Bedload transport monitoring and modelling: state of the art

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Photo: Walliser Bote, 2000
1) Direct bedload transport measurements

2) Surrogate bedload transport measurements with acoustic systems

3) Bedload transport modelling: example applications of the „sedFlow“ code

4) Concluding remarks
Direct measurements of bedload transport

Helley-Smith and pressure difference samplers

Retention basin

Erlenbach, Switzerland

Bunte trap

Riedbach, Switzerland

Metal basket

Erlenbach, Switzerland

Bedload net with truck

Saldurbach, South Tyrol

Slot sampler

Nahal Eshtemoa, Israel

Gray et al. (2010)

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Sediment budget from repeated cross-section surveys

Example of Emme River (sedFlow simulation)
The Erlenbach bedload observatory

- small catchment (0.7 km²)
- long-term sediment transport observations (>30 years)
- step-pool morphology
- channel slope: 0.17 mean; 0.105 us of station

Acoustic bedload measurements
(Swiss impact plate geophone)

Surveys of sediment deposits
Automatic bedload sampling with moving baskets (2009 ff)

Swiss plate geophone

Miniplate accelerometer

Japanese pipe microphone

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Automatic bedload sampling with moving baskets (video)
1) Direct bedload transport measurements

2) **Surrogate bedload transport measurements** with acoustic systems

3) Bedload transport modelling: example applications of the „sedFlow“ code

4) Concluding remarks
Different generations of acoustic systems

• Steel plates with standard dimensions (36 cm x 50 cm)
• acoustic isolation (elastomer)
• sensor mounted in aluminum housing, fixed in center of plate
• sensor records deformation velocity of steel plate

1986 – 1999
piezoelectric bedload impact sensor

2000 ff
geophone sensor

2016 ff
Miniplate accelerometer

2013 ff
Japanese pipe microphone
## Swiss plate geophone measurements at various sites

<table>
<thead>
<tr>
<th>Stream</th>
<th>Location</th>
<th>Drainage area (km²)</th>
<th>Operation period (sensor type)</th>
<th>Calibration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Erlenbach (basin)</td>
<td>Alptal, Schwyz, CH</td>
<td>0.7</td>
<td>1986-1999 (PBIS), 2000+ (GS)</td>
<td>yes</td>
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<tr>
<td>Erlenbach (bridge)</td>
<td>Alptal, Schwyz, CH</td>
<td>0.5</td>
<td>1995-1997 (PBIS), 2002+ (GS)</td>
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<tr>
<td>Vogelbach</td>
<td>Alptal, Schwyz, CH</td>
<td>1.6</td>
<td>1999+ (GS)</td>
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<tr>
<td>Pitzbach</td>
<td>Pitztal, Tyrol, AT</td>
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<td>1994-1995 (PBIS)</td>
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<tr>
<td>Spissibach</td>
<td>Leissigen, Berne, CH</td>
<td>2.5</td>
<td>1998-2010 (PBIS)</td>
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<tr>
<td>Rofenache</td>
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<td>98</td>
<td>2000+ (GS)</td>
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<tr>
<td>Drau</td>
<td>Lienz, Tyrol, AT</td>
<td>1876</td>
<td>2002+ (GS)</td>
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<tr>
<td>Drau</td>
<td>Dellach, Carynthia, AT</td>
<td>2300</td>
<td>2006+ (GS)</td>
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<tr>
<td>Isel</td>
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<td>1199</td>
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<td>Schweibbach</td>
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<td>9.7</td>
<td>2007+ (GS)</td>
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<tr>
<td>Fischbach</td>
<td>Mühllau, Tyrol, AT</td>
<td>71</td>
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<tr>
<td>Ruetz</td>
<td>Mutterbergalm, Tyrol, AT</td>
<td>28</td>
<td>2008+ (GS)</td>
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<tr>
<td>Riedbach</td>
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<td>18.7</td>
<td>2009+ (GS)</td>
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<tr>
<td>Nahal Eshtemoa</td>
<td>Negev Desert, Israel</td>
<td>119</td>
<td>2009+ (GS)</td>
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<td>Elwha River</td>
<td>Washington, USA</td>
<td>833</td>
<td>2009+ (GS)</td>
<td>yes</td>
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<tr>
<td>Navisence</td>
<td>Zinal, Valais, CH</td>
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<tr>
<td>Ötztaler Ache</td>
<td>Sölden, AT</td>
<td>197</td>
<td>2011+ (GS)</td>
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<td>Urslau</td>
<td>Maria Alm, Salzburg, AT</td>
<td>55</td>
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<td>Suggadinbach</td>
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<td>Ashiaraidani</td>
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<td>Solda River</td>
<td>Valle Venosta, I</td>
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<td>2014+ (GS)</td>
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<tr>
<td>Albula River</td>
<td>Tiefencastel, CH</td>
<td>529</td>
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<tr>
<td>Avancon de Nant</td>
<td>Pont de Nant, Vaud, CH</td>
<td>13.5</td>
<td>2015+ (GS)</td>
<td>(yes)</td>
</tr>
</tbody>
</table>

GS = geophone sensor, AS = Acceleration Sensor, PBIS = piezoelectric bedload impact sensor

(Rickenmann 2017, JHE)
Swiss plate geophone (SPG): Example of signal, Impuls counts

Impulses are recorded whenever the signal exceeds a predefined threshold value (on positive amplitude range), typically $A_{\text{min}} = 0.1 \, \text{V}$

Triggering and number of impulses depends on:

- grain size, grain shape, type of movement, number of grains, grain velocity
- limiting grain size is about 10 - 20 mm

Raw signal is recorded only at a few sites during the calibration measurements.

(Rickenmann et al. 2014, ESPL)
Calibration of the Swiss plate geophon system at the Erlenbach

Linear calibration between impulses and bedload mass works well at Erlenbach

D₁: many particle sizes in critical detection range
D₂: impulses not well constrained
D₃: short sampling time

(Rickenmann et al. 2012, ESPL)
Effect of extreme flood event (20 June 2007) on transport

- Large events influence bedload transport for several years
- Shift both in
  - Transport efficiency
  - Threshold of motion

Erlenbach: Bedload transport measurement 2002-2010

1-Minute data
- 18990 data points
- 316.5 hours
- 128 individual events

(Turowski et al. 2009, ESPL)
Comparison of SPG signal response at different sites

Maximum grain size correlates with signal strength, almost independent of site

(Rickenmann et al. 2014, ESPL; Wyss et al. 2016, WRR)
Grain size identification and flux estimation with the SPG

Hypothesis:

- signal amplitude is a function of the size of the transported particle
- every particle collides only once against the steel plate
- amplitude thresholds can discriminate between grain-size classes

\[ \text{Amplitude Histogram method} \]

(Wyss et al. 2015, JHE)
Grain size identification: Amplitude Histogram (AH) method

old AH method (46 samples)

new AH method (88 samples)

$y = 1.26 \times 0.94$
$R^2 = 0.96$

$M = \text{bedload mass}$
$D84 = \text{grain size}$

(Ryss et al. 2016, JHE)

(M = bedload mass

$D84 = \text{grain size}$

(Rickenmann et al. 2018, River Flow)
Application of AH method to Erlenbach

Grain sizes correlate with bedload flux (over 2 orders of magnitude)

[*] moving average over 10 min

Grain size versus Qb (kg/min/m) and Q (m³/s) for 26 July 2014 and 2 May 2015.

Regression equations for different grain sizes on 26 July 2014:
- D-max: \( y = 39.3 x^{0.31} \) with \( R^2 = 0.95 \)
- D-84: \( y = 32.3 x^{0.18} \) with \( R^2 = 0.89 \)
- D-50: \( y = 17.0 x^{0.14} \) with \( R^2 = 0.91 \)

Regression equations for different grain sizes on 2 May 2015:
- D-max: \( y = 40.7 x^{0.34} \) with \( R^2 = 0.89 \)
- D-84: \( y = 34.7 x^{0.22} \) with \( R^2 = 0.68 \)
- D-50: \( y = 19.4 x^{0.11} \) with \( R^2 = 0.75 \)

\( q_{b_m} \) (kg/min/m) (*)

\( Q \) (m³/s)

\( q_b \) (kg/min/m)

\( D_m \) (mm)
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**sedFlow-WSL: 1d bedload transport simulation**

**Main objectives**
Application to mountain rivers, fast computations (multiple scenarios)

**Key elements**
- rectangular cross section, 1-dimensional calculation (hydraulics and bedload transport)
- fractional bedload transport calculations, active layer, evolution of longitudinal profile
- optional limitation of erosion depth (bedrock, large boulders)
- channel network, lateral water and or sediment input (fluvial or debris flows)

**Hydraulics**
- kinematic wave (explicit, implicit with analytic approximation after Liu & Todini 2002)
- simplified hydraulics (no flow routing), also allowing for adverse bed slopes
- variable power equation of Ferguson (2007) for steep and shallow flows

**Bedload transport**
- Lamb et al. (2008) for initiation of motion
- Rickenmann (2001) or Wilcock-Crowe (2003) for transport
- use of reduced energy slope to account for macro-roughness (Rickenmann-Recking 2011)

(Heimann et al. 2015a, 2015b)
sedFlow: calibration in Swiss mountain rivers

Kleine Emmer River
- Catchment size: 480 km²
- Period: 2000 - 2005
- Cross-section surveys

Brenno River
- Catchment size: 400 km²
- Period: 1999 - 2009

(Heimann et al. 2015a, 2015b)
sedFlow calibration: Kleine Emme River

Bedload transport [m$^3$]

- reference or initial values
- simulation
- tributaries
- silts

D$50$ [m]

D$84$ [m]

Distance to outlet [km]

(Heimann et al. 2015a, 2015b)
sedFlow calibration: Brenno River

Heimann et al. 2014a, 2014b
Application of sedFlow + BASEMENT: Vispa + debris flow
**sedFlow application: Vispa River + debris flow input**

- Debris flow event on 15 October near Neubrück (north of Stalden)
- Debris flow Beiterbach: sediment input into Vispa River: 60,000 – 80,000 m³, in three surges
- Two fatalities, damage to (railroad) infrastructure, damming of Vispa River, changes of channel morphology

_Flood event of 14-16 October 2000_

(Flood event of 14-16 October 2000)
sedFlow application: Vispa River + debris flow input

Date, Time
Discharge [m³/s]

3 debris-flow surges

Station Visp, Fläche des Einzugsgebietes 778 km²
Station Saas Balen, Fläche des Einzugsgebietes 202 km²

(Walliser Bote, 2000)
Flood event of 14-15 October 2000

Distance to confluence with Rhone River [km]

Grain size [cm]

Channel slope [%]

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sedFlow application: Vispa River + debris flow input

(Briner 2016; Rickenmann 2017)
sedFlow application: Vispa River + debris flow input

Flood event of 14-15 October 2000

Distance to confluence with Rhone River [km]
Elevation [m a.s.l.]

- Initial bed profile
- Simulated final bed profile, sedFlow
- Simulated final bed profile, BASEMENT*
- Observed final bed profile

*(BASEMENT: VAW-ETHZ)

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(Briner 2016; Rickenmann 2017)
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Concluding remarks

Bedload transport monitoring in steep rivers
- Direct bedload sampling in mountain rivers is possible (up to mean flow intensities) but challenging
- The Swiss plate geophone (SPG) system can be used to determine both total bedload flux and fractional bedload transport rates
- SPG or similar acoustic bedload transport measurements are helpful to improve the process understanding of bedload transport

Bedload transport simulations in mountain rivers
- for example cases: bed level changes and sediment budget is rather well constrained
- simulated changes (sedFlow examples) in bed level and total transported bedload agree reasonably well with observations
- note calibrated components: GSD (Kleine Emme), channel width (Brenno), channel slopes of tributaries (Vispa, sedFlow), selection of bedload equation (BASEMENT)
Thank you for the attention.