
3. Water and sediment outputs from sub-catchment become inputs to **reach** scale model with check dams

Rainfall

UNIVERSITÄT BERN

- AWE-GEN-2d model combines physical and stochastic approaches to generate gridded climate variables
- Rainfall is simulated at hourly and 1-km resolution

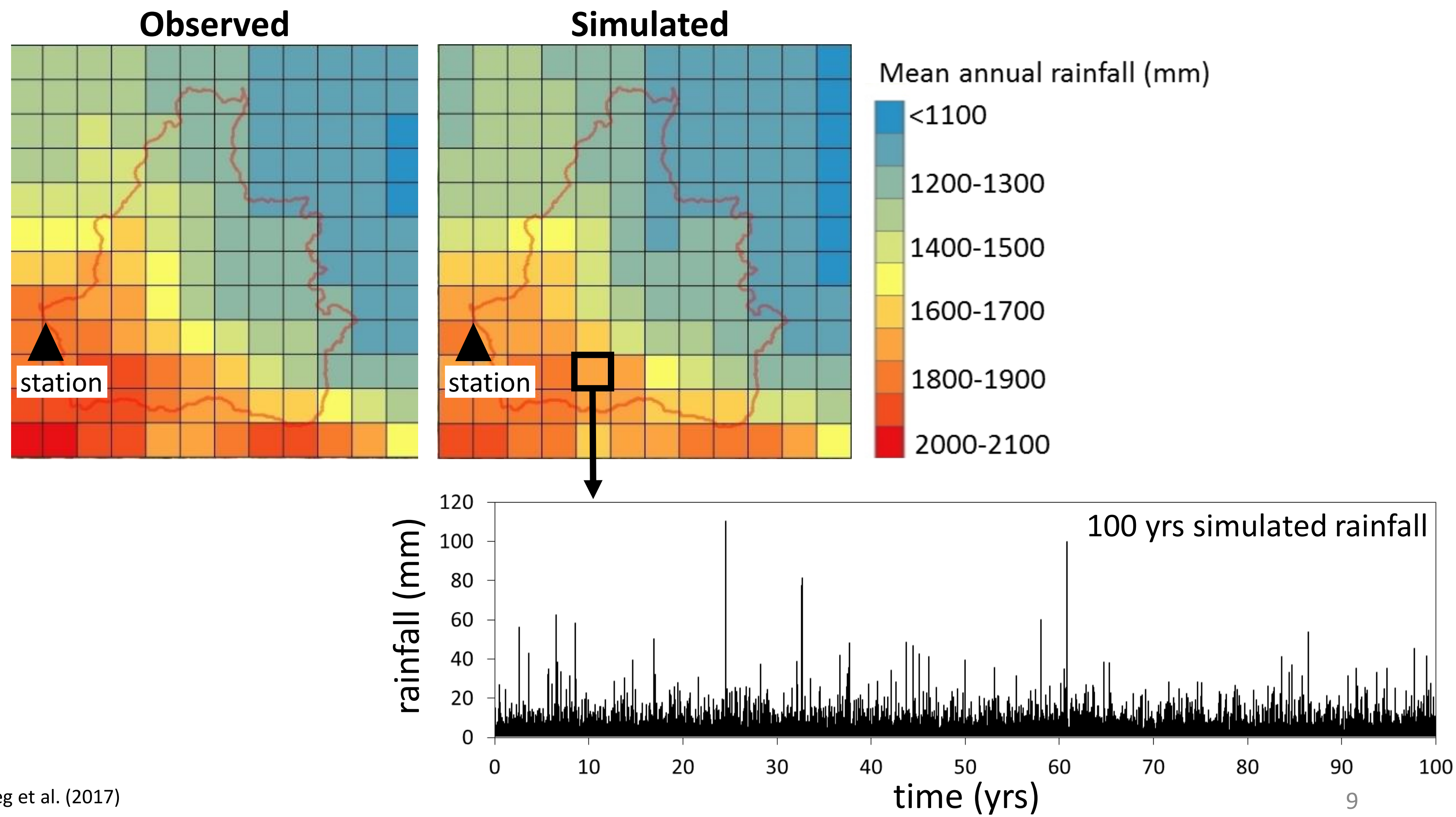
Dynamic rain fields



Peleg et al. (2017)

Rainfall

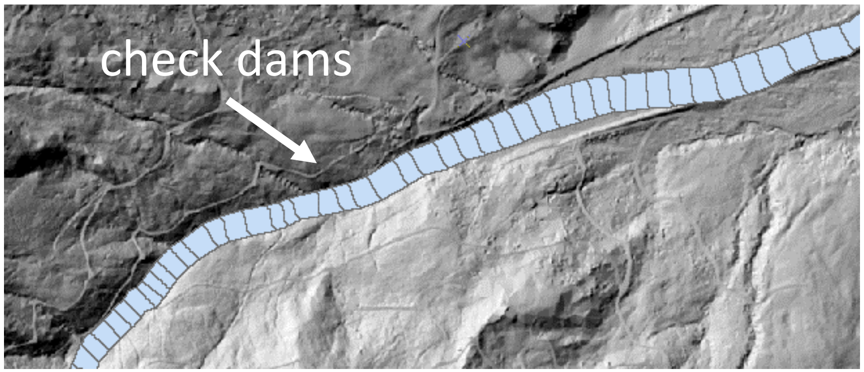
- Weather station rainfall used to calibrate storm arrival timing
- Observed daily resolution gridded rainfall used to calibrate rainfall intensity
- 100 years of rainfall based on the last 30 years of climate

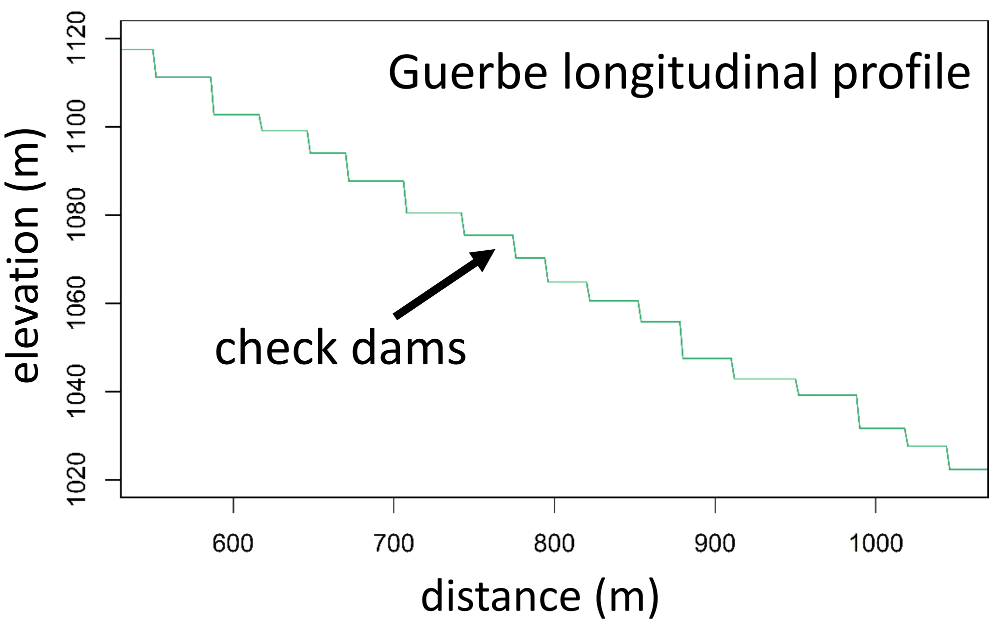


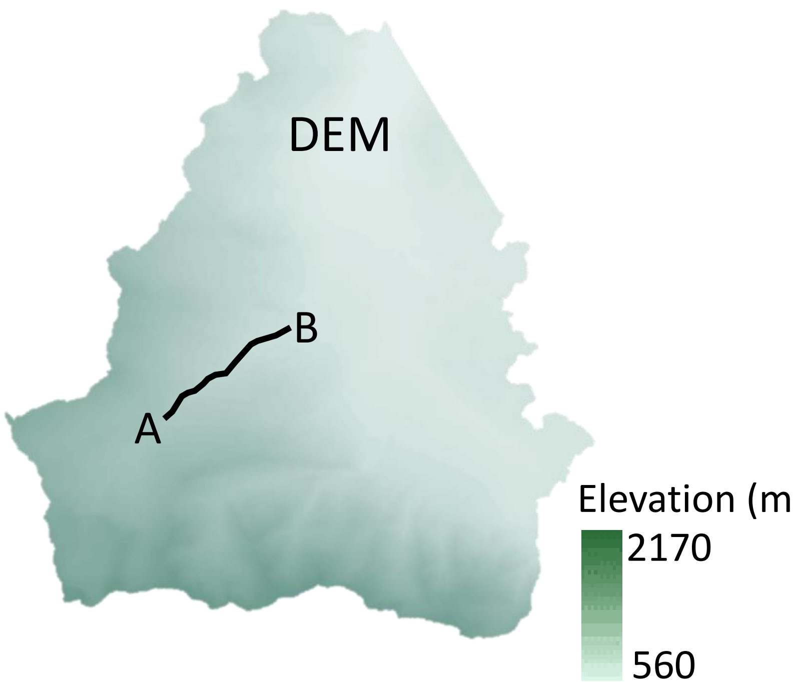
Peleg et al. (2017)

Topography

- Extracted location of check dams in 2 m spatial resolution DEM
- 2 m DEM resampled to 15 m spatial resolution
- Check dams are reinforced into DEM to ensure topographic representation

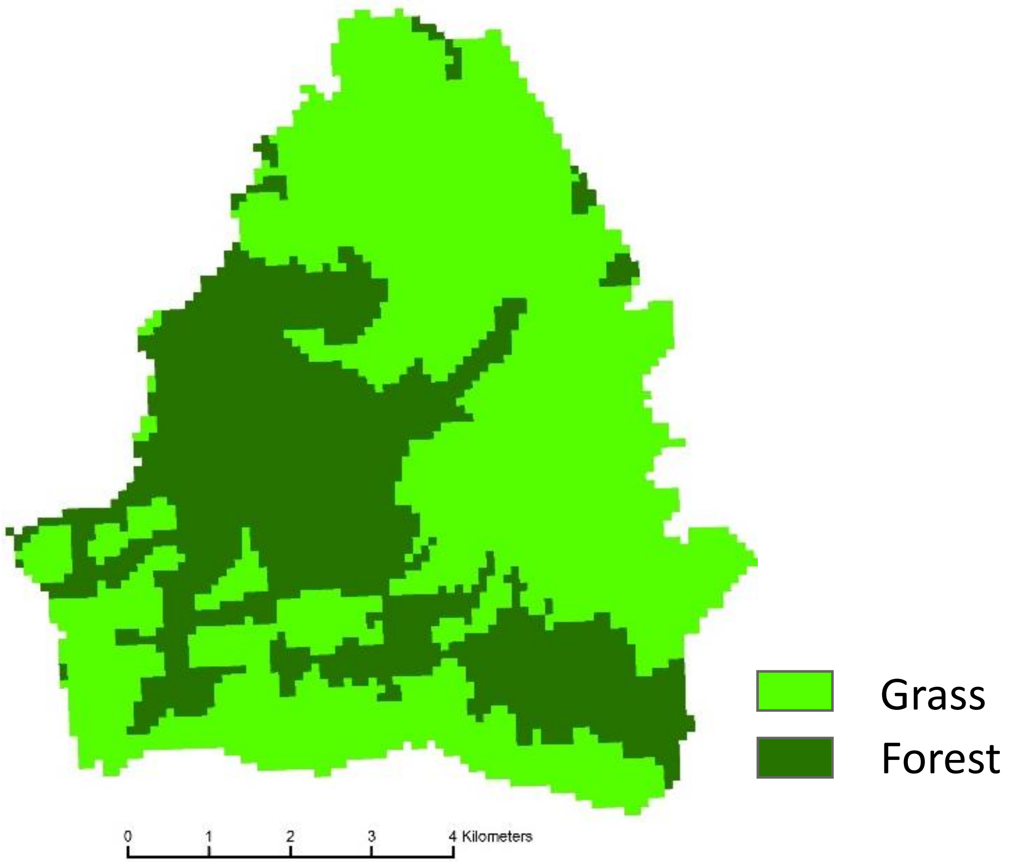






Land cover

Spatially distributed
land cover of two types

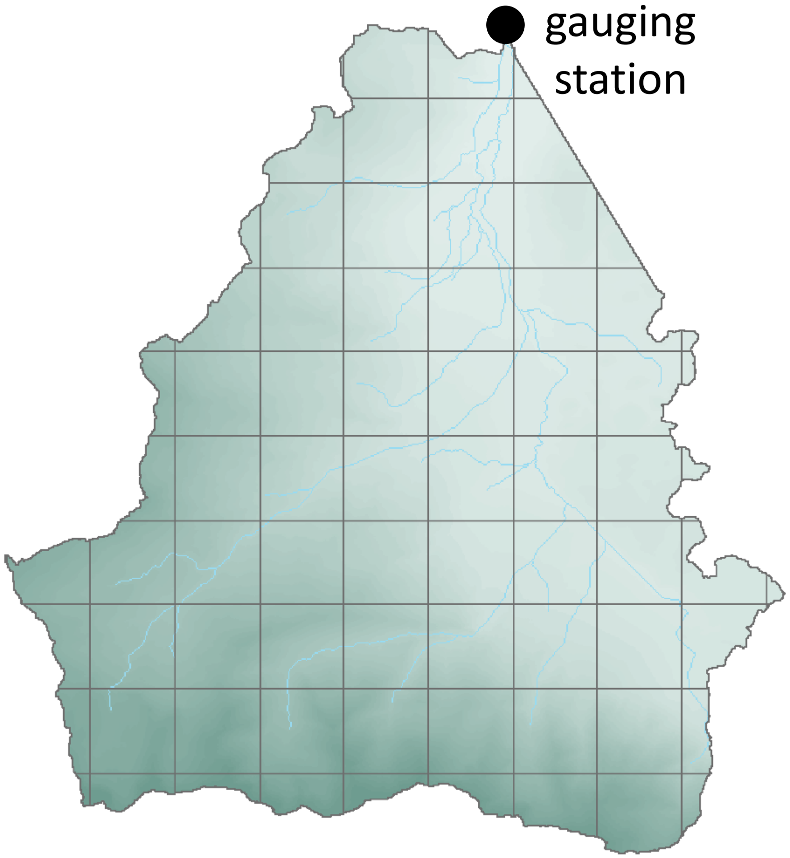


CORINE Land Cover (2012)

Hydrological calibration

UNIVERSITÄT BERN

- For the large catchment calibrate **hydrological model** using spatially distributed :
  - modelled rainfall
  - land cover
- Parameterize hydrological model for the effect of land cover on the movement and storage of water within the soil
- Replicate magnitude and frequency of hourly discharge recorded at gauging station

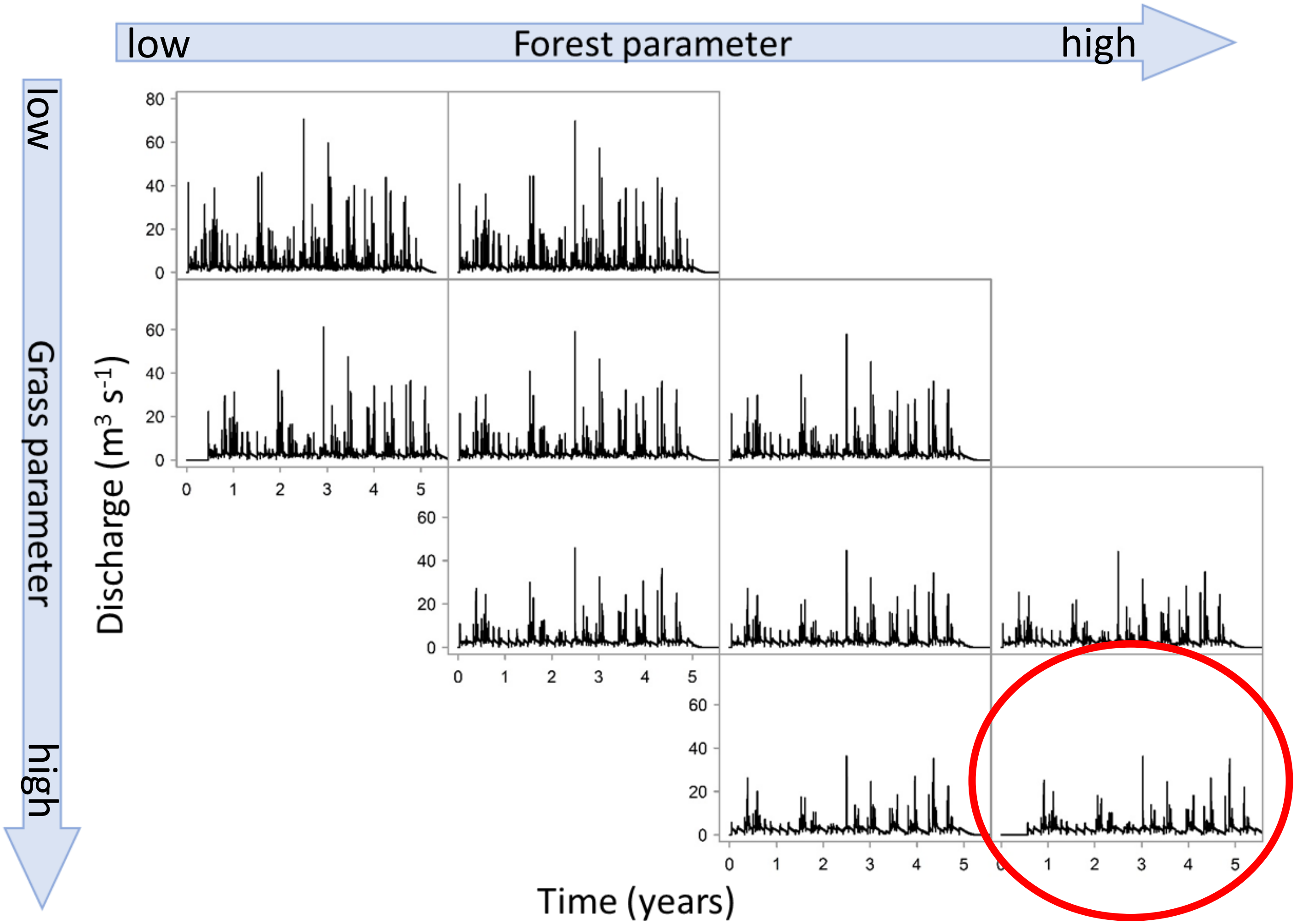


rainfall and land cover
grid structure

Hydrological calibration

UNIVERSITÄT BERN

Higher parameter values is a **well vegetated catchment**, with high soil moisture storage, and **lower flood peaks**

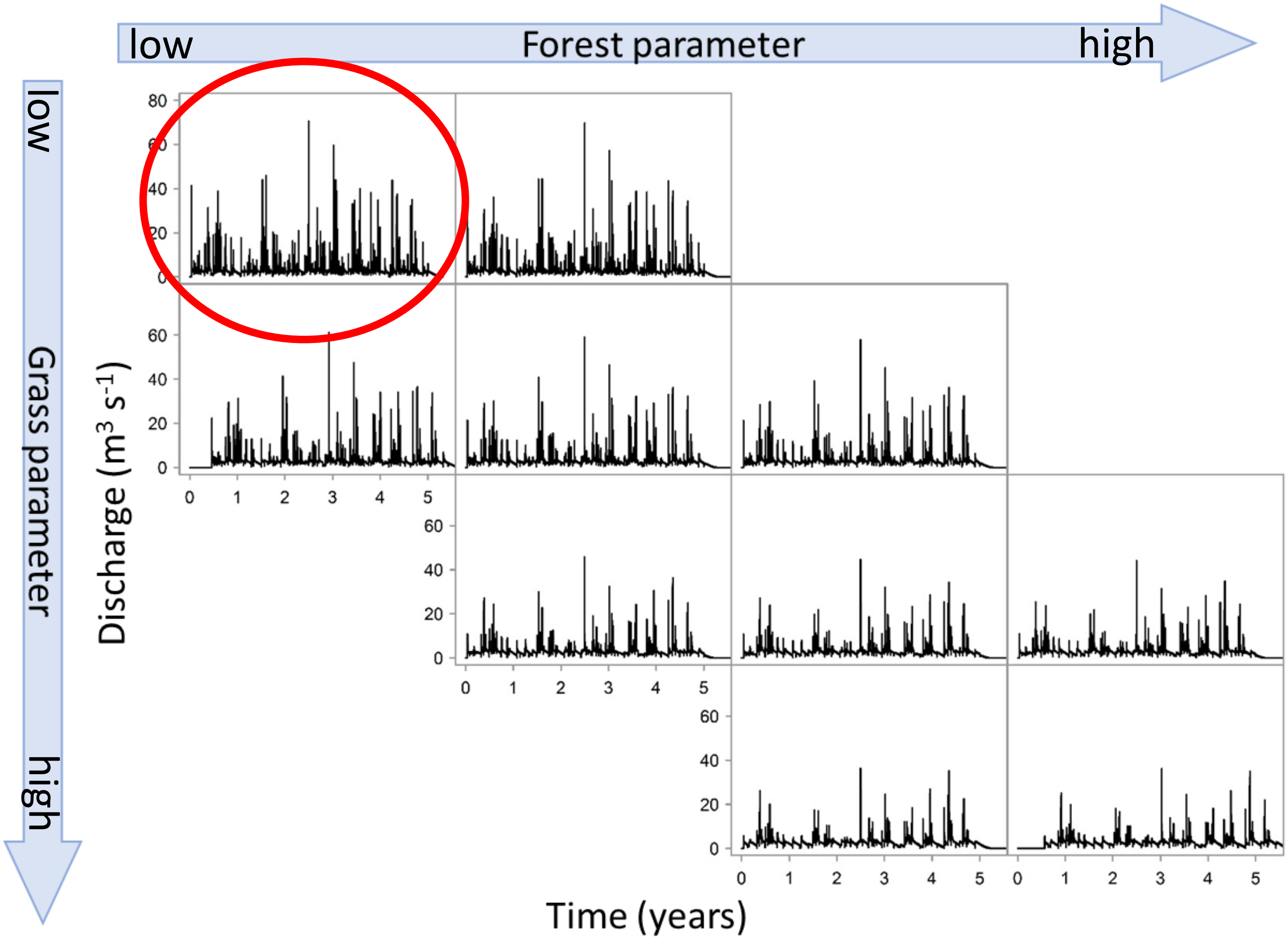


Hydrological calibration

UNIVERSITÄT BERN

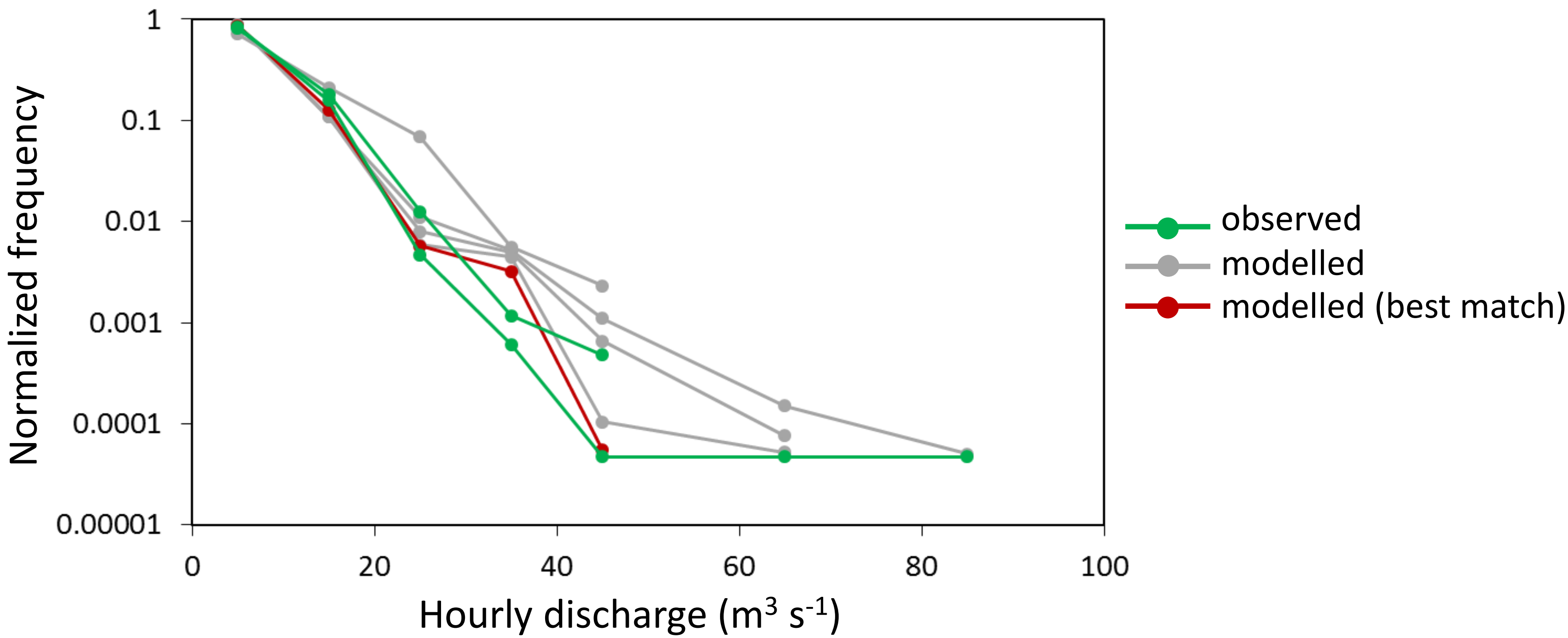
Higher parameter values is a **well vegetated catchment**, with high soil moisture storage, and **lower flood peaks**

Lower parameter values is a **sparsely vegetated catchment** and **flashier hydrological regimes**



Hydrological calibration

Hydrological calibration shows promising results, but is still in progress…

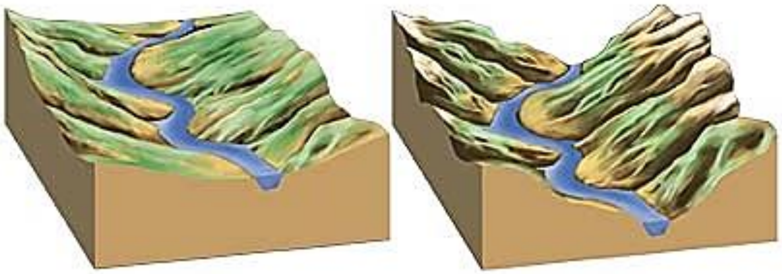


Reach scale model

UNIVERSITÄT BERN

Does a reach scale model respond to check dam failure?

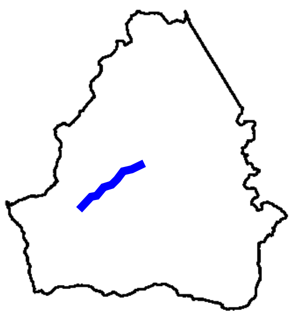
- examine channel changes after check dam failure (erosion and deposition)

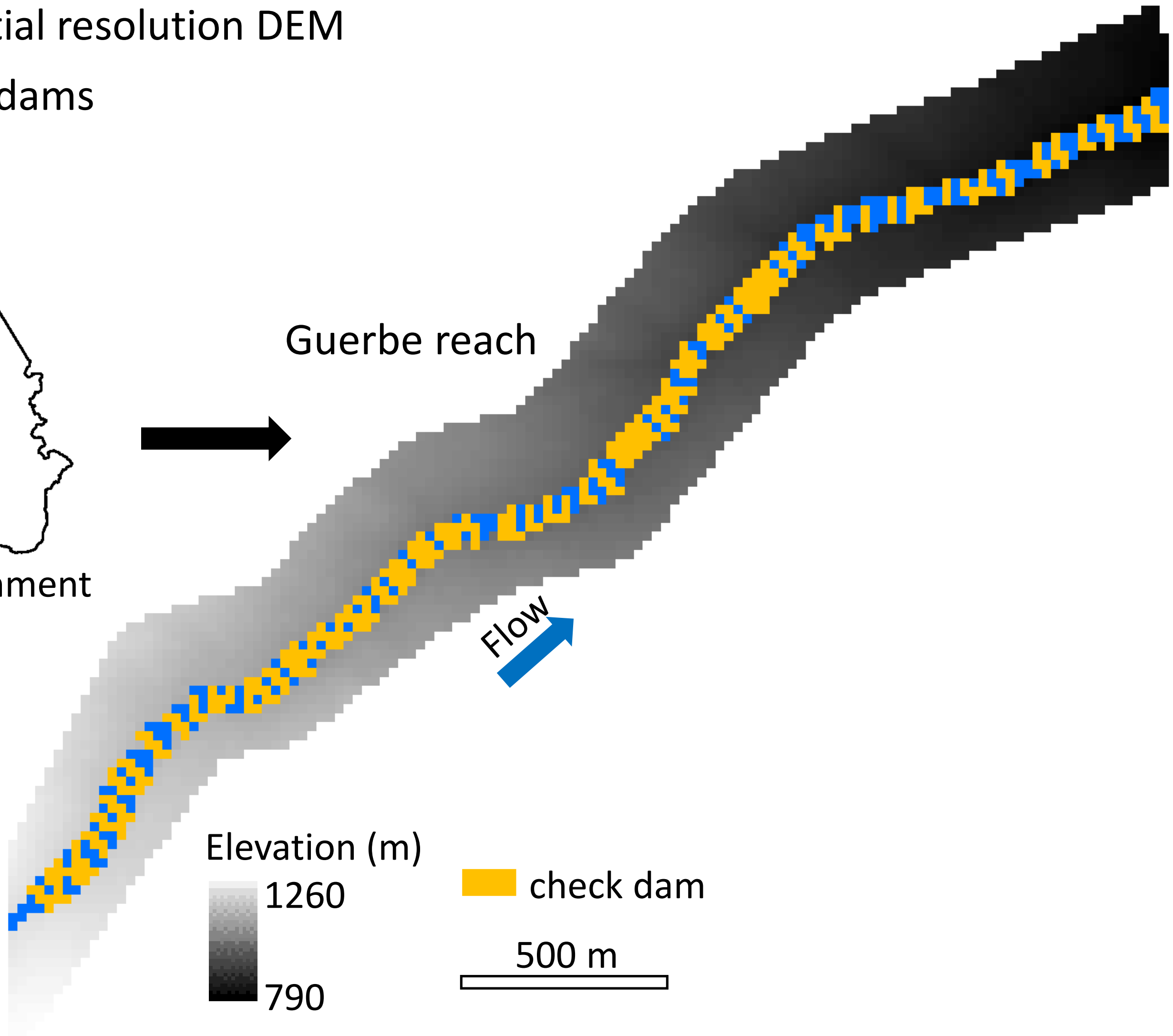


- examine the effect of check dam failure on sediment yield

Reach scale model

- 2.5 km
- 15 m spatial resolution DEM
- 73 check dams

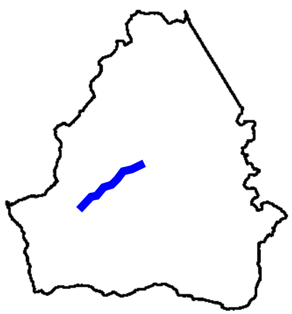


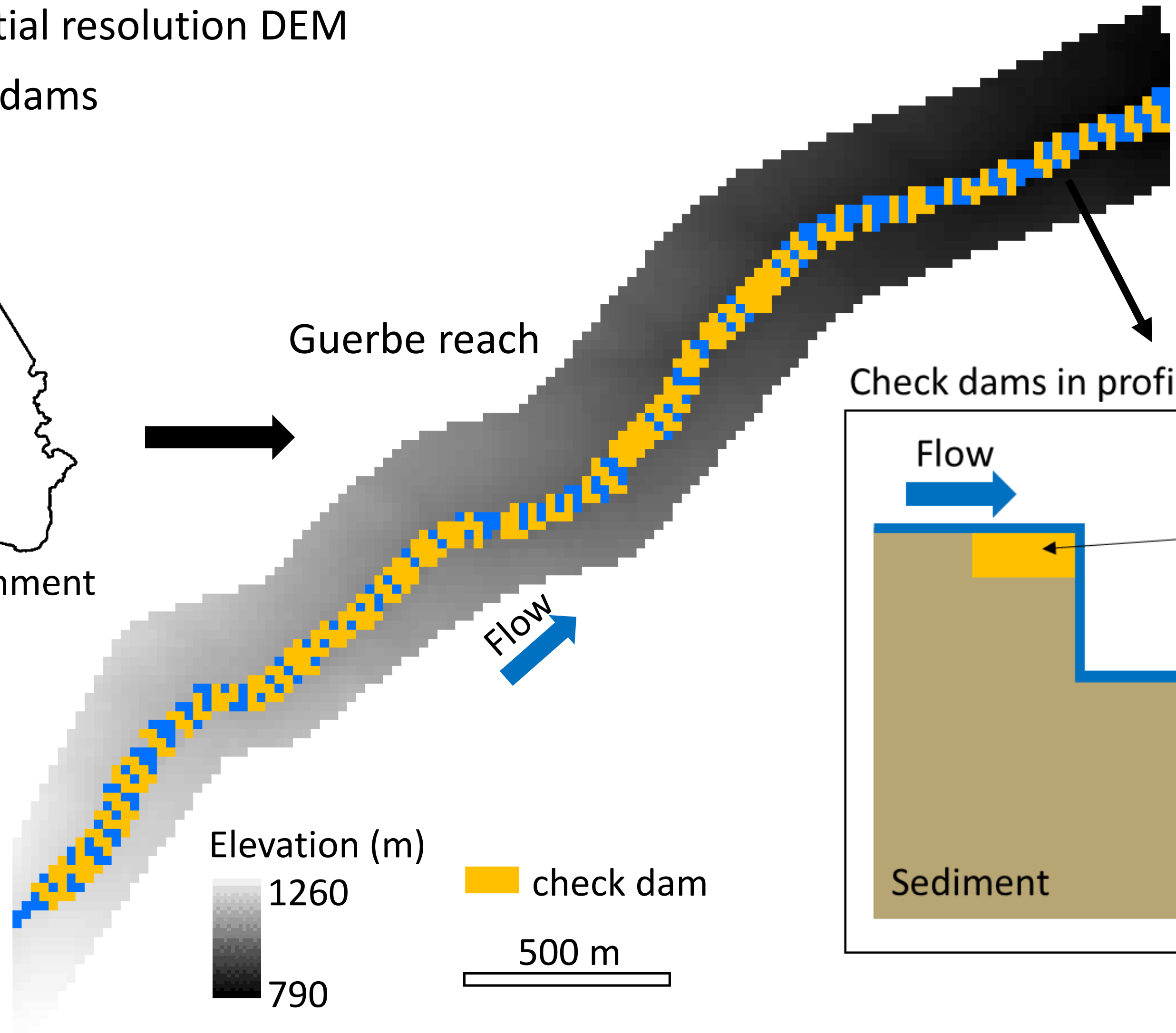


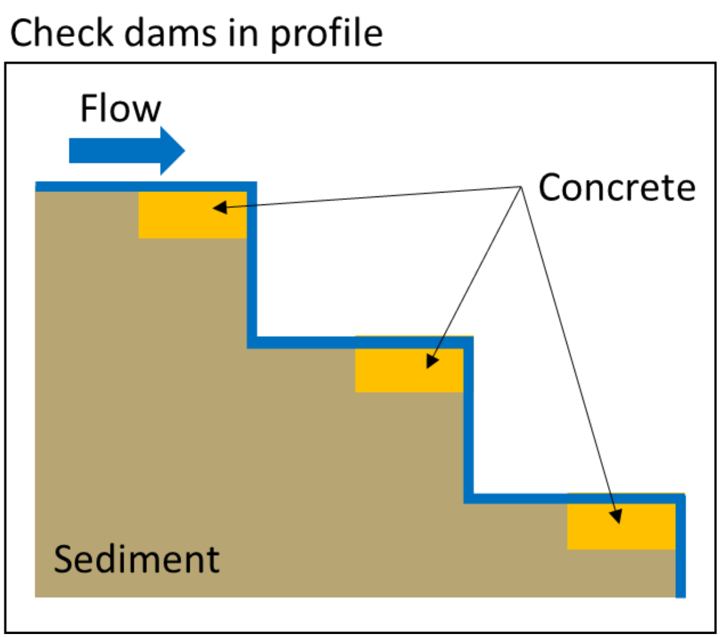
Reach scale model

UNIVERSITÄT BERN

- 2.5 km
- 15 m spatial resolution DEM
- 73 check dams

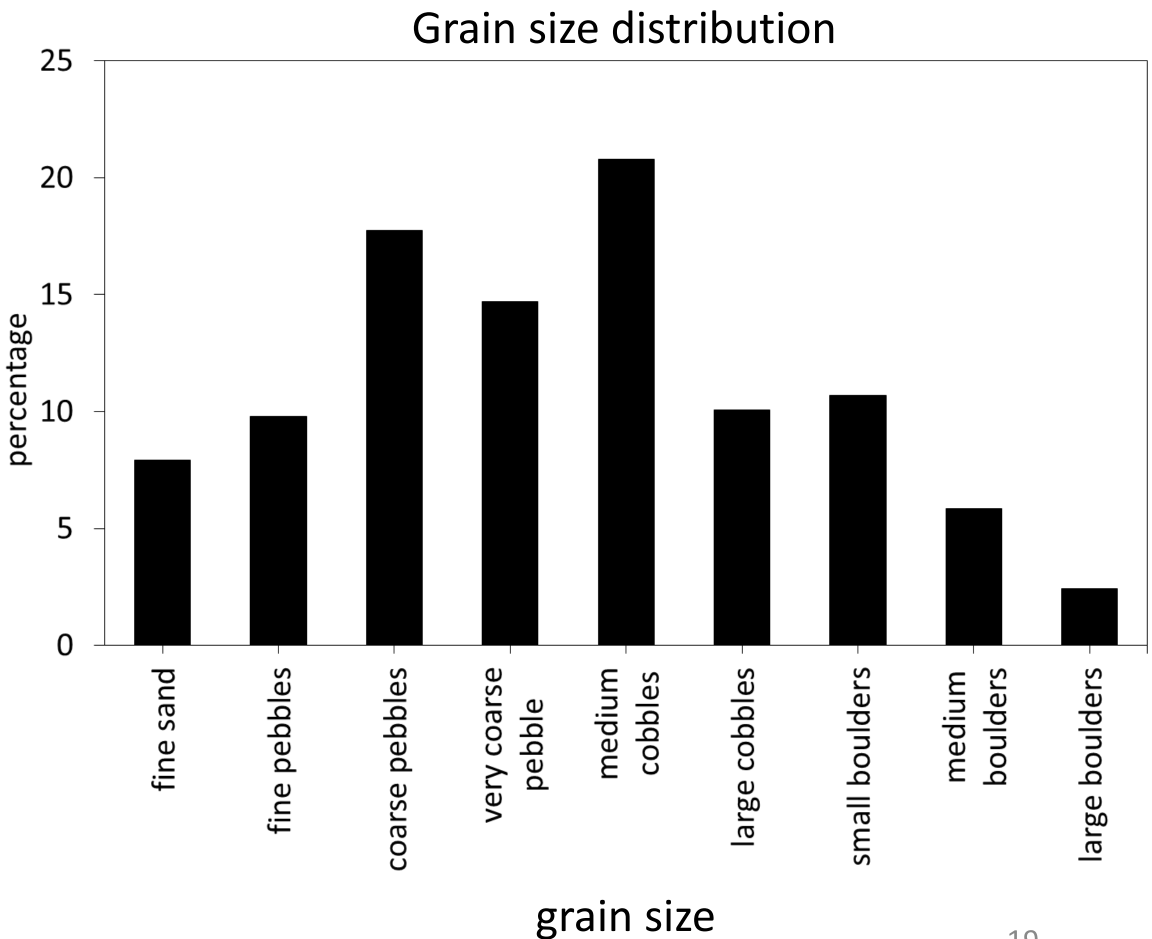






Grain size

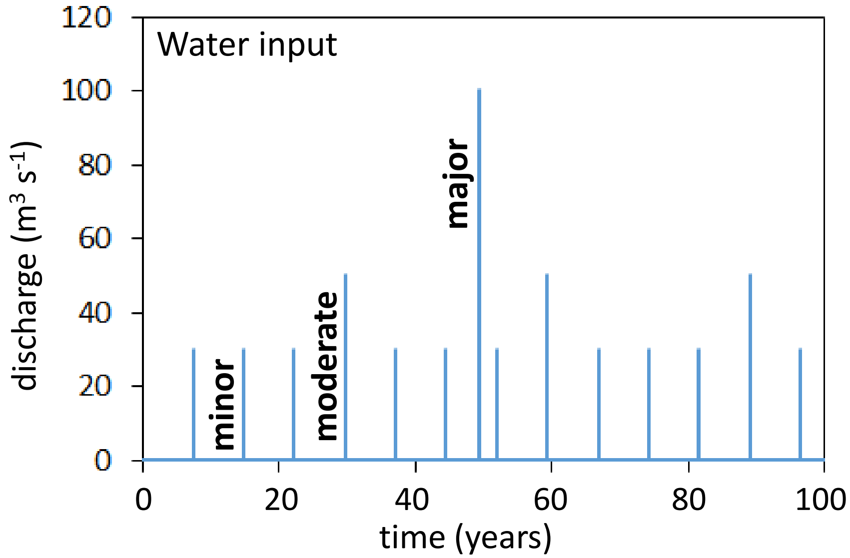
- 9 grain size classes (sand to boulder) were estimated through field methods
- Each gird cell in the model initially contains the same grainsize percentages

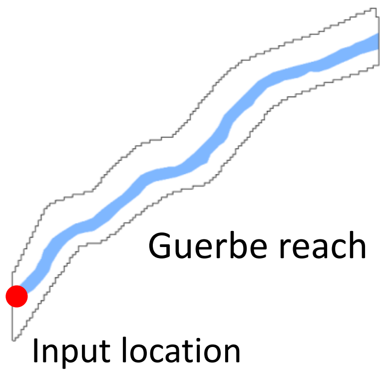


Synthetic discharge and sediment

UNIVERSITÄT BERN

- Hourly discharge
- Low flow: 0.25 $m^3 s^{-1}$
- Floods of 24 hrs duration, with peak discharge of:
  - **minor:** 30 $m^3 s^{-1}$
  - **moderate:** 50 $m^3 s^{-1}$
  - **major:** 100 $m^3 s^{-1}$

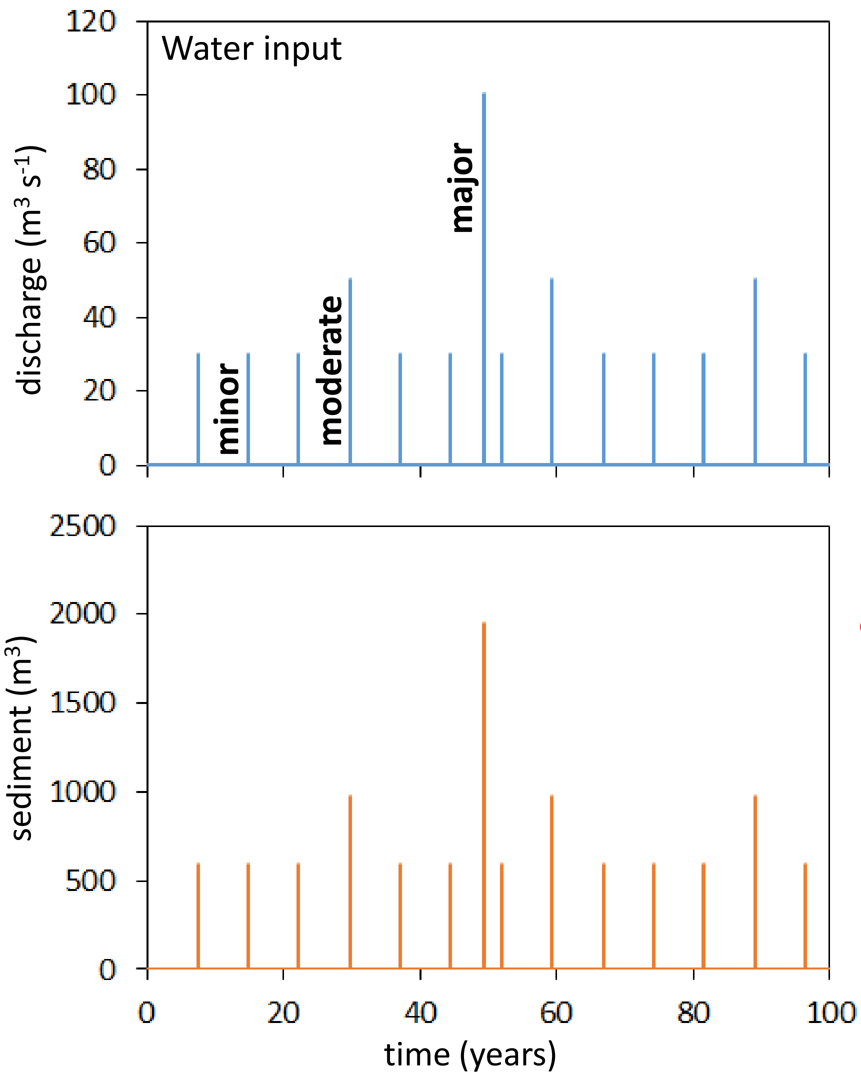


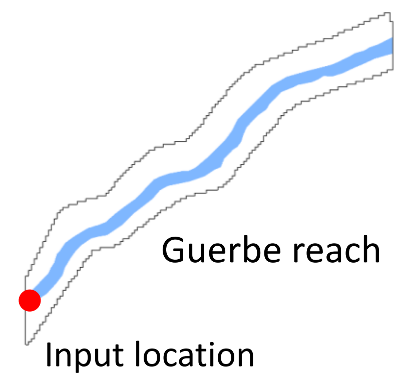


Synthetic discharge and sediment

UNIVERSITÄT BERN

- Hourly discharge
- Low flow: 0.25 $m^3\ s^{-1}$
- Floods of 24 hrs duration, with peak discharge of:
  - **minor:** 30 $m^3\ s^{-1}$
  - **moderate:** 50 $m^3\ s^{-1}$
  - **major:** 100 $m^3\ s^{-1}$

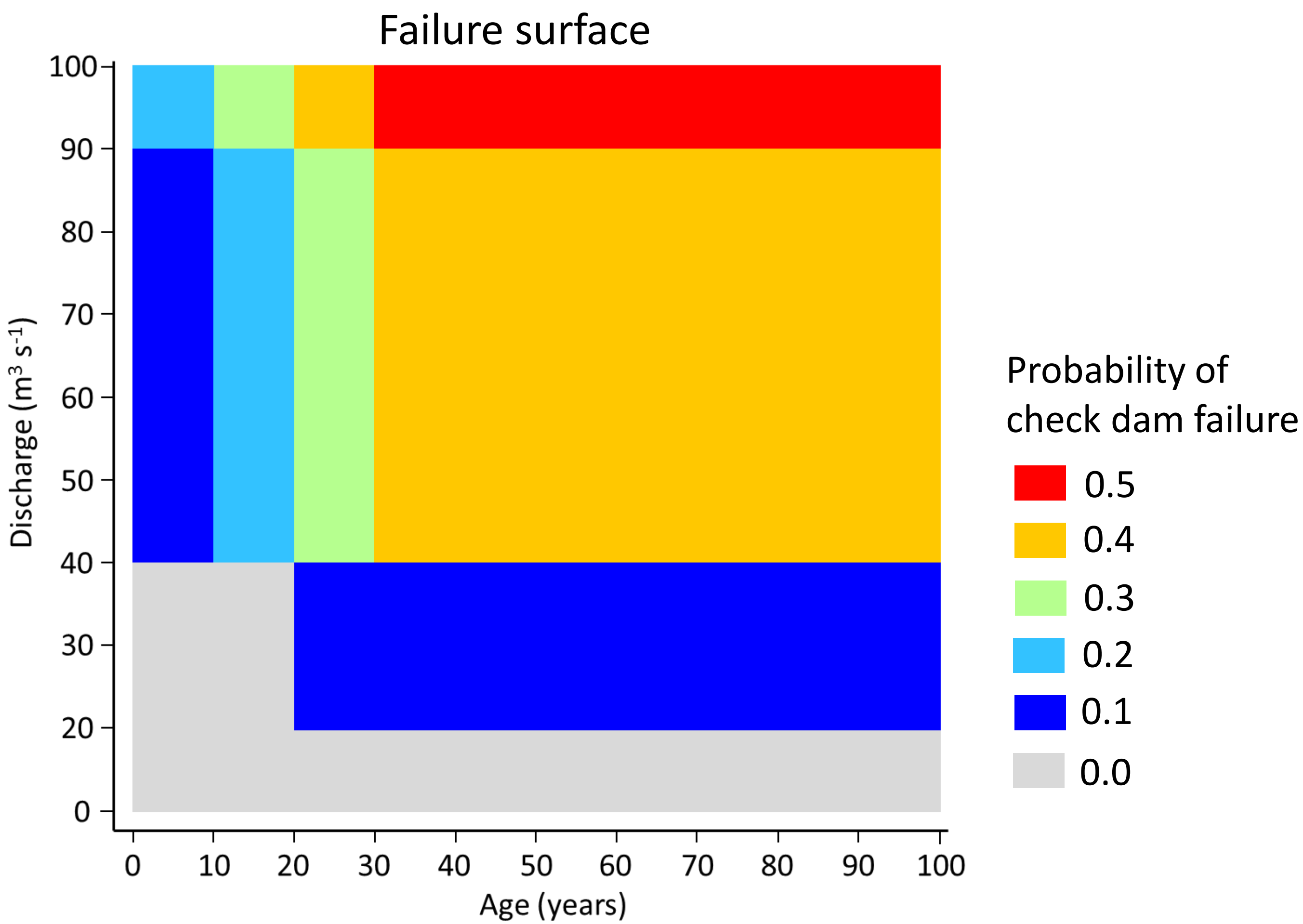




- Hourly sediment input
- Total annual sediment: 1300 m^3 (reach in equilibrium)
- Amounts of sediment were proportionally added over time based on the discharge that was above 5 $m^3\ s^{-1}$

Check dam failure rules

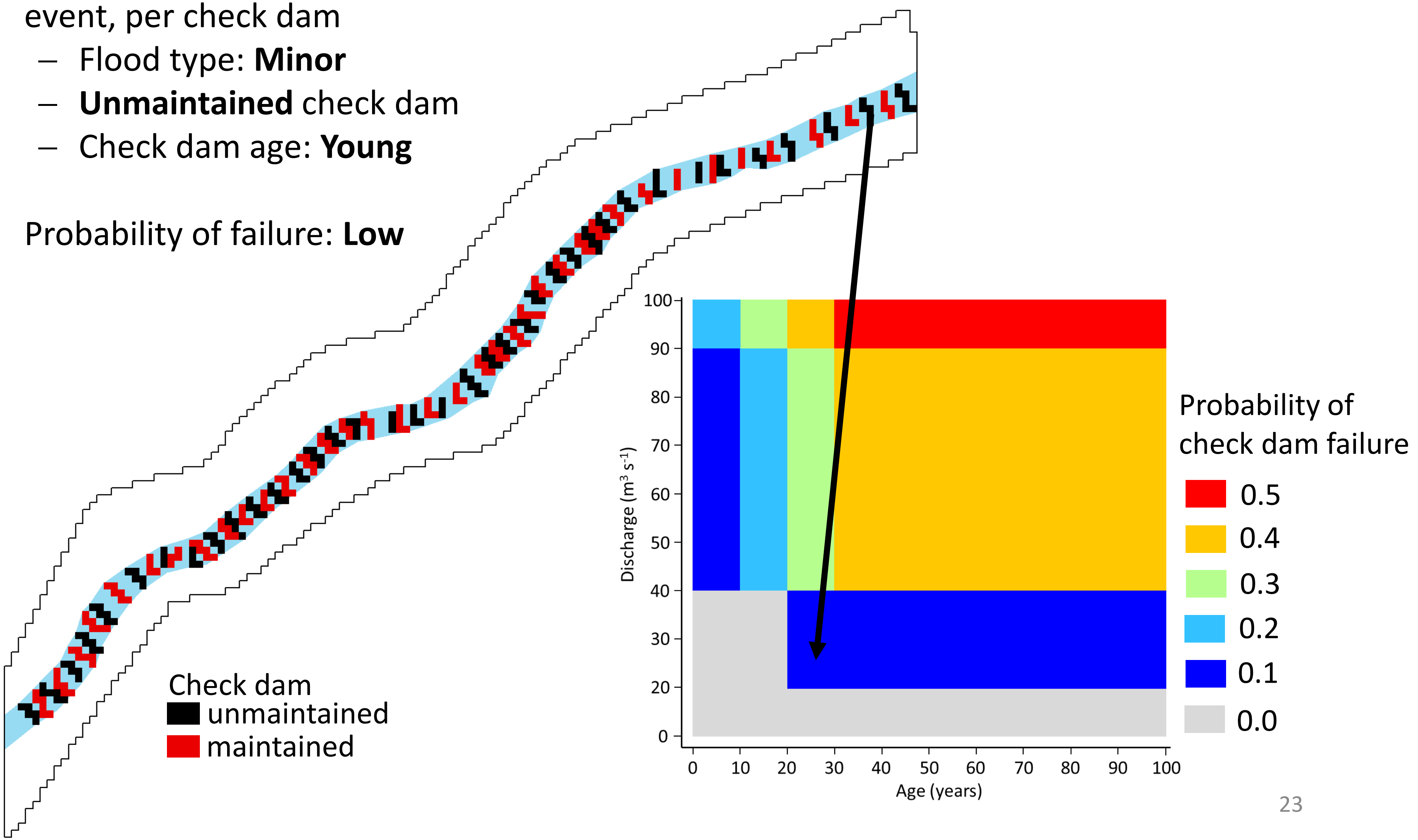
- Expert knowledge used to develop rules
- Check dam failure is determined through a combination of **check dam age** and **discharge**
- Maintained check dams do not fail



Check dam failure rules

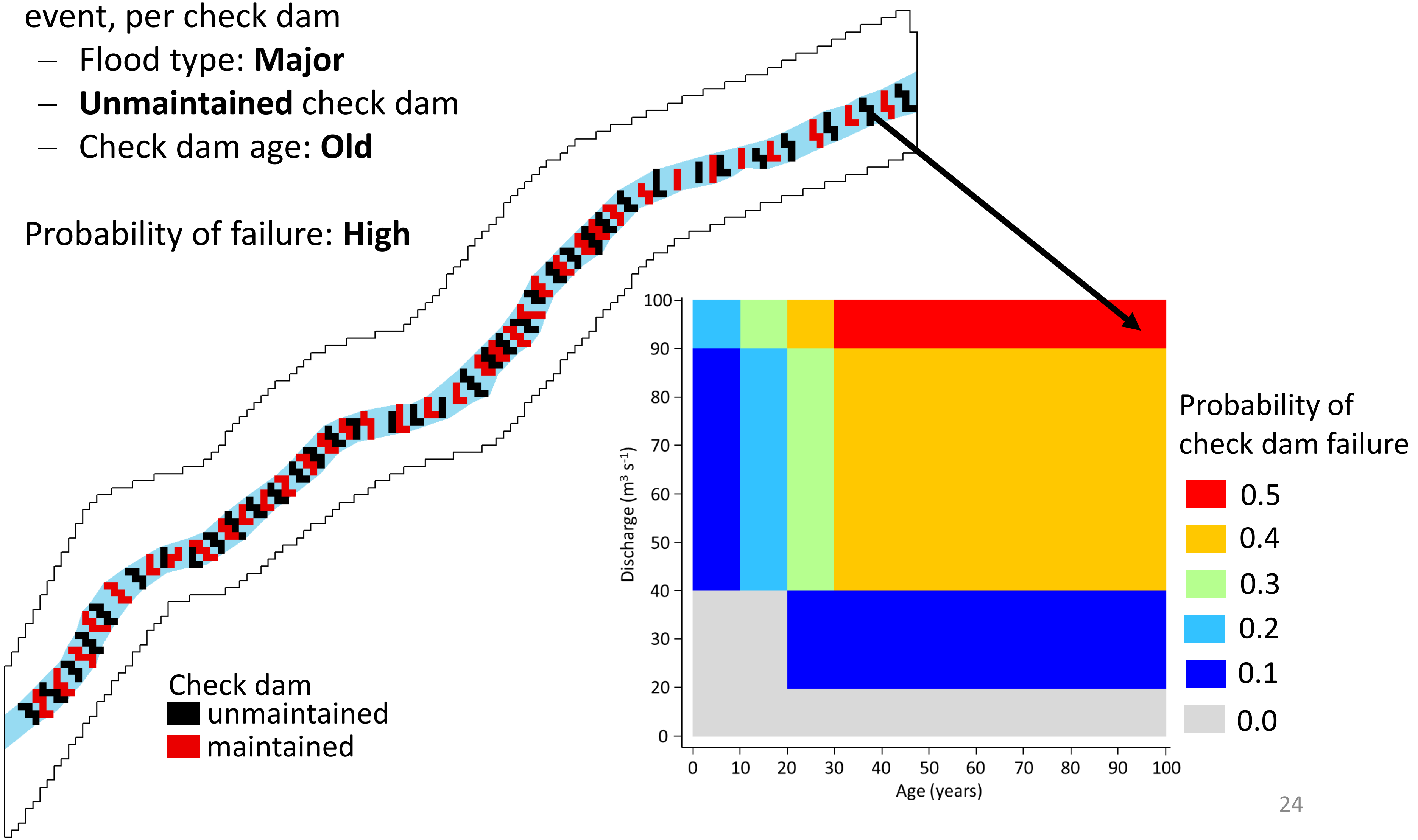
UNIVERSITÄT BERN

- Failure rules executed once per flood event, per check dam
  - Flood type: **Minor**
  - **Unmaintained** check dam
  - Check dam age: **Young**
- Probability of failure: **Low**

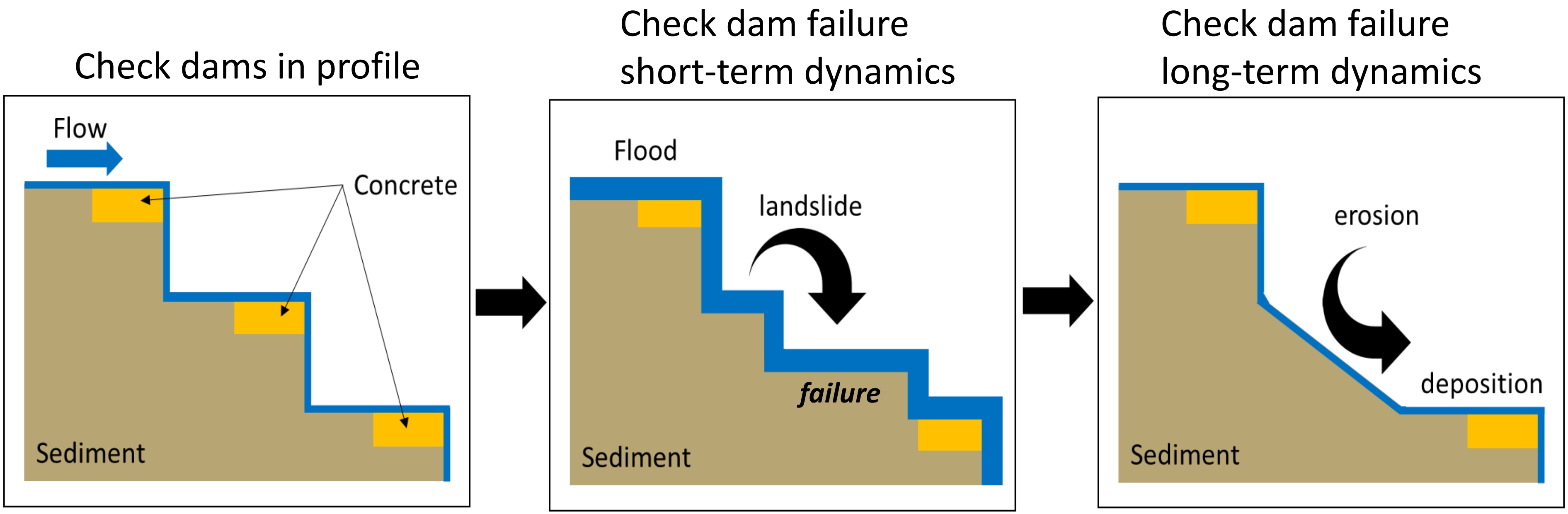


Check dam failure rules

- Failure rules executed once per flood event, per check dam
  - Flood type: **Major**
  - **Unmaintained** check dam
  - Check dam age: **Old**
- Probability of failure: **High**

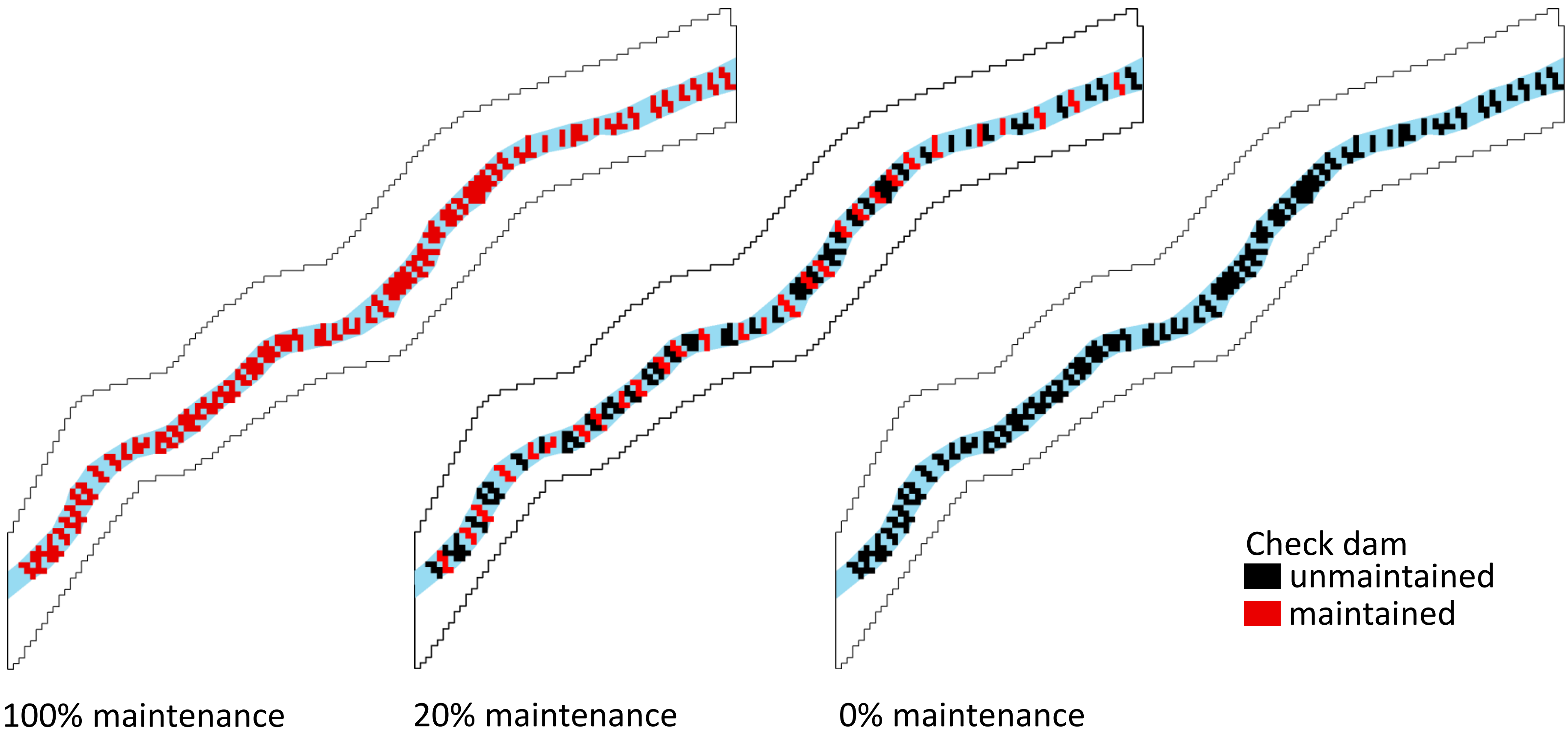


Check dam failure implementation



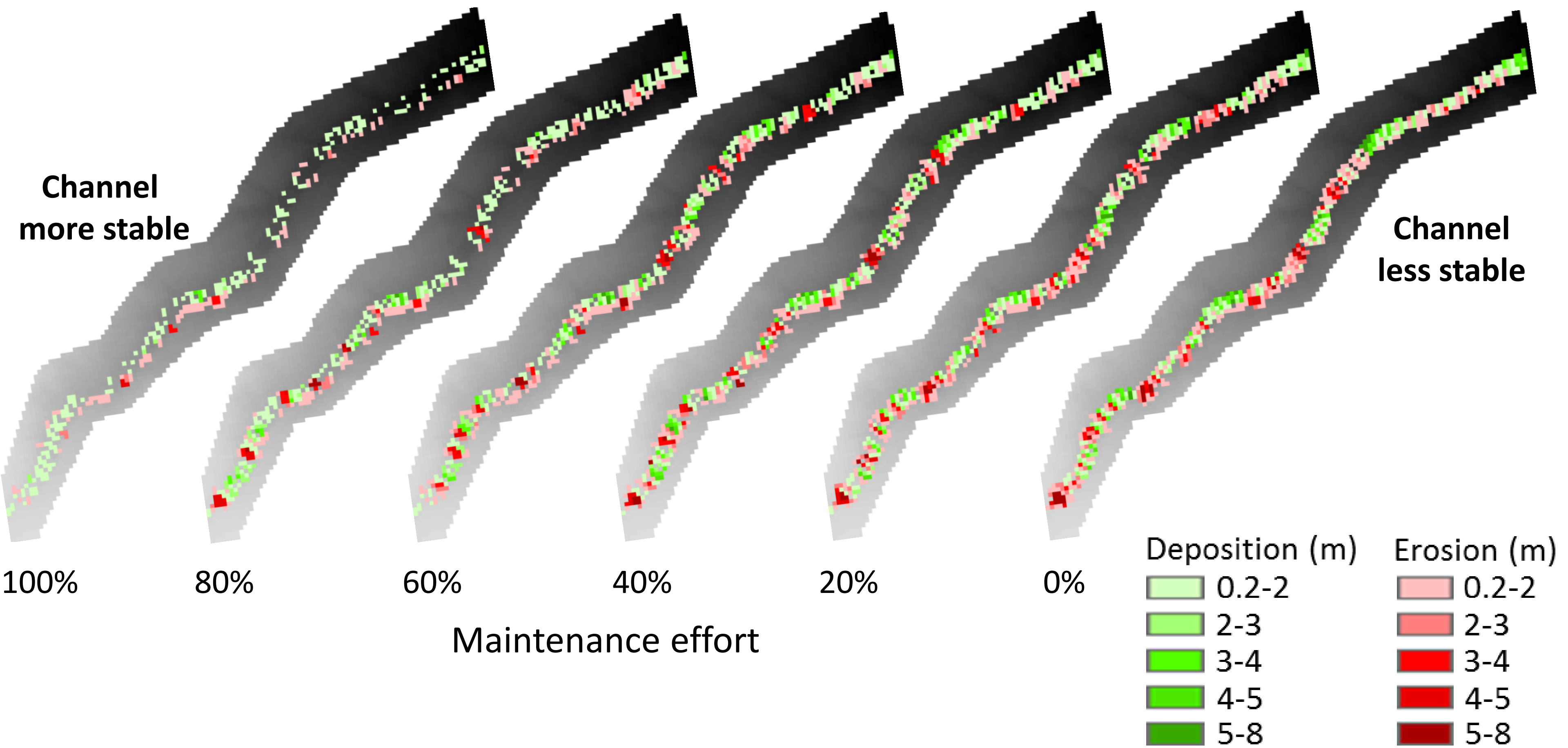
Check dam maintenance scenarios

- 6 scenarios trialed
- 0-100% maintenance effort in increments of 20%
- Maintained check dams selected in spatially equal intervals



Results: Channel change

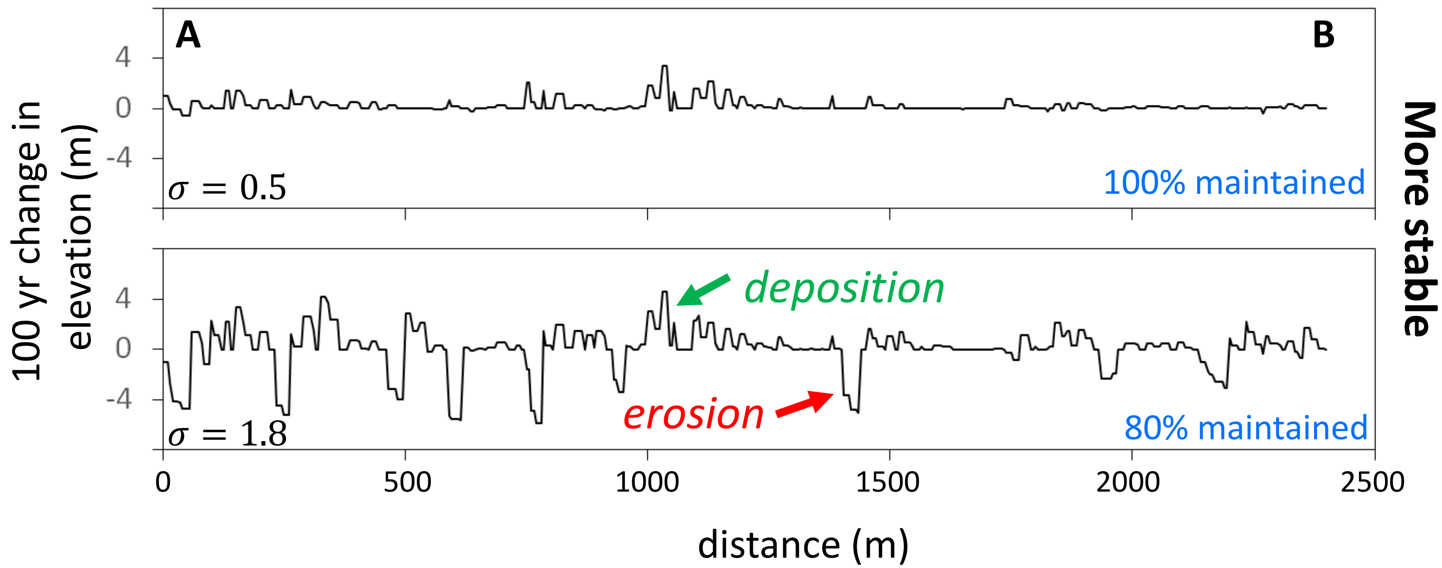
- Channel change = DEM year 0 – DEM year 100
- Major changes in channel elevation

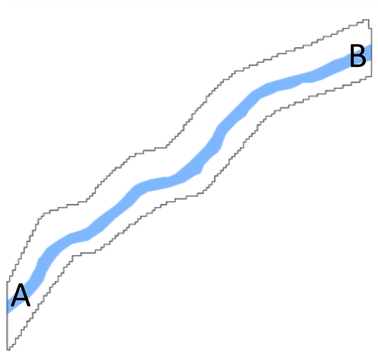


Results: Channel change

UNIVERSITÄT BERN

- Profiles of 100 years of channel change
- Check dams stabilize channel
- With less maintenance the channel become progressively less stable (standard deviation)

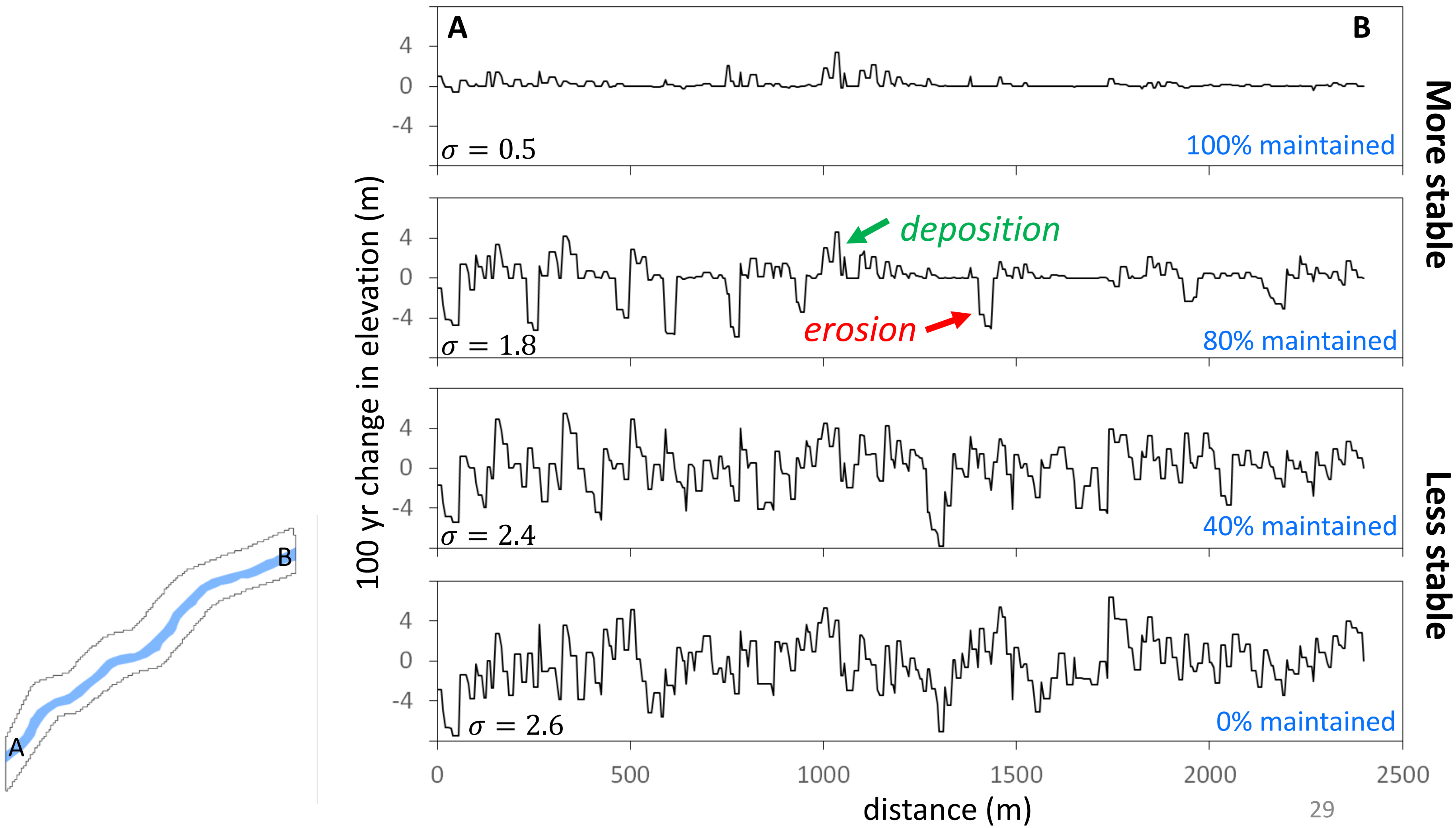




Results: Channel change

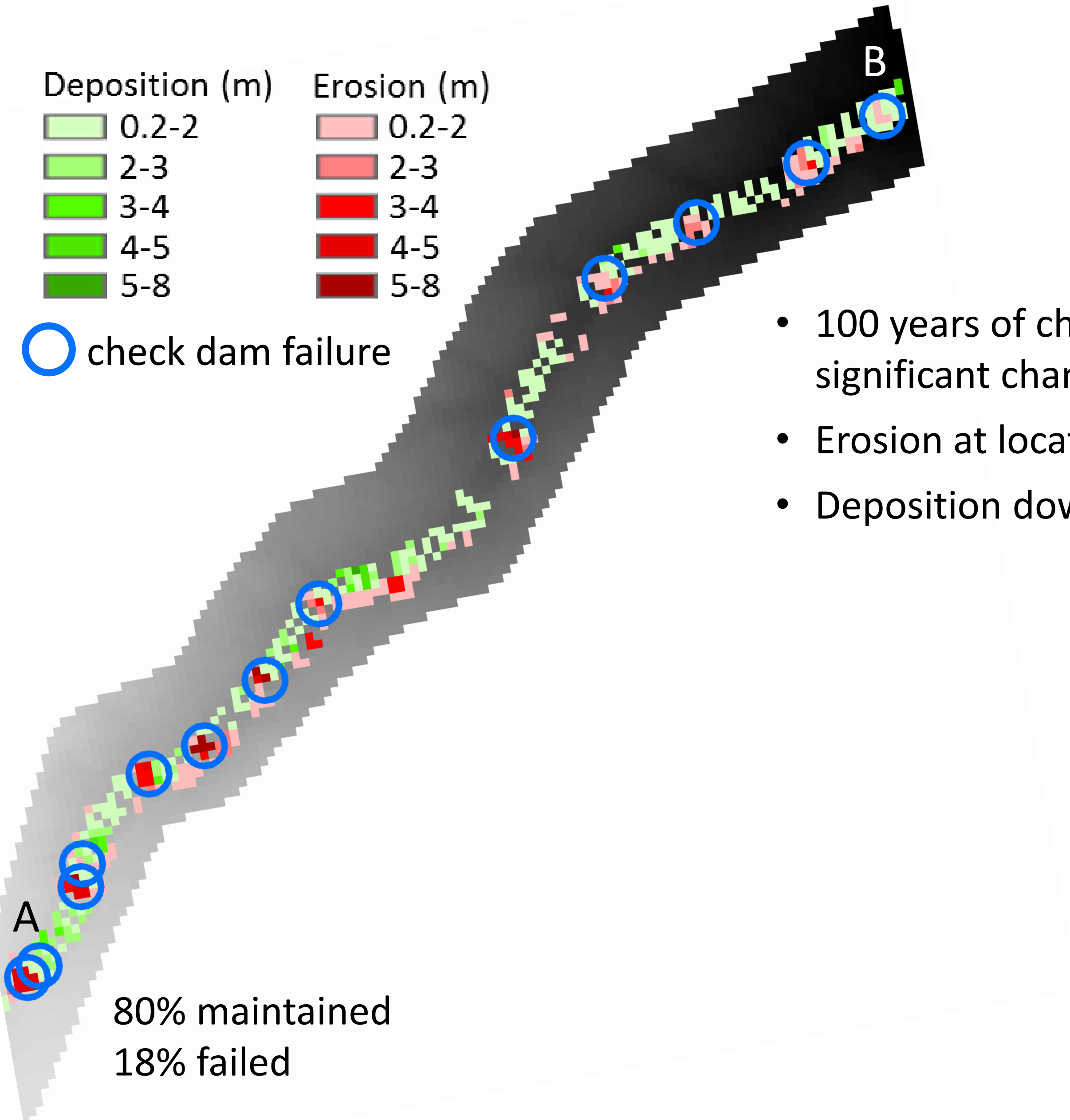
UNIVERSITÄT BERN

- Profiles of 100 years of channel change
- Check dams stabilize channel
- With less maintenance the channel become progressively less stable (standard deviation)



Results: Channel change

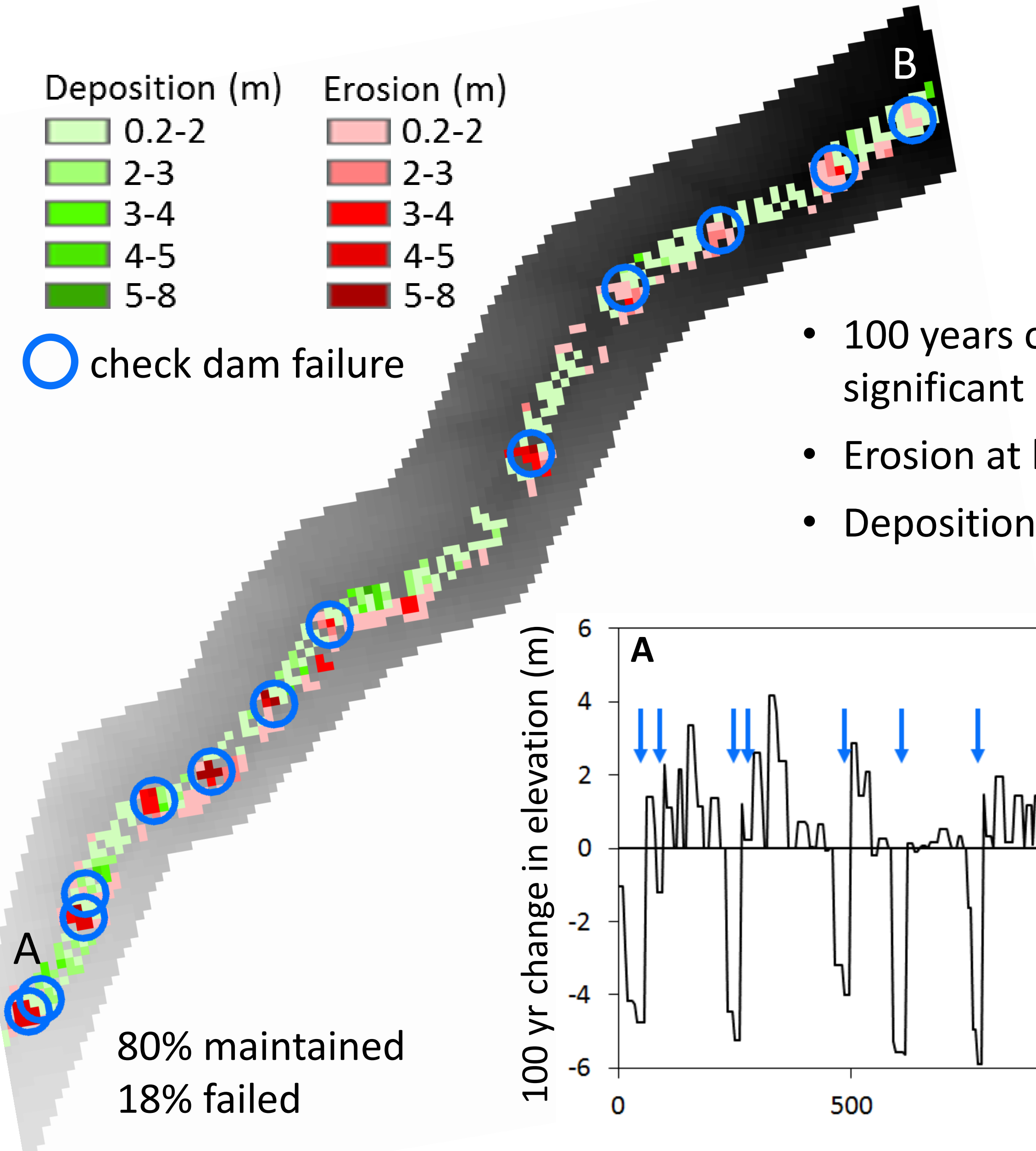
UNIVERSITÄT BERN



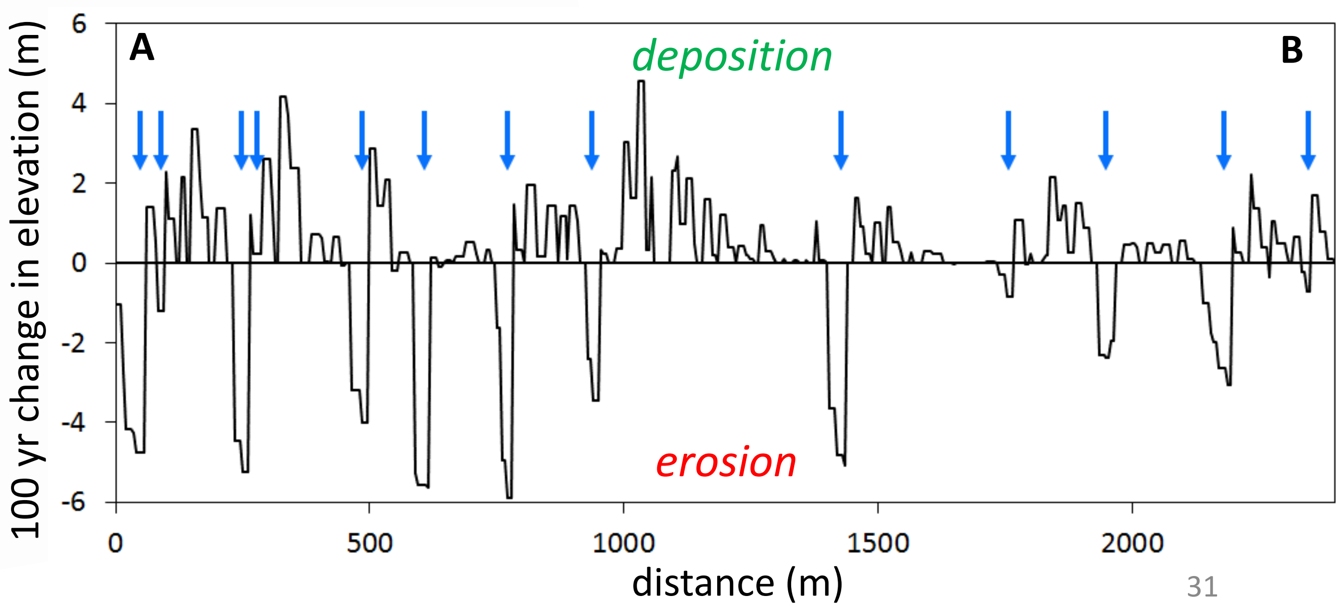
- 100 years of check dam failure produces significant channel changes
- Erosion at location of check dam failure
- Deposition downstream from check dam failure

Results: Channel change

UNIVERSITÄT BERN



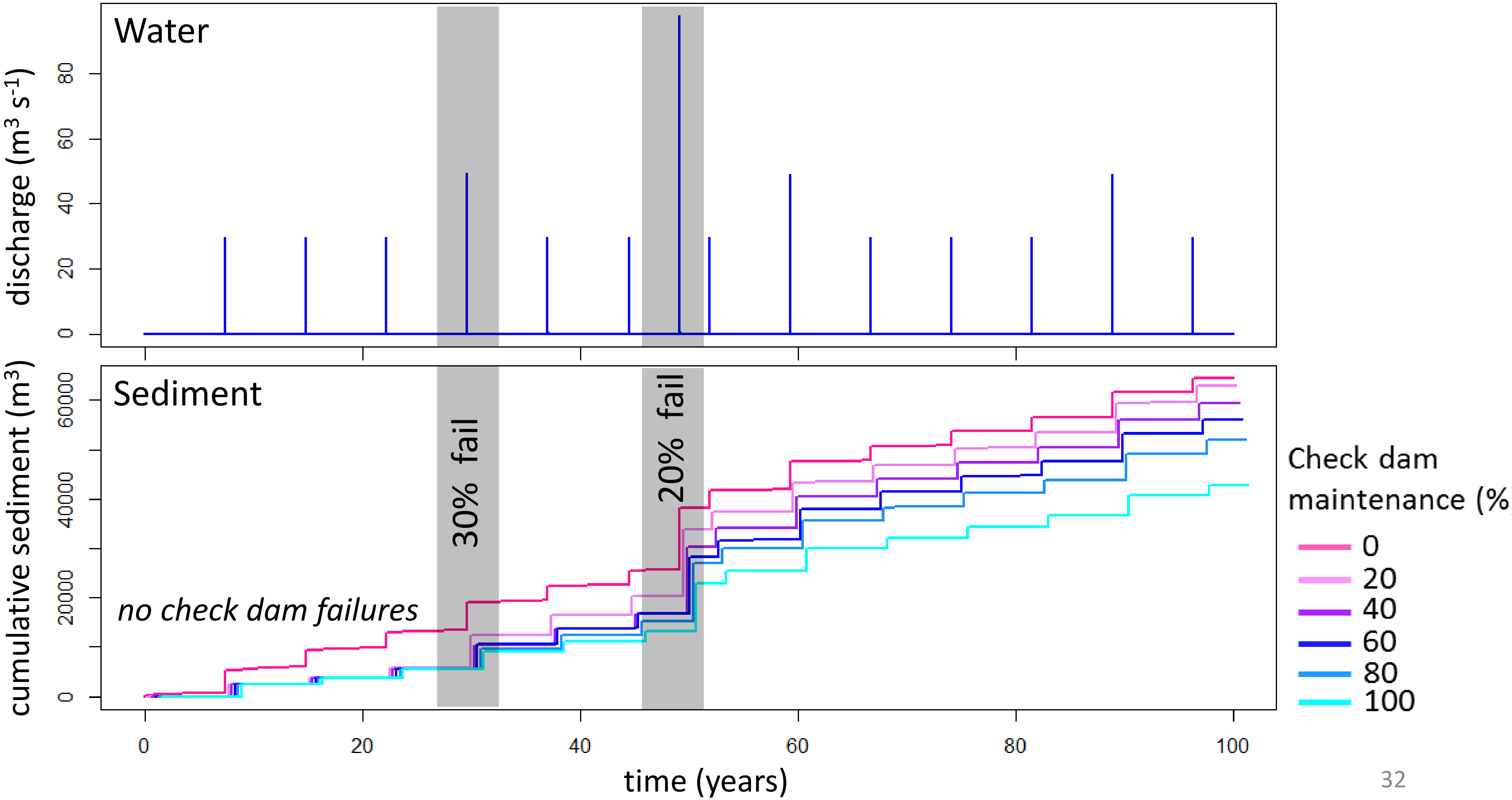
- 100 years of check dam failure produces significant channel changes
- Erosion at location of check dam failure
- Deposition downstream from check dam failure



Results: Sediment yield

UNIVERSITÄT BERN

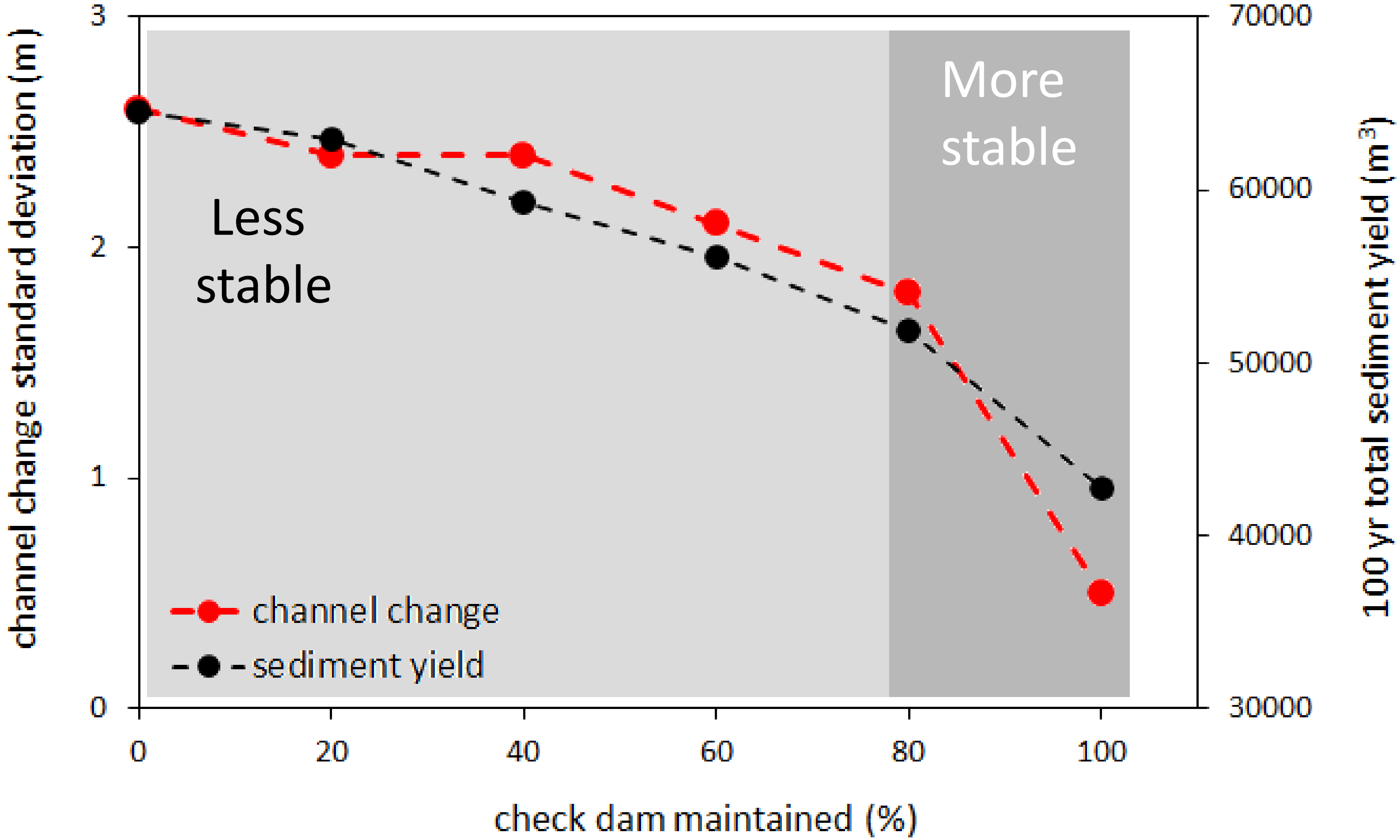
- Check dam maintenance has an effect on sediment yield
- First 20 years no check dam failures
- At two moments in time, check dam failures produce changes in sediment yield



Results: Summary

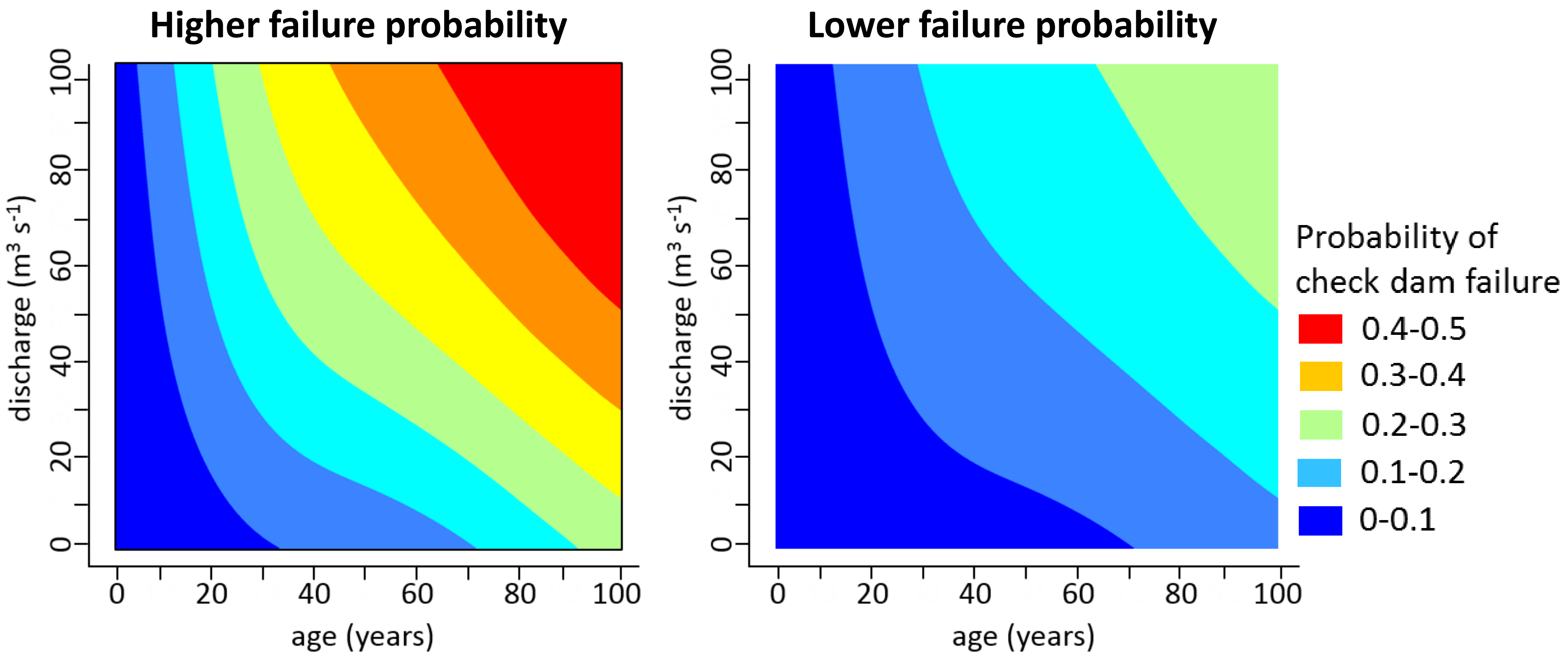
UNIVERSITÄT BERN

- 50% increase in sediment yield between 100% and 0% maintenance of check dams
- Channel change and sediment respond quickly to less check dam maintenance
- >80% of the check dams are needed to maintain a stable river



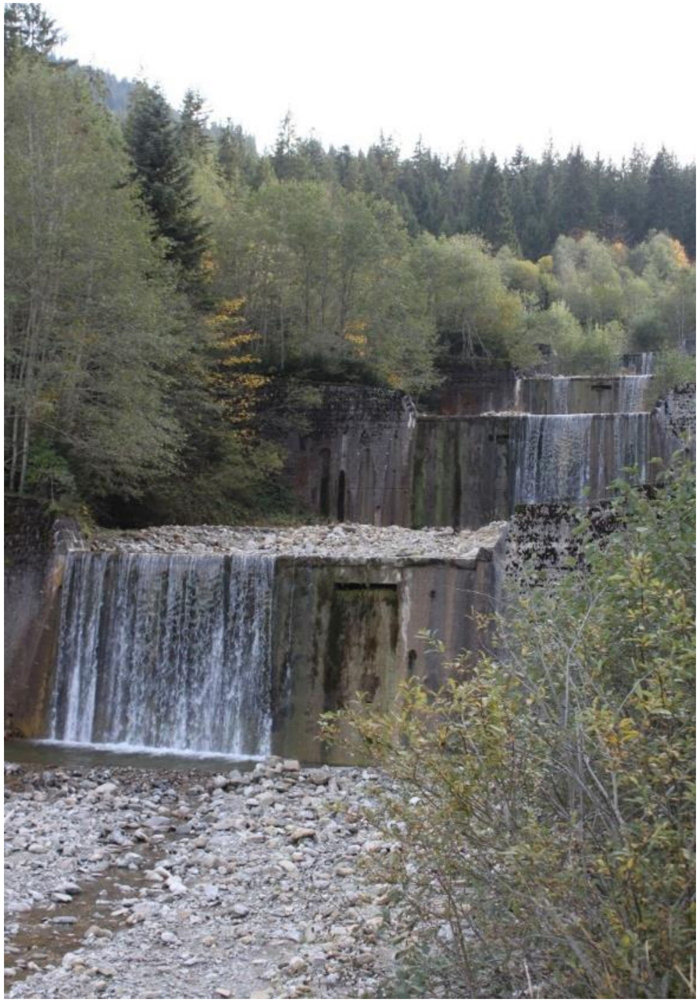
Future work

- Generate plausible discharge and sediment inputs for the reach
- Failure rules
  - Check dam failure is a combination of **age** and **discharge** on a continuous scale
  - Try different failure surfaces



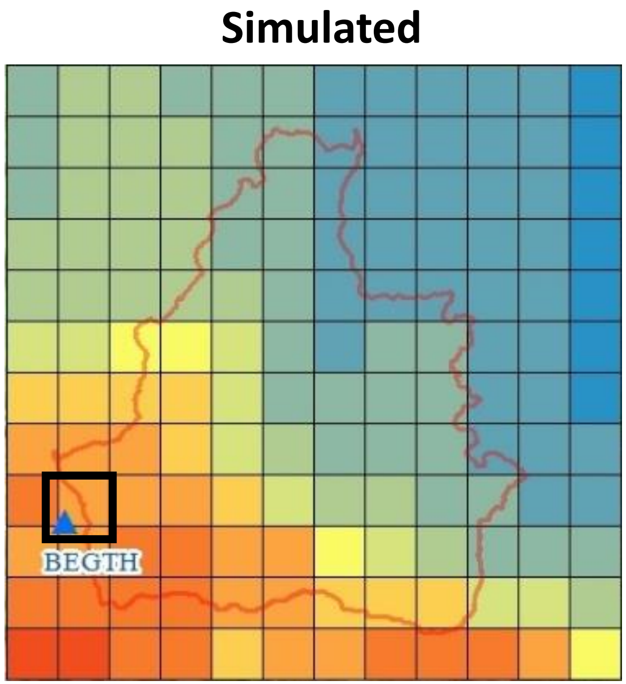
Discussion and Conclusions

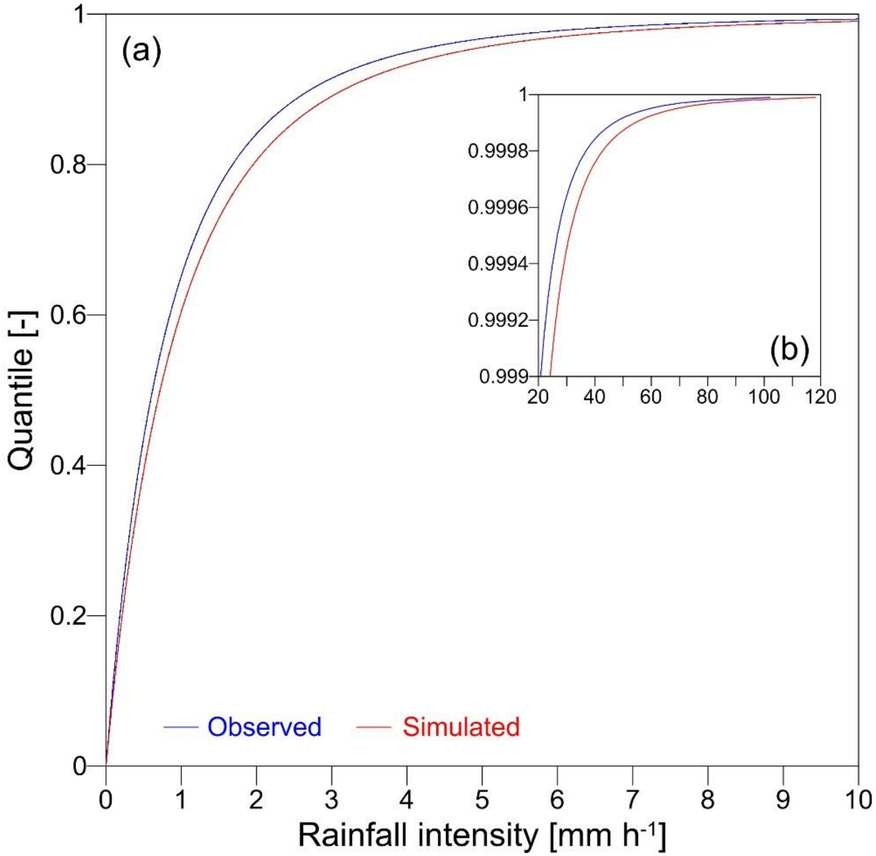
- What is the effect of climate change, including precipitation extremes, on check dam failure and geomorphic change?
- Are their phases in time when the reach is stable and unstable?
- What is the effect of model resolution (e.g. 5 m spatial resolution reach model)?
- The proof of concept model responds to check dam failure including **changes in channel elevation** and **sediment yield**
- Preliminary model results suggest that **more than 80%** of the check dams are needed to maintain a stable river



Backup slides

Modelled rainfall calibration

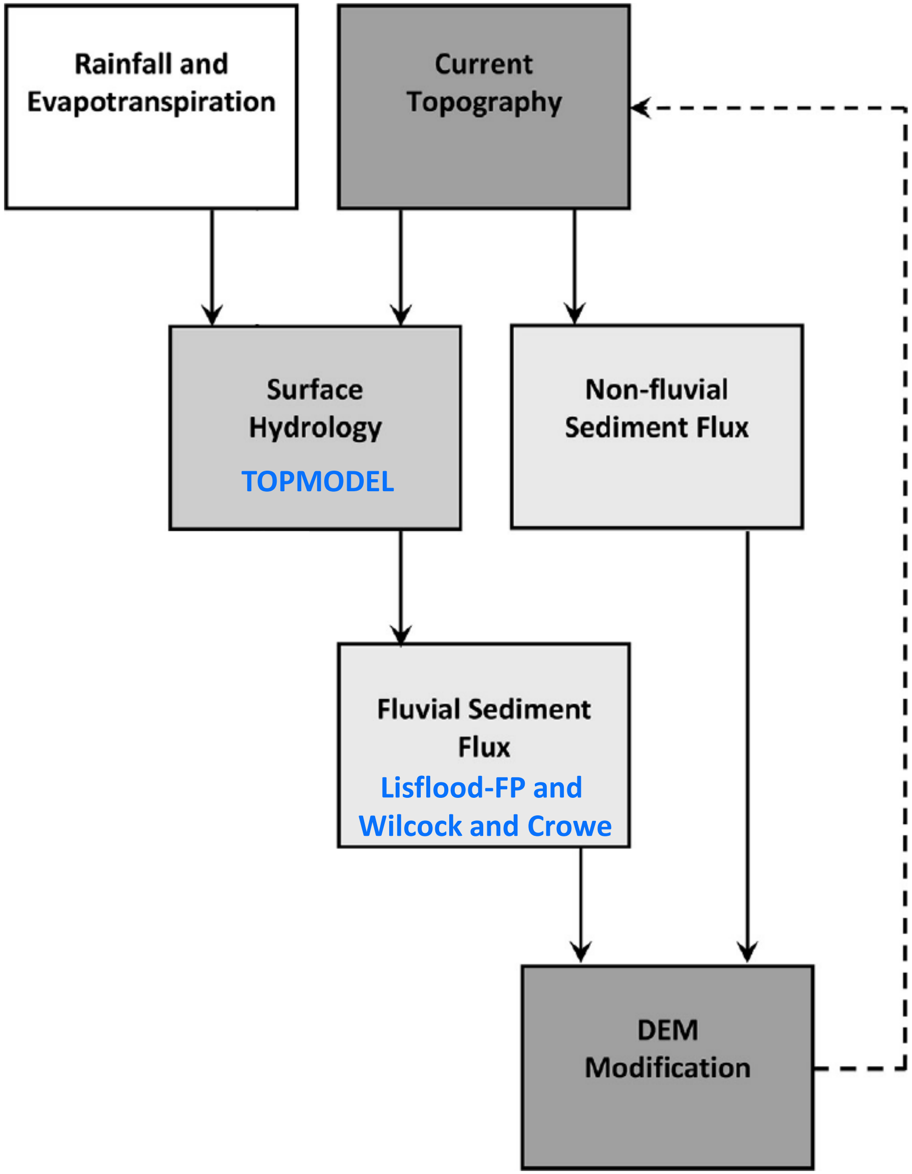




A comparison (CDF) of the observed hourly rainfall from the MeteoSwiss gauge (19-year) and the overlaying simulated grid cell (30-year).

CAESAR-Lisflood hydrology

UNIVERSITÄT BERN



TOPMODEL

calculate surface runoff (Q_{tot})

$$Q_{tot} = \frac{m}{T}\log\left(\frac{(r - j_t) + j_t \exp\left(\frac{rT}{m}\right)}{r}\right)$$

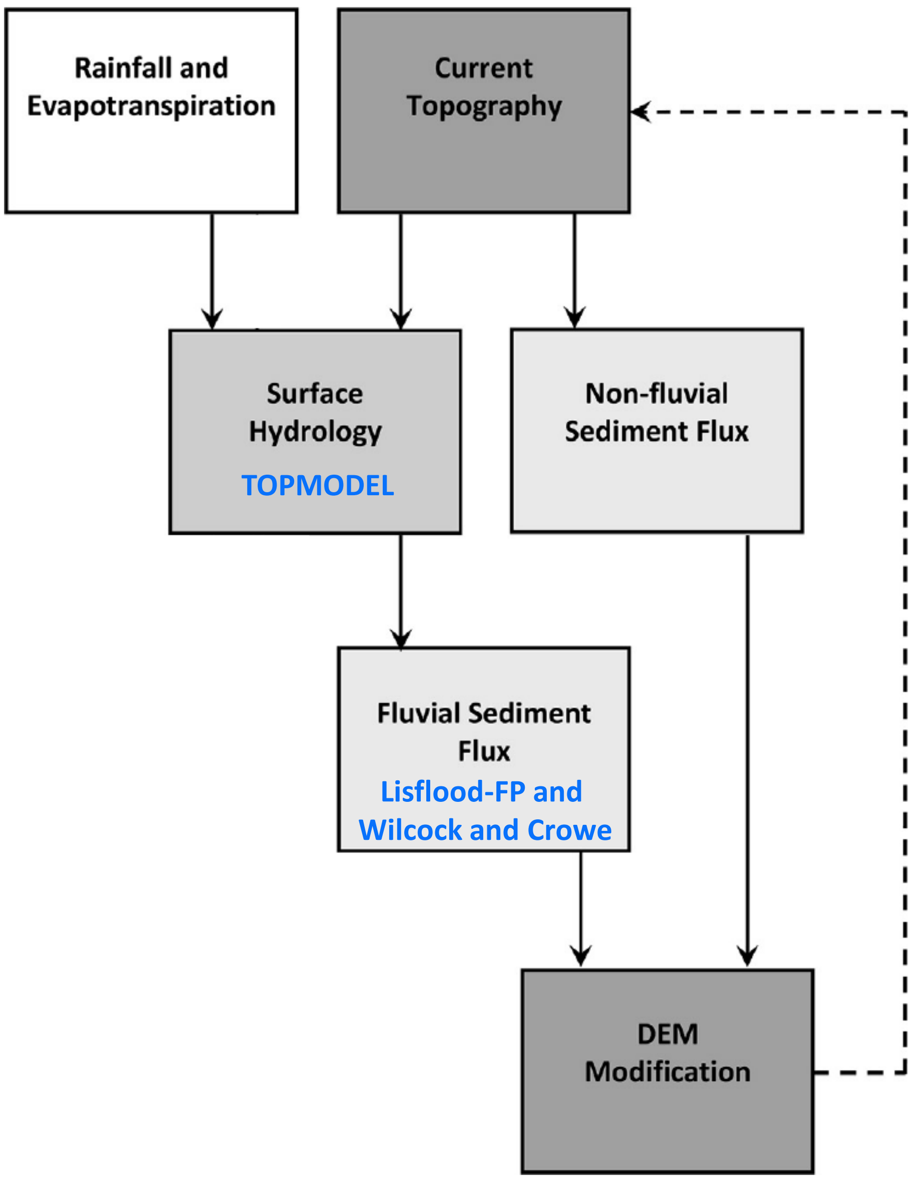
$$j_t = \frac{r}{\left(\frac{r - j_{t-1}}{j_{t-1}} \exp\left(\left(\frac{(0-r)T}{m}\right) + 1\right)\right)}$$

m is a user-defined parameter
j_t is the soil moisture store
$j_t - 1$ is the soil moisture store from the previous iteration
T is time
r is the rainfall rate

Barkwith et al. (2015), Coulthard et al (2013)

CAESAR-Lisflood hydraulics

UNIVERSITÄT BERN

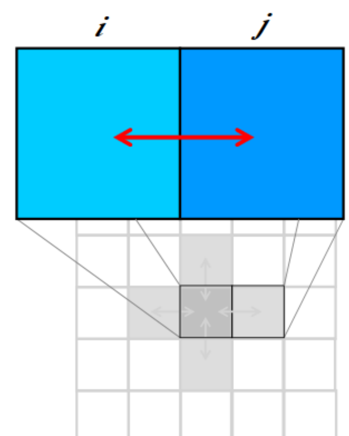


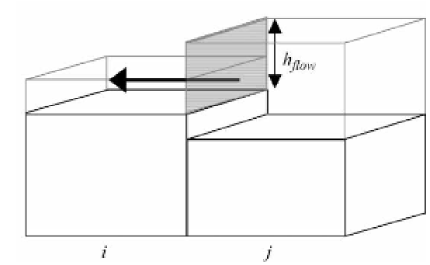
Lisflood-FP

calculate the flow (Q) between cells

$$Q = \frac{q - g h_{flow} \Delta t \frac{\Delta(h+z)}{\Delta x}}{\left(1 + g h_{flow} \Delta t n^2 |q| / h_{flow}^{10/3}\right)} \Delta x$$

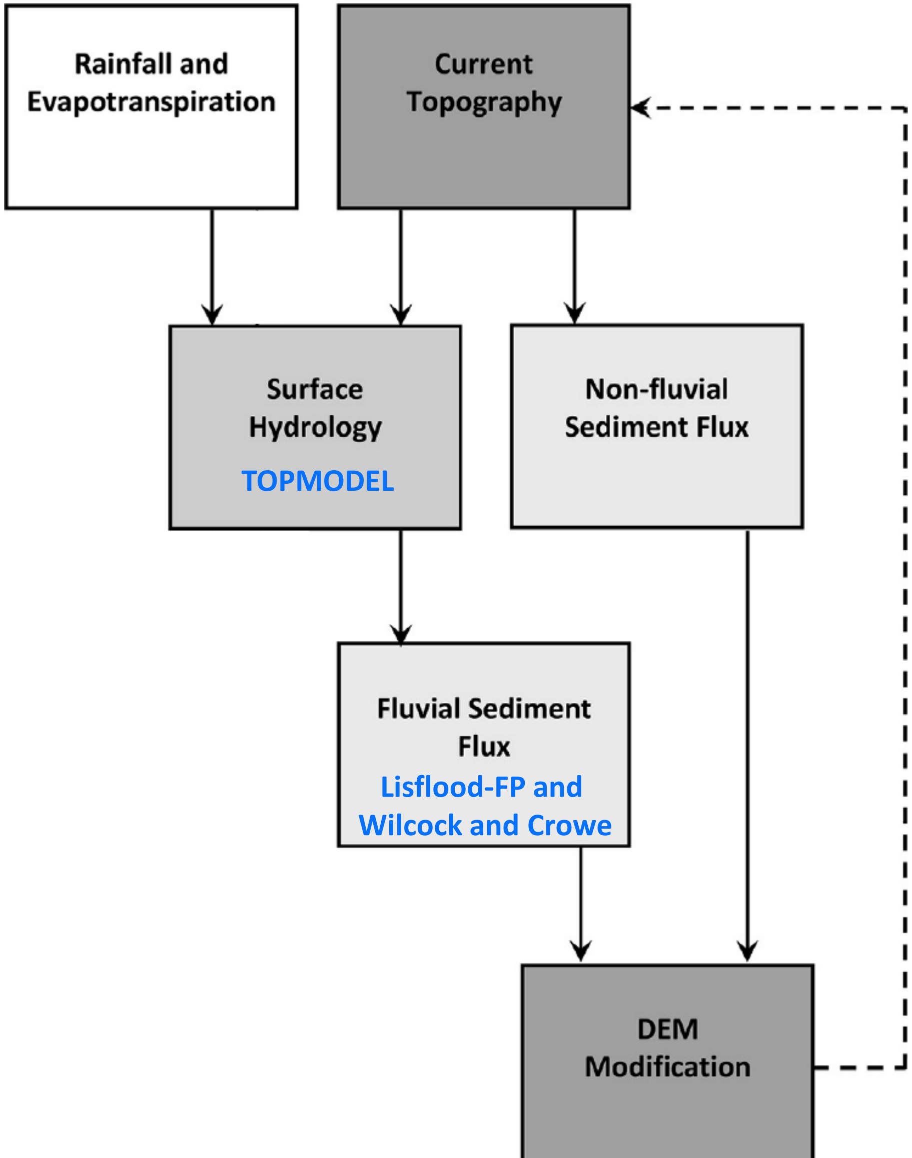
q is the flux between cells from the previous iteration ($m^2 s^{-1}$)
g is acceleration due to gravity ($m\ s^{-1}$)
n is Mannings roughness coefficient ($m^{1/3} s^{-1}$) h is depth (m)
z is elevation (m)
hflow is the maximum depth of flow between cells
x is the grid cell width (m)
t is time (s)





Barkwith et al. (2015), Coulthard et al (2013)

CAESAR-Lisflood sediment transport



Wilcock and Crowe

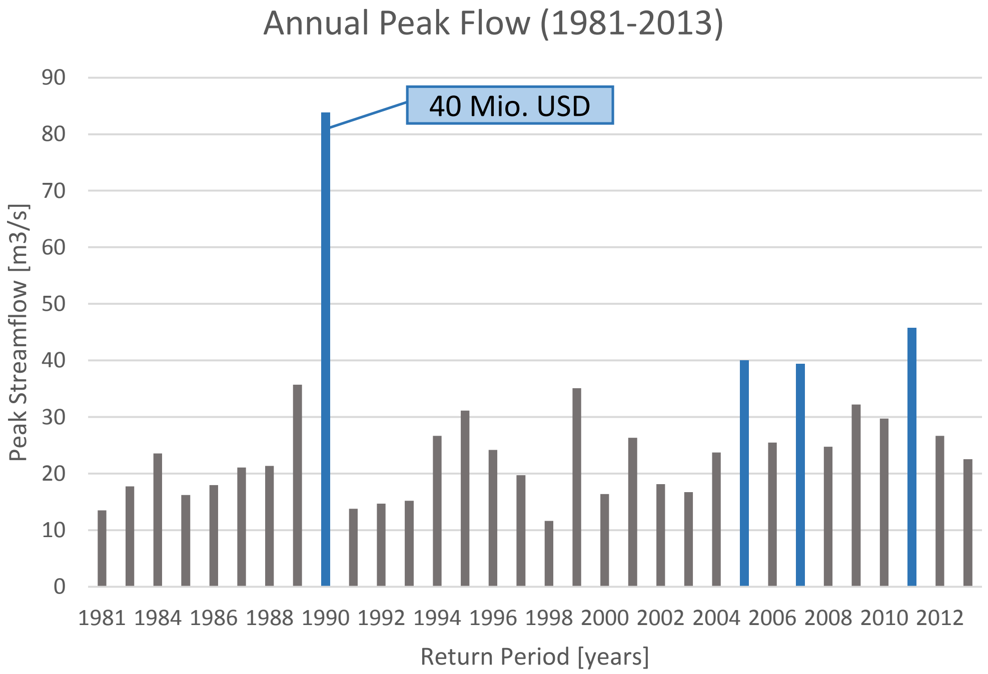
Sediment transport is driven by a mixed-size formula, which calculates transport rates, q_i, for each sediment fraction i

$$q_i = \frac{F_i U_*^3 W_i^*}{(s-1)g}$$

F_i denotes the fractional volume of the i-th sediment in the active layer
U* is the shear velocity
s is the ratio of sediment to water density
g denotes gravity
W_i* is a complex function that relates the fractional transport rate to the total transport rate

Barkwith et al. (2015), Wilcock and Crowe (2013)

Flood statistic for Guerbe, Burgistein



Return period [yrs]	Discharge [m3/s]	Confidence interval [m3/s]
2	24	19-29
10	44	39-49
30	56	51-61
100	69	64-74
300	80	75-85