Sediment cascades and sediment budgets in Alpine basins

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SedAlp, Final Conference, Bozen, 9. 06. 2015
Content

- Sediment cascade and sediment budget – general considerations and concepts
- Temporal and spatial scales
- Methods (mapping, geophysics, modelling/GIS)
- Case studies: Gradental (Hohe Tauern, Austria)
  Turtman-valley (Wallis, Switzerland)
  Schnalstal (South Tyrol)
  Pasterze (Hohe Tauern, Austria)
- Lessons learned: Conclusion & Outlook
Sediment cascade

Inputs
- Interfluve
- Free-face
- Talus
- Talus foot
- Valley floor
- Stream channel

Internal transfers
- Bedrock weathering
- Atmospheric dust and solutes

Outputs
- Lake sedimentation
- Outlet channel

Davies & Korup (2010): 90

Caine (1974)
Characteristics

► flow of energy and mass
► input – storage – output
► coupling – decoupling
► regulators (e.g. slope, vegetation)
► buffering capacity
Sediment budget

\[ I \pm \Delta S = O \]

Storage

\[ \Delta S = I - O \]

“The sediment budget is defined as the accounting of sources, sinks and redistribution pathways of sediments in a unit region over unit time”.

(Slaymaker 2003, 71)

“A sediment budget is an accounting of the sources and disposition of sediment as it travels from its point of origin to its eventual exit from a drainage basin.“ (Reid & Dunne, 1996)
Approaches in sediment budget studies, sediment fluxes and storages

<table>
<thead>
<tr>
<th>Modern 1 - 50 yrs</th>
<th>Middle-term 10 - 200 yrs</th>
<th>Long-term 0.001 - several Million yrs</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>River loads</strong></td>
<td><strong>Reservoirs</strong></td>
<td><strong>Excavated rock volumes</strong></td>
</tr>
<tr>
<td>Operation time</td>
<td>Survey growth</td>
<td>Cosmogenic isotopes</td>
</tr>
<tr>
<td>Rating curve</td>
<td>Alluvial fan</td>
<td>Thermochronology</td>
</tr>
</tbody>
</table>

- Climate short-term
- Land use, human impact
- Climate long-term
- Tectonics, relief, rocktype

**Control**

**Hydrology**

**Geomorphology**

**Sedimentology**

**Geochemistry, Petrology**

Hinderer (2012)
$I - O = \Delta S$

$$DR_{me} = \frac{SV \rho_b}{(\rho_r A_d T)} \text{[mm a}^{-1}]$$

$$SY = \frac{SV \rho_b}{(A_d T)} \text{[t km}^{-2} \text{a}^{-1}]$$

Sediment yield ≠ sediment budget
What do we need to construct a sediment budget?

1. Recognition and quantification of transport processes
2. Recognition and quantification of storage elements
3. Identification of linkages amongst transport processes

From sediment yield to sediment budget

Sediment yield [t/a]

- Specific sediment yield [t/km²/a]
- Sediment delivery ratio, [SDR = Y/E]
- Sediment budget [I=O±ΔS]
"The biggest challenge in use of sediment budgets is in making the link between intensively studied smaller scale systems to the global scale” (Slaymaker 2009, 19)
How useful are catchment sediment budgets?

Anthony J. Parsons
University of Sheffield, UK

Abstract
Catchment sediment budgeting is an attempt to identify the sources, sinks and pathways of eroded material within catchments. However, the identification of these quantities is not straightforward, and the conceptual underpinnings of sediment budgets make unwarranted and untested assumptions about process stability. Many sediment budgets leave one or more quantities unmeasured and obtain estimates of them by subtraction (assuming budget closure). Consequently, errors in sediment budgets are often hidden and are not quantified. There has been an emphasis on suspended sediment, which, for management purposes, may not be useful. Sediment budgeting can act as a framework for a research agenda on catchment processes. What has been lacking from this agenda has been an adequate consideration of the time taken for sediment to travel via the various pathways to the catchment outlet. The storage term in such budgets has been used as a poor substitute for a thorough understanding of sediment velocity through catchments.

Keywords
budget closure, catchment sediment budgets, sediment sources, sediment storage, sediment travel time
Sediment cascades provide answers to

+ flowpath (direction) of sediments
+ amount and type of temporary sinks, processes and regulators
+ subsystems
+ coupled and decoupled areas
but...
- not considering process response systems

Sediment budgets provide answers to

+ sedimentary systems
+ quantitative approach of sediment flux and storage
but...
- lacks a consideration of time
- some quantities remains unmeasured
Specific sediment yields in the Alps (data from river loads and reservoirs)

- negative trend with basin area
- poor corr. with relief
- positive trend with discharge
- positive trend with glaciated areas

Hinderer et al. 2013
Large scale versus small scale studies

>> the missing link

Large scale studies:
• Jäckli (1957)
• Hinderer (2001)
• Hinderer (2012, 2013)
• Straumann & Korup (2009)

Small-scale sediment budget studies (tributaries):
• Rapp (1960)
• Schrott et al. (2003)
• Götz et al. (2013)(this talk)
• Otto et al. (2009)(this talk)
Why are tributaries important?

- The are an important component in the sediment cascade.
- They are an important component in the sediment budget (e.g. Illgraben supplies 5-15% of the entire sediment volume of Rhone River to Lake Geneva).
- They are subject to intense changes and probably the most dynamic area in recent times (glacier retreat, increasing proglacial area, permafrost degradation, etc.).
- Our knowledge of temporary storages, sediment input and output is poor.
Methods

- Geomorphological Mapping
- Terrestrial Laserscanning/TLS
- 2D Electrical Resistivity Tomography/ERT
- Refraction Seismic /RS
- Ground-Penetrating Radar/GPR
- Core-Drilling, Sampling, Radiocarbon Dating [AMS; a cal. B.P.]
- Palynologic Analyses (cooperation R. Krisai, Univ. Salzburg)
- GIS-based Bedrock Interpolation (spline) and 3D Modelling of Landform Volumes (cut/fill)
Case study (local scale)

- Gradental (Hohe Tauern, Austrian Alps)
The Gradenmoos Basin

- a (semi)closed denudation-accumulation-system
- subcatchment: 4.5 km², 1920 - 3283 m
- negligible suspended and no clastic output
- multiple processes (debris flow, rockfall, fluvial, lacustrine)

\[ I = \Delta S \]

Götz et al. (2013)

**rockwall retreat can be reconstructed in detail, since**

(1) sediment output can be neglected,
The Gradenmoos Basin

→ \( I = \Delta S \)

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- subcatchment: 4.5 km², 1920 - 3283 m
- negligible suspended and no clastic output
- multiple processes (debris flow, rockfall, fluvial, lacustrine)
- favourable logistics and accessibility

[Rockwall retreat can be reconstructed in detail, since](#) (1) sediment output can be neglected, (2) source areas (3D) are clearly defined,

Götz et al. (2013)
The Gradenmoos Basin

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\[ l = ΔS \]

Rockwall retreat can be reconstructed in detail, since

1. sediment output can be neglected,
2. source areas (3D) are clearly defined,
3. sediment storage volumes can be quantified (spatial scale, method. approach),

Götz et al. (2013)
The Gradenmoos Basin

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rockwall retreat can be reconstructed in detail, since
(1) sediment output can be neglected,
(2) source areas (3D) are clearly defined,
(3) sediment storage volumes can be quantified (spatial scale, method. approach),
(4) intermediate storage is small (small source-sink distance, steep gradient), and

Götz et al. (2013)
The Gradenmoos Basin can be reconstructed in detail, since:

1. Sediment output can be neglected,
2. Source areas (3D) are clearly defined,
3. Sediment storage volumes can be quantified (spatial scale, method. approach),
4. Intermediate storage is small (small source-sink distance, steep gradient), and
5. Onset of sedimentation can be established.

\[ I = \Delta S \]

- A (semi)closed denudation-accumulation-system
- Subcatchment: 4.5 km², 1920 - 3283 m
- Negligible suspended and no clastic output
- Multiple processes (debris flow, rockfall, fluvial, lacustrine)

\[ DR_{long-term} = SV \frac{\rho_b}{\rho_s} * A_d * T \]

Götz et al. (2013)
Results

- Long-term (postglacial) sediment storage volumes
  - Total: 19.7 Mio m³ (postglacial volume: 18.3 Mio m³)
  - Landform volumes (Mio m³) and sediment thickness (m)

Götz et al. (2013)
Short-term sediment flux 2009-2014

Two recent debris flows

(TLS, DEMs of Diff.)

Götz & Schrott (2015) submitted
Short term input overbalances the postglacial rate by an order of magnitude!
Case study

- Turtmann valley (Valais, Switzerland)

Otto et al. (2009)
Sediment storage in the Turtmann valley
Sediment cascade and quantification of sediment storage

- Over 60% stored in hanging valleys!
- Important temporary sinks
- Decoupled from the main system

Otto et al. (2009)
Case study

- Schnalstal, South Tirol & Sella, Dolomites
Sella, Dolomites / Italy

Sella, Grödner Joch

Source area – permafrost warming

Krainer et al. 2012
Schnalstal, South Tyrol (debris flow activity 1983 – 2006)

H 1: Thawing of permafrost (degradation) is causing an increased debris flow activity
H 2: The presence of permafrost favours the occurrence of debris flows
Debris flow activity and permafrost

- Increasing debris flow activity between 1983 and 2006 (46%)
- Most starting zones of debris flows are situated above 2850 m (with permafrost occurrence)
- Increasing active layer depth lead to higher proportions of loose debris

Sattler et al. 2011
Case study

- Pasterze (Hohe Tauern, Austrian Alps)
Sediment cascade and budget, Pasterze

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Area [km²]</th>
<th>Area [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slope (I)</td>
<td>12</td>
<td>30.2</td>
</tr>
<tr>
<td>Glacier (II)</td>
<td>20.8</td>
<td>52.3</td>
</tr>
<tr>
<td>Glacier forefield (III)</td>
<td>7</td>
<td>17.5</td>
</tr>
<tr>
<td>Catchment</td>
<td>39.8</td>
<td>100</td>
</tr>
</tbody>
</table>

Geilhausen et al. 2012
Pasterze – dynamic glacier forefield

1953-2009:
- increase (1.3 km² /100%) of sediment storage
- main changes in the proglacial & south-western part of the forefield
- since 1998: significant retreat in the south-eastern part

de glaciation

Geilhausen et al. 2012
Scenario: Glacier retreat will lead to ~600 new lakes in Switzerland!

>> This will alter sediment flux and storage in the proglacial area!

Temperature increase of 4°C until 2199, time steps of 15 years

(Haeberli et al. 2013, Linsbauer et al. 2012)
Conclusion & Outlook

we have achieved...

- sediment cascades help to identify subsystems and the flowpath of sediment fluxes
- sediment budgets can provide a unifying framework

storage component is important for hazard assessment!

we need to...

- focus on linkages between small and large scale (> 500 km²) studies
- focus on sediment-connectivity (coupled-decoupled systems)
- address limitations/uncertainties in sediment budget studies
  (only short or unsufficient measured sediment balance equation components)
"We must above all shift from a culture of reaction to a culture of prevention. Prevention is not only more human than cure... it is also much cheaper..." (Kofi Annan 1998)

Thank you very much for your attention!


