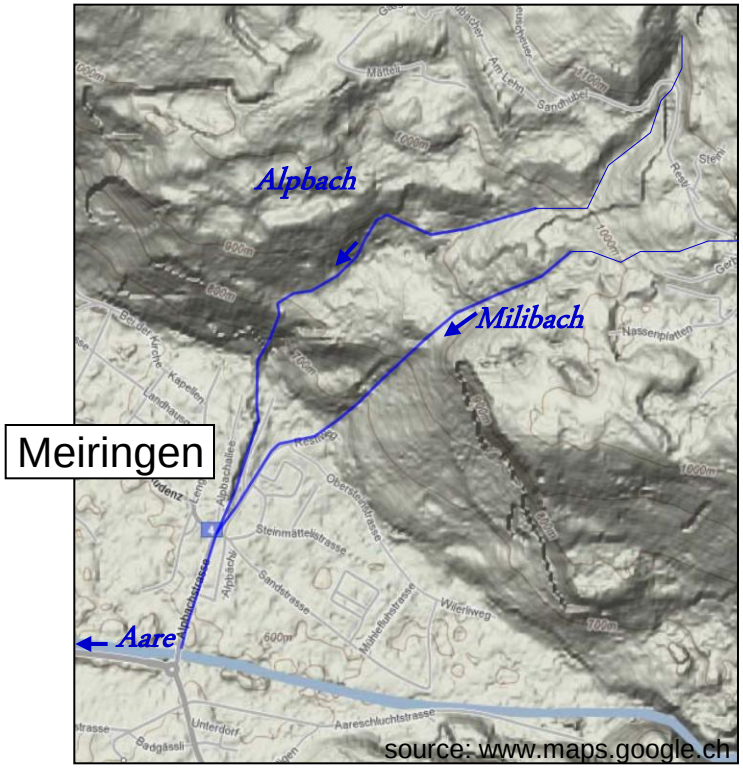
Bed load transport in a physical scale-model of two merging mountain streams



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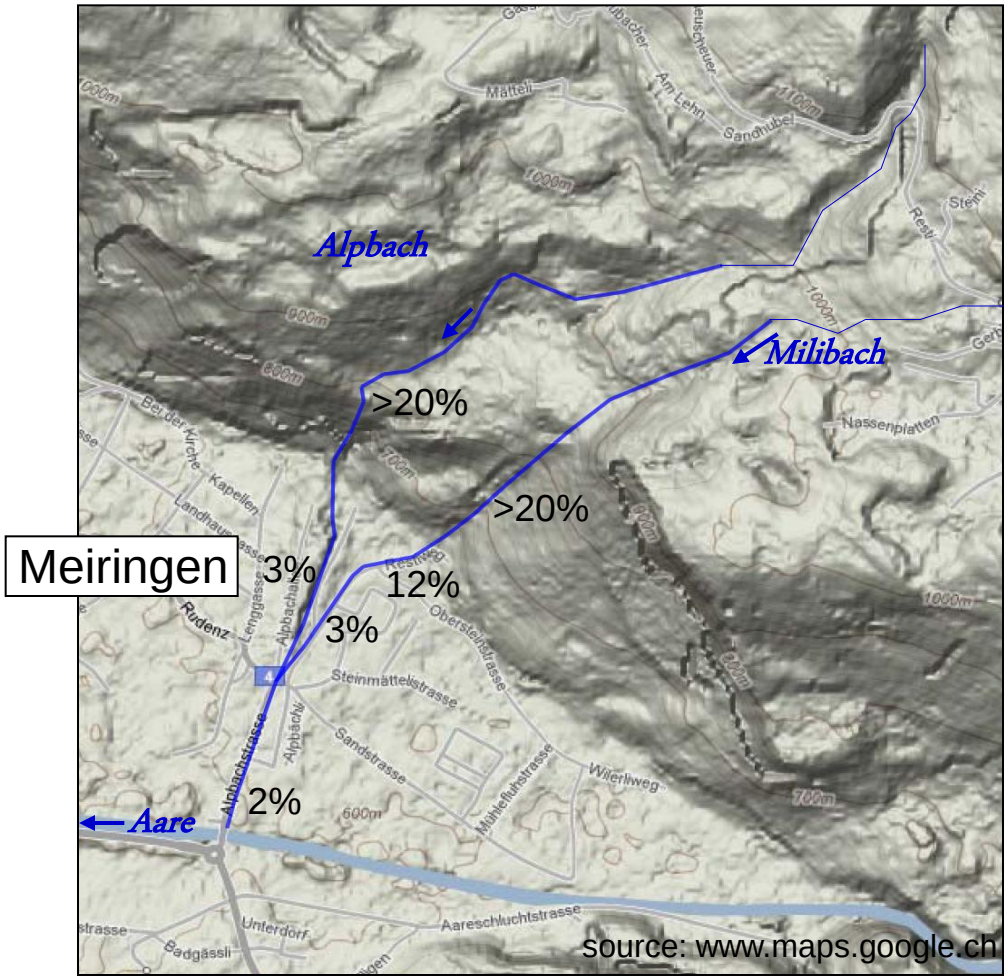
Content

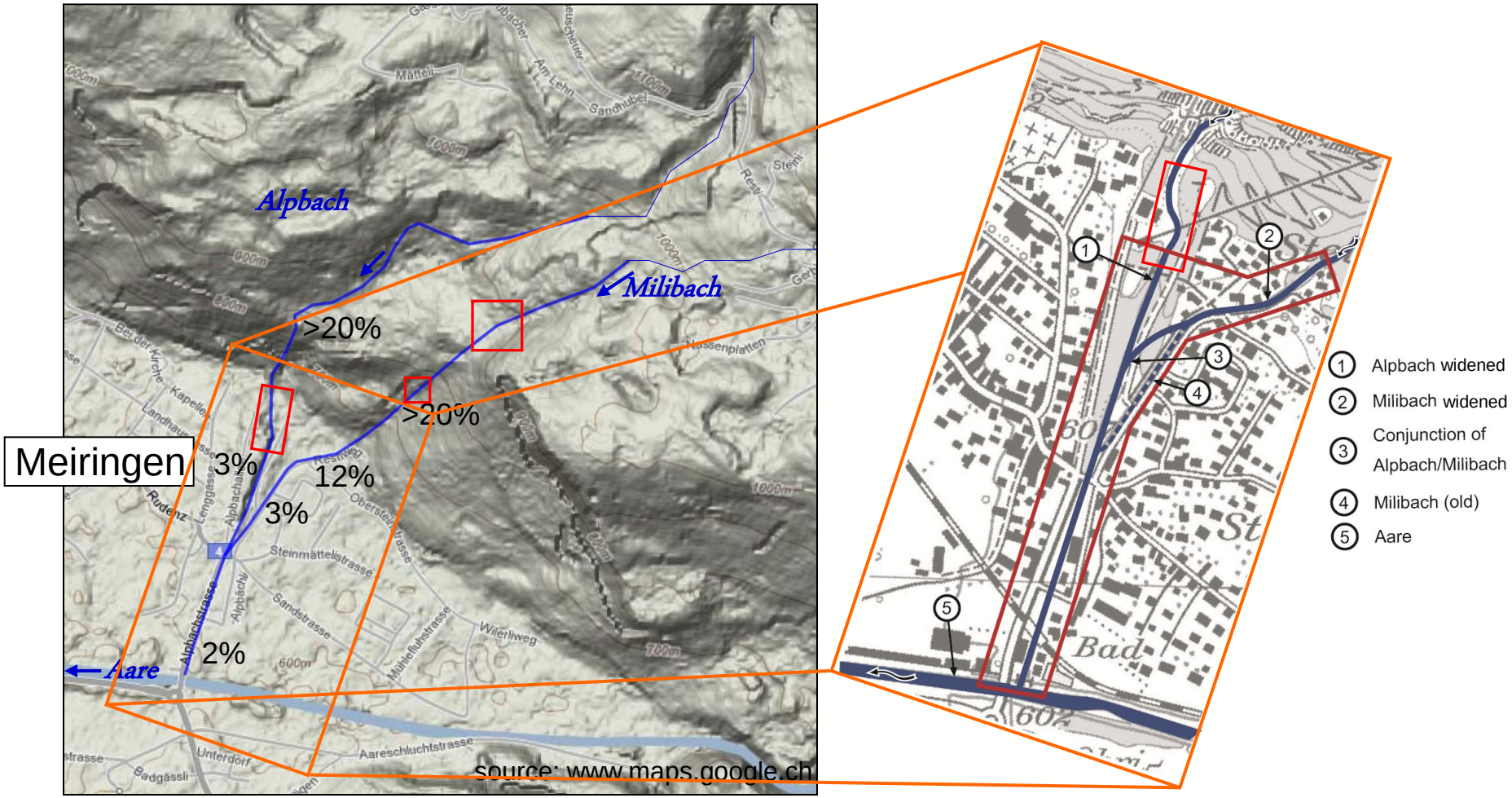
- Introduction to the physical model
- Challenge of modelling bed load transport in physical models
- Methodology for modelling bed load transport
  - Conversion of the grain size distribution into model scale
  - Adaptation of the sediment input and hydrograph
- Results
- Conclusion and outlook

The situation in Meiringen



- High bed load input
- Strong slope changes
- Supercritical flow

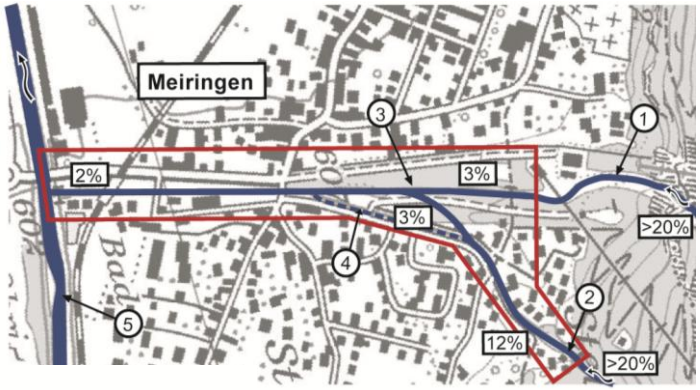
The flood protection project



Sediment retention basin

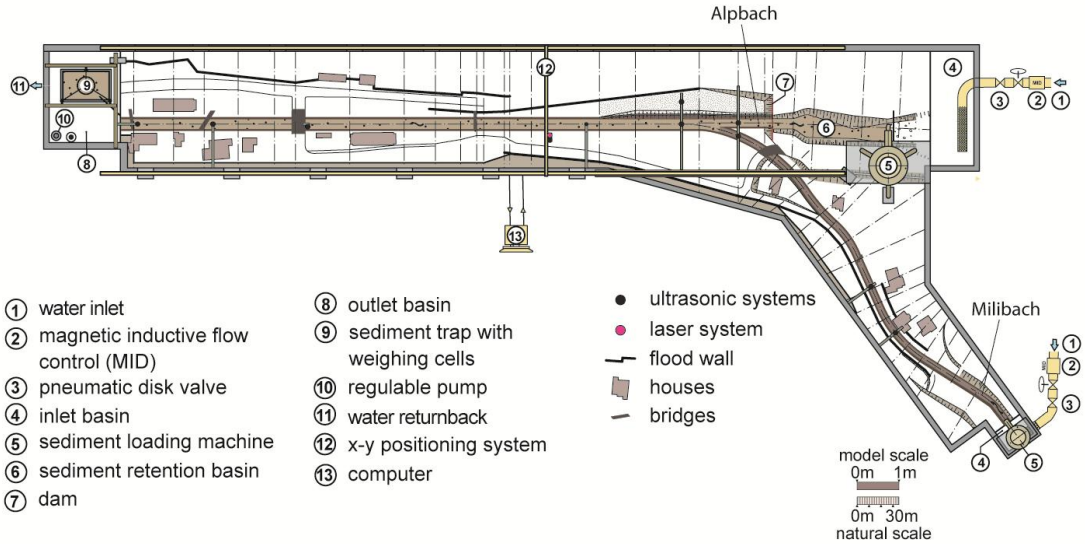
Aim of the physical model

- Test and optimization of flood protection project
- Evaluation of flood safety
- Analysis of bed load transport
- Detection of deposition zones



① Alpbach
② Milibach
③ Conjunction of Alpbach/Milibach
④ Milibach (old)
⑤ Aare

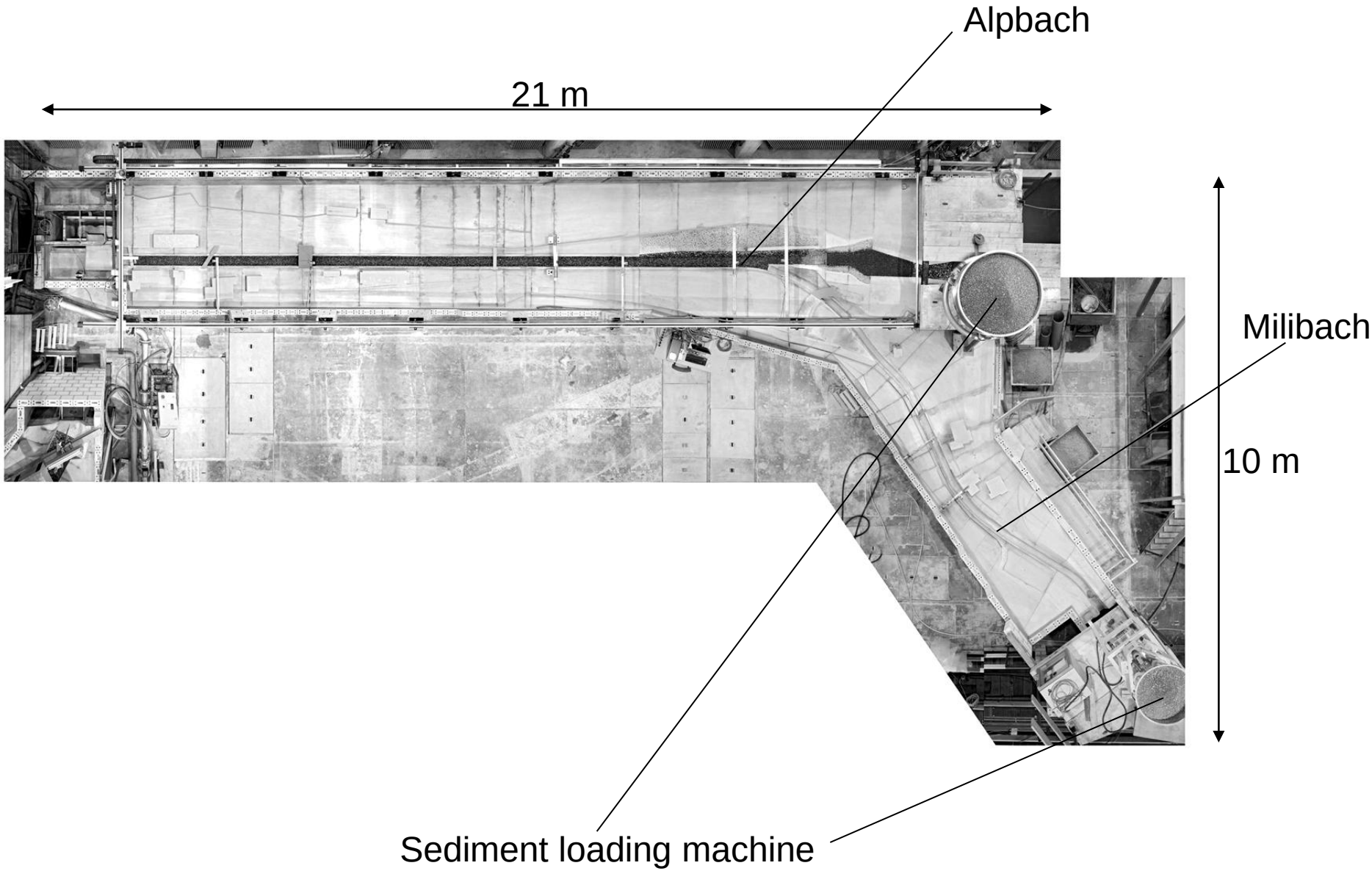
The model is built with Froude similarity and a scale of 1:35



① water inlet
② magnetic inductive flow control (MID)
③ pneumatic disk valve
④ inlet basin
⑤ sediment loading machine
⑥ sediment retention basin
⑦ dam
⑧ outlet basin
⑨ sediment trap with weighing cells
⑩ regulable pump
⑪ water returnback
⑫ x-y positioning system
⑬ computer

- ultrasonic systems
- laser system
- flood wall
- houses
- bridges

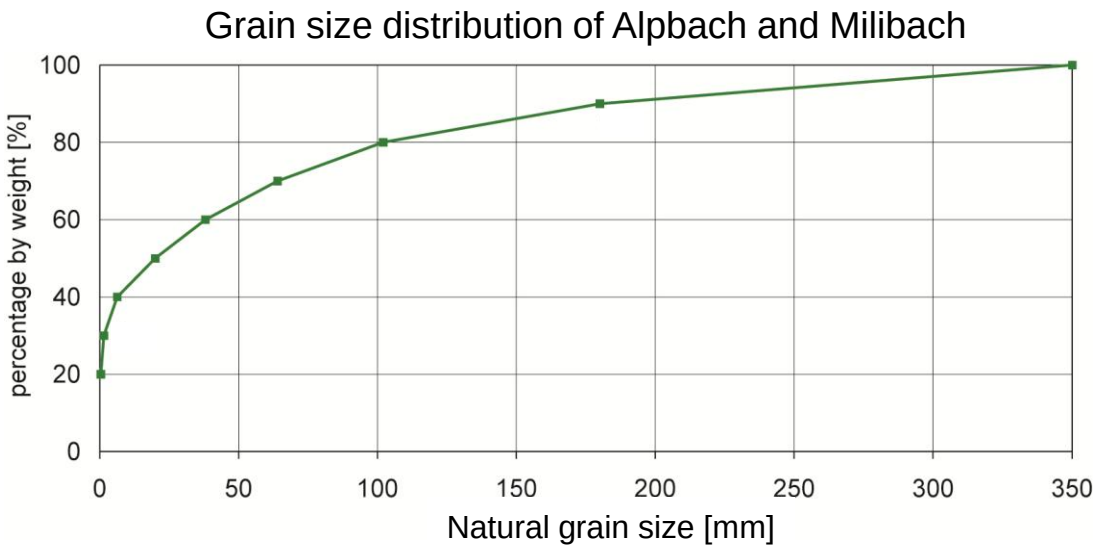
The physical model



Characteristics of nonuniform sediment

Nonuniform Sediment:

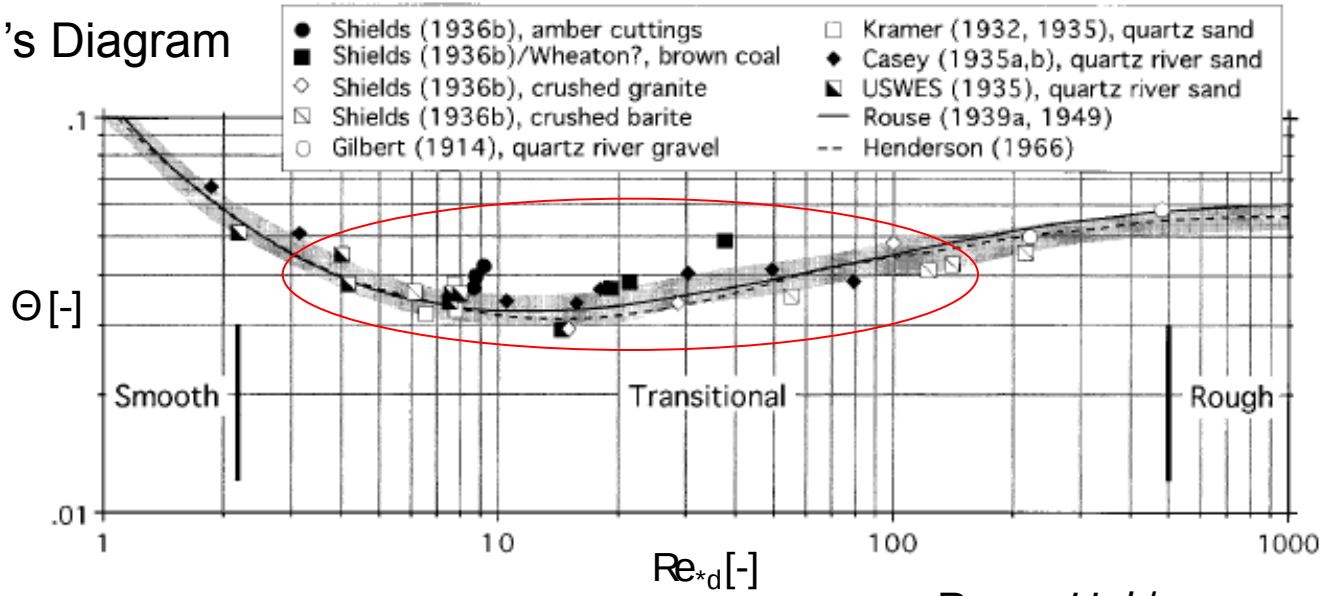
- contains different grain size classes
- is described by the grain size distribution
- incipient motion depends on the grain size, density and shape



Incipient motion

- Incipient motion occurs, when the dimensionless shear stress $\Theta > \Theta_{cr}$
- For $Re_{*d} > 200$, Θ_{cr} can be regarded as constant
- Grains in the range of $Re_{*d} = 2 – 200$ feature incipient motion at lower Θ_{cr}

Shield's Diagram



$Re_{*d} = U_* d / \upsilon$

with U_* = shear velocity [m/s]

Incipient motion

Gravel beds in nature: Re_{*d} > 200

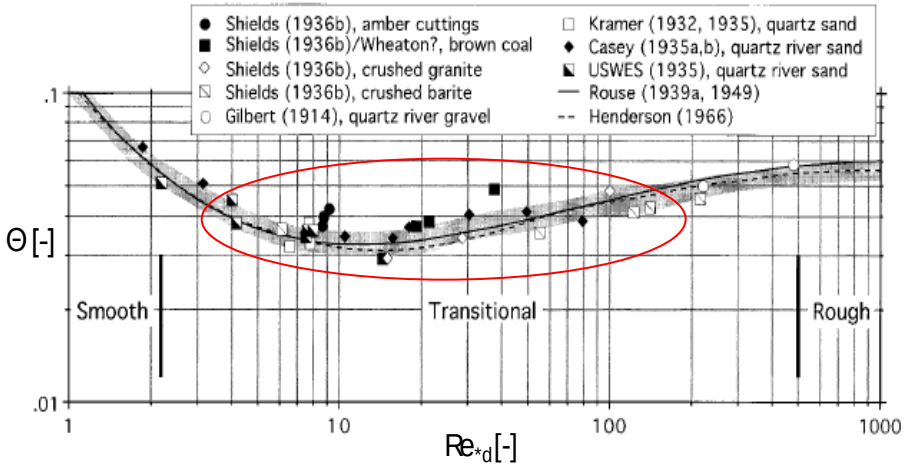
Geometrical scaling with model scale λ: d_{model} [m] = d_{nature} [m] / λ

→ **for Re_{*d} = 2 - 200:** $\Theta_{cr,\ model}$ [-] < $\Theta_{cr,\ nature}$ [-]

- Grains get transported by a smaller discharge:

  $U_{*cr,\ model}$ [m/s] < $U_{*cr,\ nature}$ [m/s] / √λ (→U_{*cr} not Froude scaled)

- Overestimation of bed load transport in the model



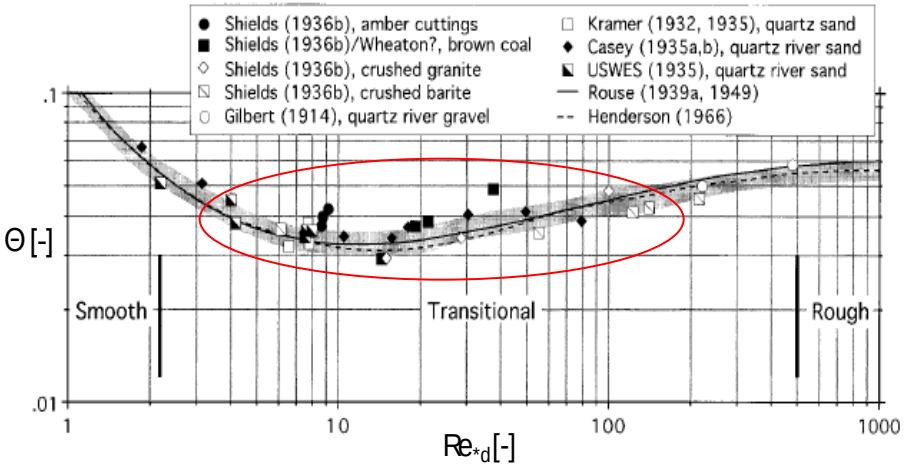
Conversion of the grain size distribution

Zarn's Approach (1992):

- Adaptation of the geometrical scaled grain size distribution
- Correct simulation of incipient motion
- Froude similitude for U_{*cr} for all grain fractions:

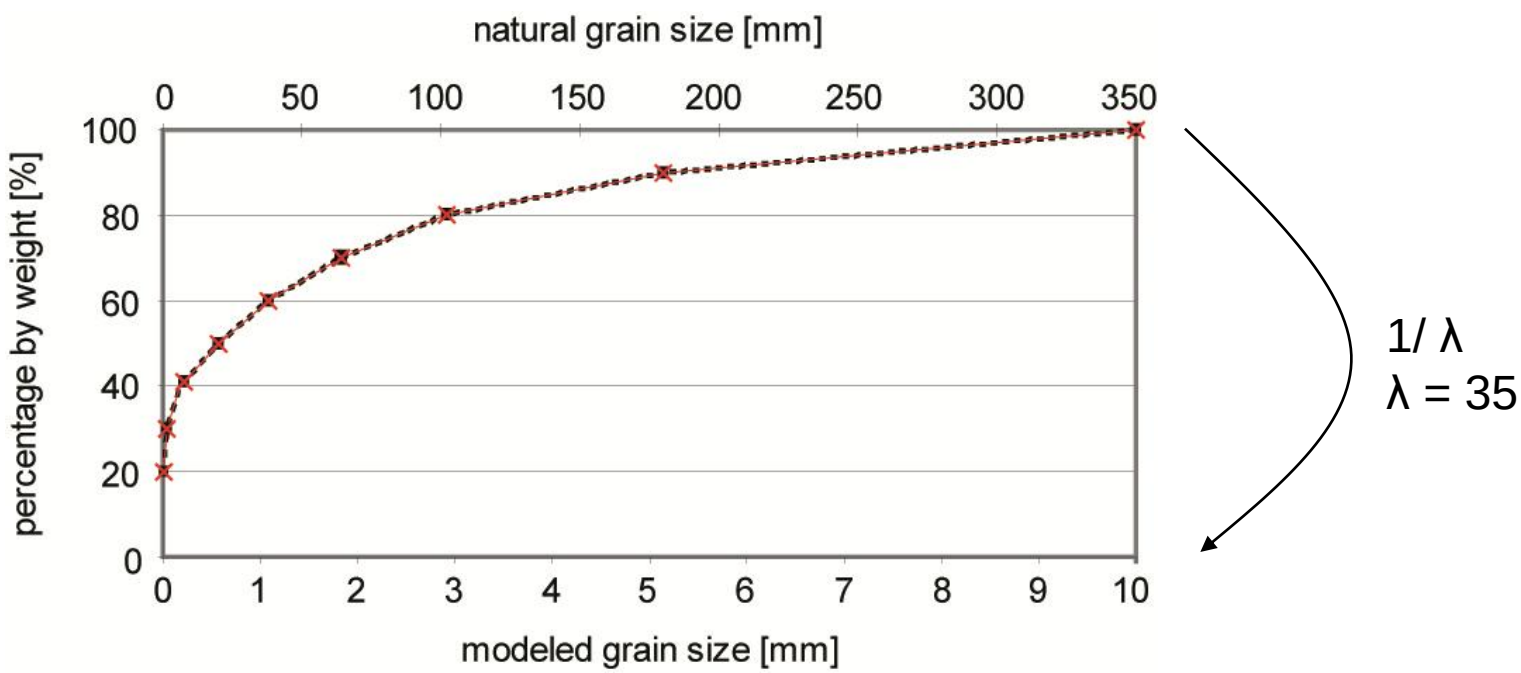
  $U_{*cr,\ model} = U_{*cr,\ nature} / \lambda^{1/2}$

→ **Coarsening of the grains in the range of Re_{*d} = 2 - 200**



Conversion of the grain size distribution

Step 1:
Geometrical scaling by the multiplication with the scale 1/λ → $d_{model} = d_{nature} / \lambda$

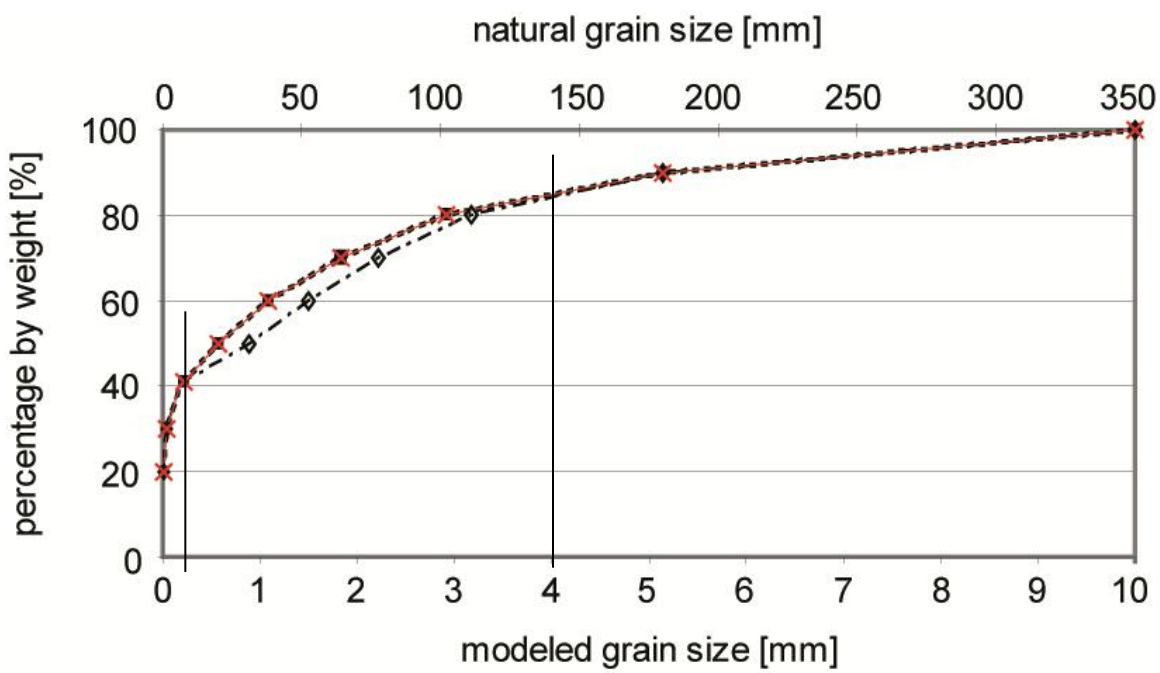


Conversion of the grain size distribution

Step 2:

Coarsening of the grains with Re_{*dcr} = 2 - 200, belonging to d = 0.22 - 4 mm, to get

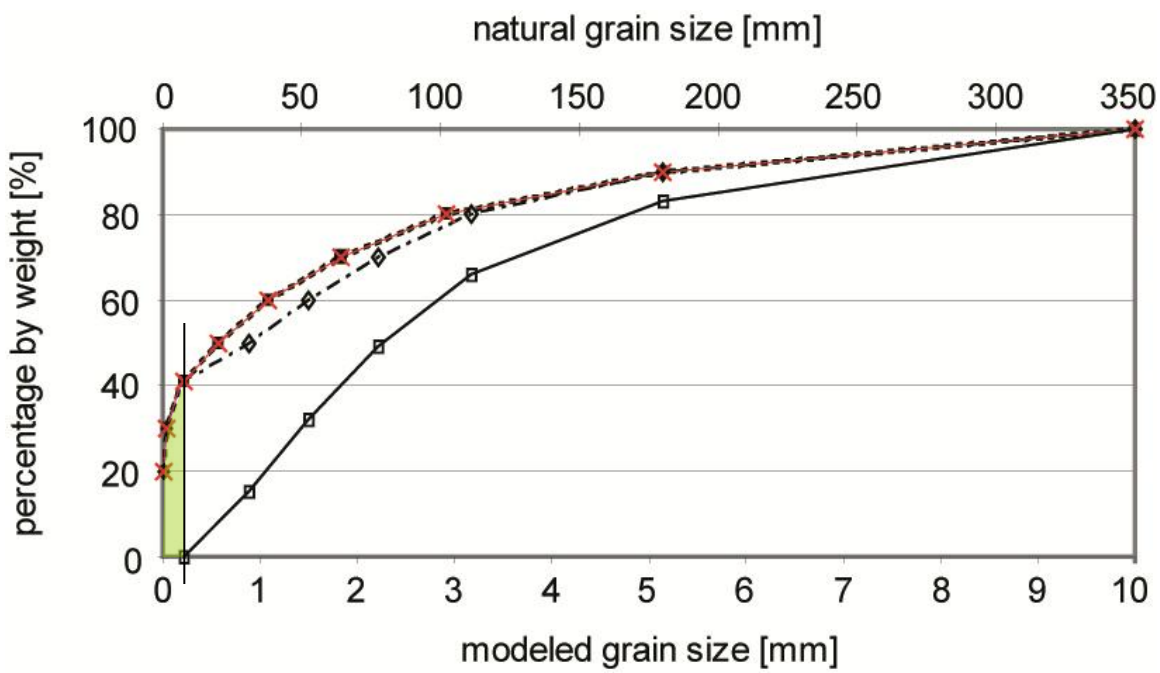
$U_{*cr,\ model} = U_{*cr,\ nature} / \lambda^{1/2}$



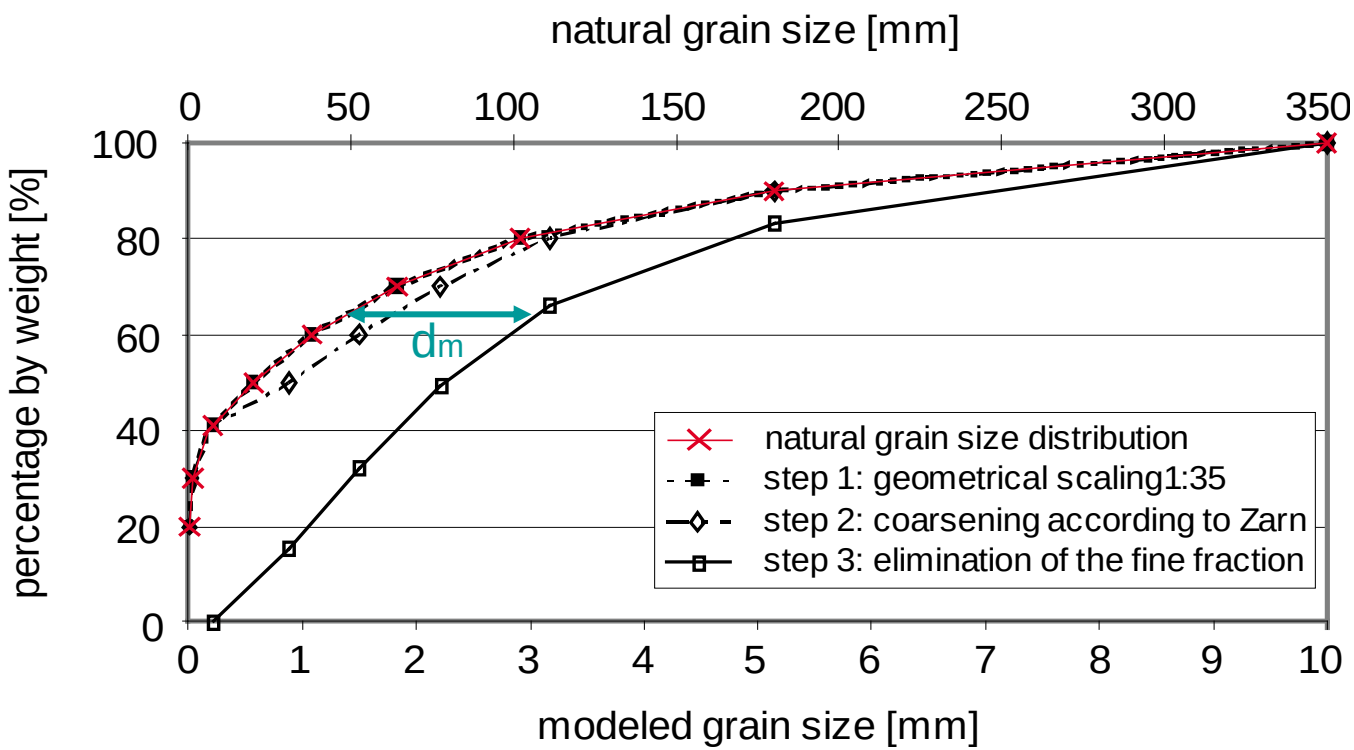
Conversion of the grain size distribution

Step 3:

Elimination of the fine fraction of $Re_{*d} < 2$, belonging to $d < 0.22$ mm as cohesive properties of the material might play a role and riffles could be generated



Conversion of the grain size distribution



Eliminated fine grain fraction = 40%

→ A larger scale than 1:35 would lead to a weaker coarsening

Effects of the coarser grain size distribution

In the model compared to nature:

- Lower transport capacity
- Steeper equilibrium slope
- Higher deposition at same sediment load

Adaptation of sediment input load:
Reduction of input and expansion of hydrograph

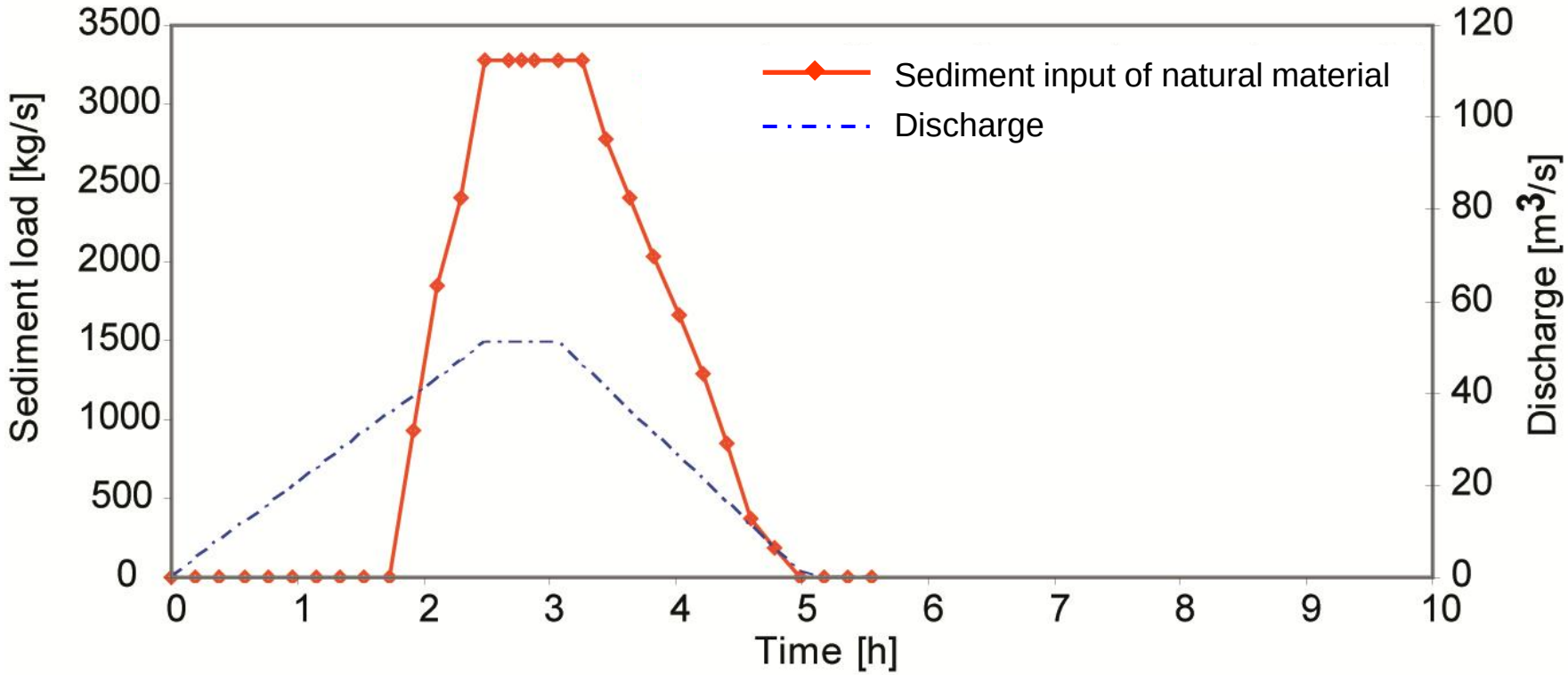
Reduction of the sediment input

$$\frac{\text{bed load input}_{\text{nature}}}{\text{max. transport capacity}_{\text{nature}}} = \frac{\text{bed load input}_{\text{model}}}{\text{max. transport capacity}_{\text{model}}}$$

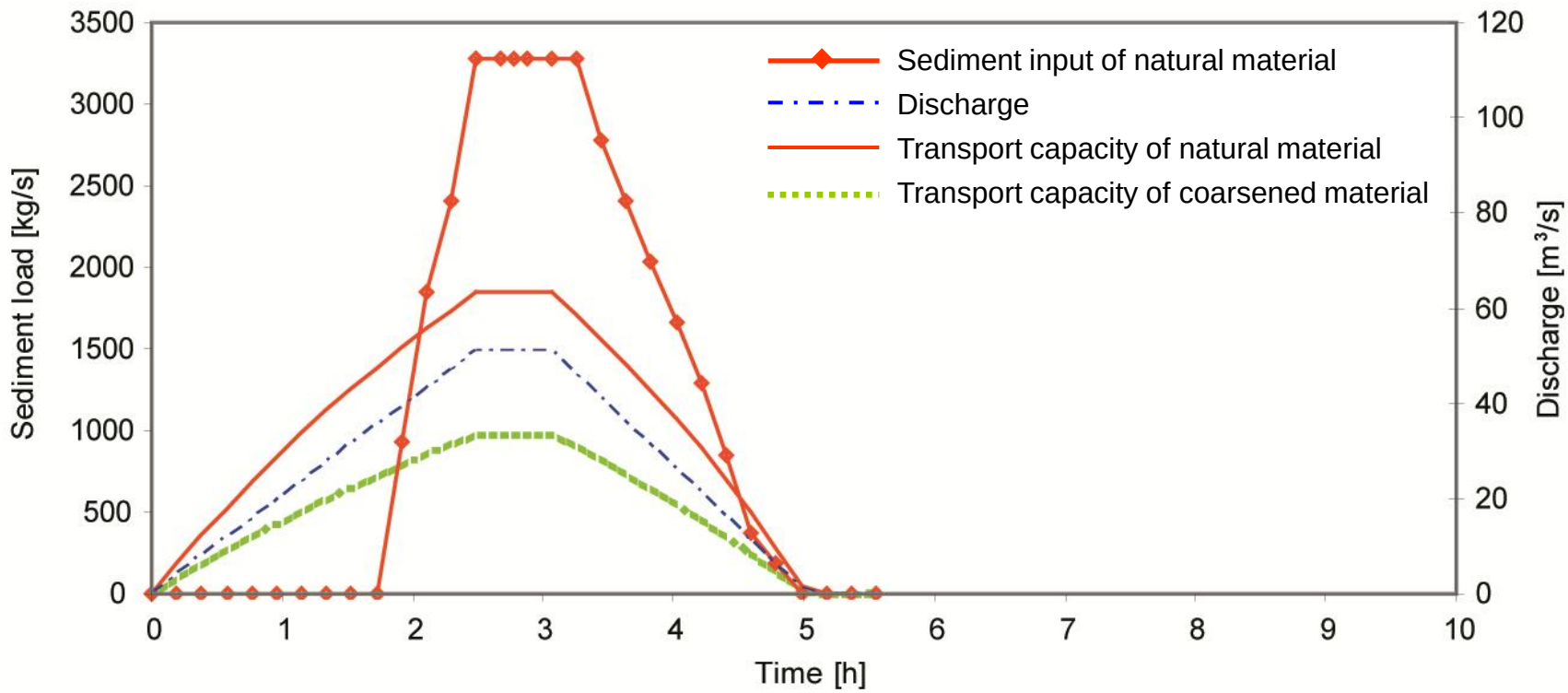
Maximum transport capacity: calculated by the formula of Smart & Jäggi (1983) for slopes of 3 – 20%

Reduction of the sediment input

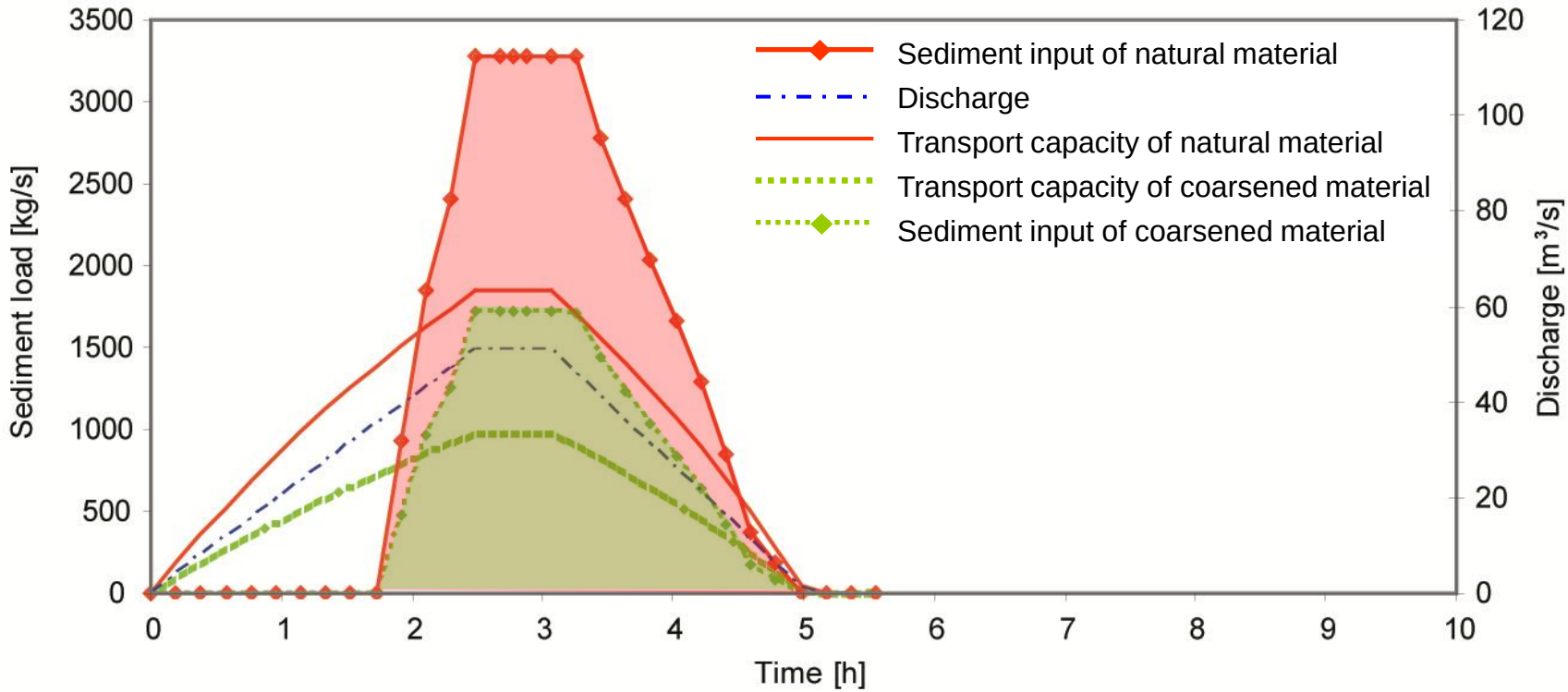
Extreme flood event Alpbach



Reduction of the sediment input

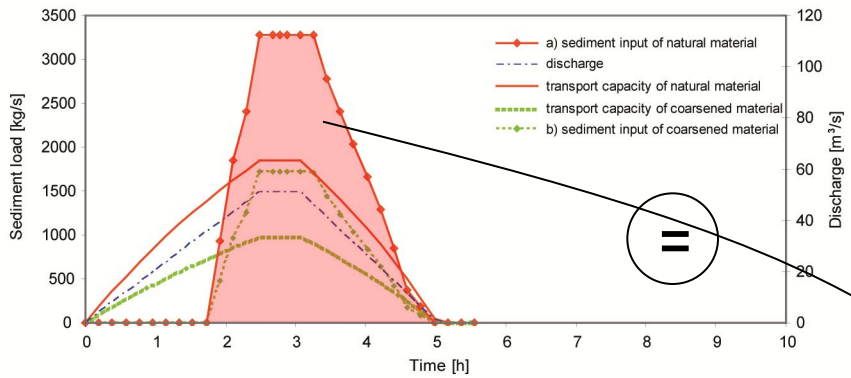


Reduction of the sediment input



→ Volume is not Froude scaled

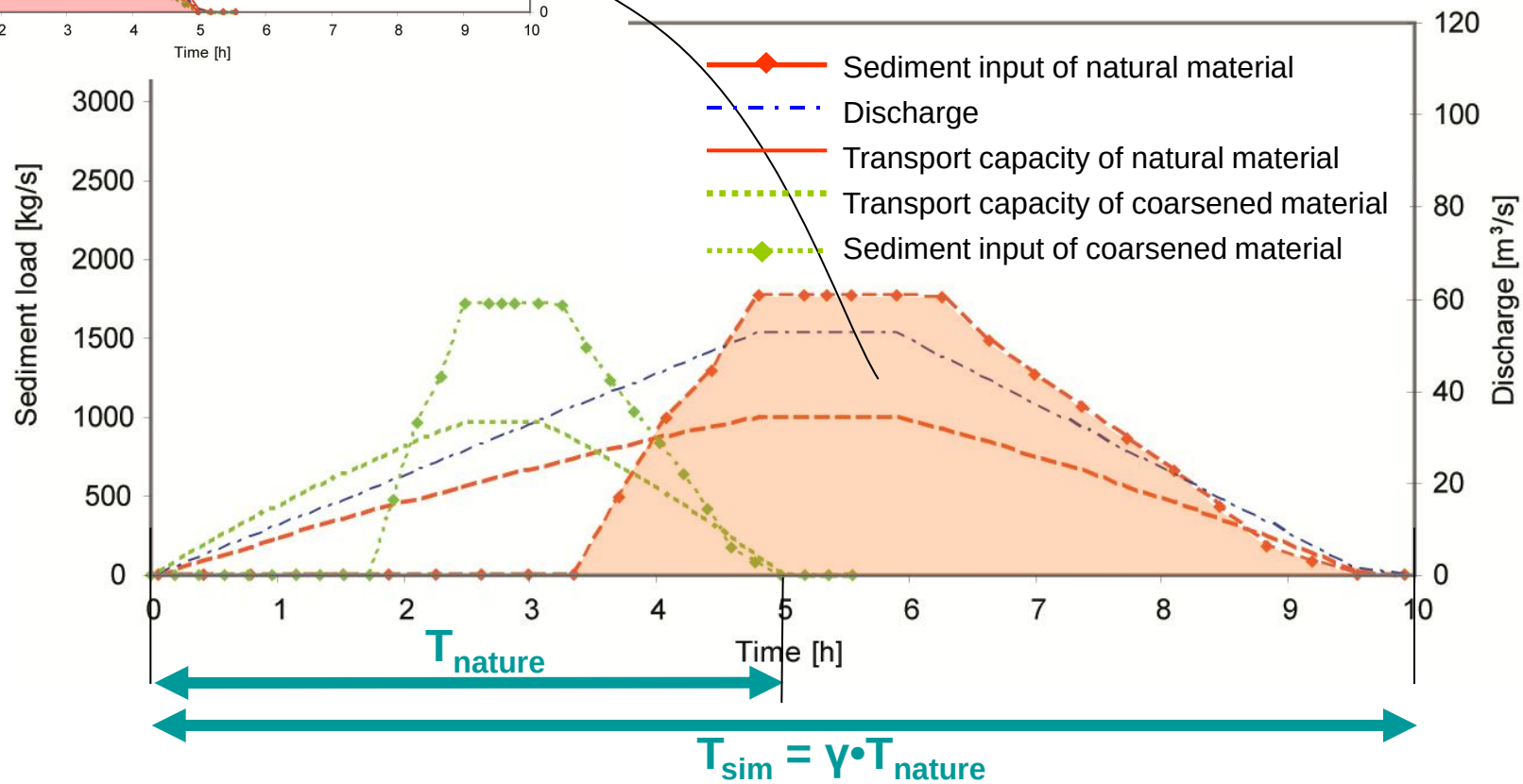
Hydrograph expansion



$V_{sim} = V_{nature} = \gamma \cdot V_{reduced}$

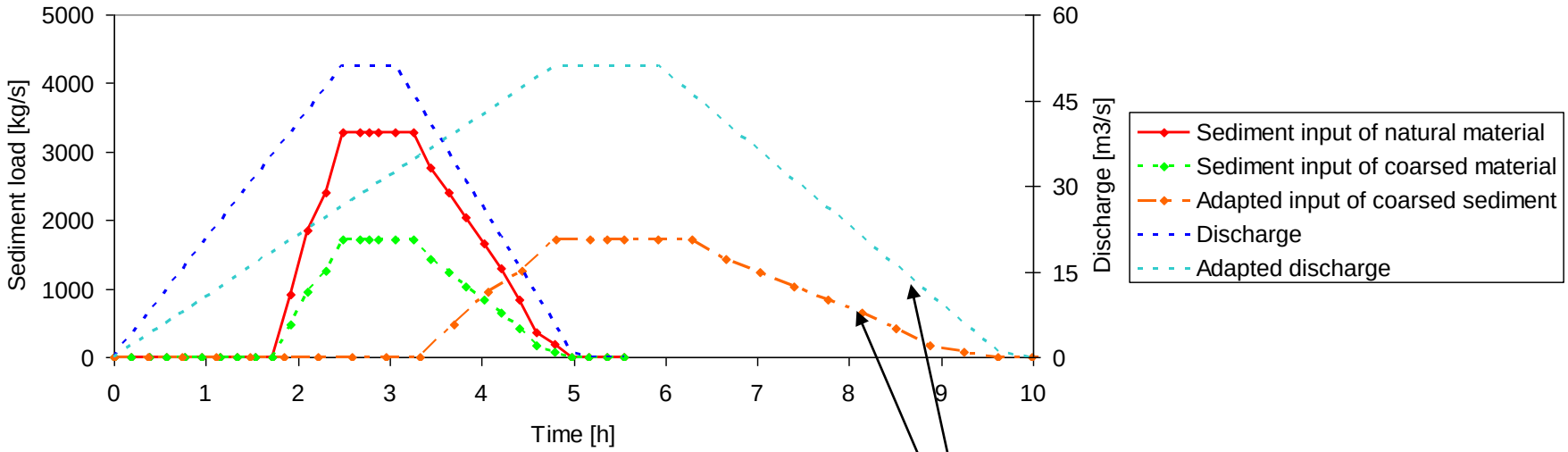
Time expansion factor: $\gamma = V_{nature} / V_{reduced}$

$t_{sim} = t_{nature} \cdot \gamma$



Resulting model test hydrograph

Extreme flood hydrograph Alpbach



Model test hydrograph

$$t_{model} = \underbrace{t_{nature} / \lambda^{1/2}}_{\text{Froude scale factor}} \underbrace{\bullet \gamma}_{\text{Expansion factor}}$$

Conclusion

- Correct initial motion of all grain fractions
- A larger scale has smaller effects on the coarsening of the grain size distribution
- Correct simulation of equilibrium slope by the reduction of sediment input
- Correct volume and bed load balance by the expansion of the hydrograph
- The proposed methodology is only valid for systems exhibiting turbulent flow in each zone of interest. Not valid for systems with different kind of flow, e.g. low Re flow in basins

Outlook

- Compare bed load transport of geometrical scaled and Zarn-scaled sediment distribution in steady model tests to evaluate the effect of Zarn‘s approach

- Conduct model tests with hydrographs with reduced and expanded inputs to evaluate the effect of the expansion