Suspended sediment transport monitoring and modelling: state of the art

Sediment Management in Channel Networks: from Measurements to Best Practices

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Outline

1. Objectives
2. Monitoring technologies and strategy
3. Suspended sediment transport modelling
4. Conclusions
## Suspended sediment monitoring techniques

<table>
<thead>
<tr>
<th>Technology</th>
<th>Operating Principle</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acoustic</td>
<td>Sound backscattered from sediment is used to determine size distribution and concentration.</td>
<td>Good spatial and temporal resolution, measures over wide vertical range, nonintrusive</td>
<td>Backscattered acoustic signal is difficult to translate, signal attenuation at high particle concentration</td>
</tr>
<tr>
<td>Bottle sampling</td>
<td>Water-sediment sample is taken isokinetically by submerging container in streamflow and is later analyzed.</td>
<td>Accepted, time-tested technique, allows determination of concentration and size distribution, most other techniques are calibrated against bottle samplers</td>
<td>Poor temporal resolution, flow intrusive, requires laboratory analysis to extract data, requires on-site personnel</td>
</tr>
<tr>
<td>Pump sampling</td>
<td>Water-sediment sample is pumped from stream and later analyzed.</td>
<td>Accepted, time-tested technique, allows determination of concentration and size distribution</td>
<td>Poor temporal resolution, intrusive, requires laboratory analysis, does not usually sample isokinetically</td>
</tr>
<tr>
<td>Focused beam reflectance</td>
<td>Time of reflection of laser incident on sediment particles is measured.</td>
<td>No particle size dependency, wide particle size and concentration measuring range</td>
<td>Expensive, flow intrusive, point measurement only</td>
</tr>
<tr>
<td>Laser diffraction</td>
<td>Refraction angle of laser incident on sediment particles is measured.</td>
<td>No particle-size dependency</td>
<td>Unreliable, expensive, flow intrusive, point measurement only, limited particle-size range</td>
</tr>
<tr>
<td>Nuclear</td>
<td>Backscatter or transmission of gamma or X-rays through water-sediment samples is measured.</td>
<td>Low power consumption, wide particle size and concentration measuring range</td>
<td>Low sensitivity, radioactive source decay, regulations, flow intrusive, point measurement only</td>
</tr>
<tr>
<td>Optical</td>
<td>Backscatter or transmission of visible or infrared light through water-sediment sample is measured.</td>
<td>Simple, good temporal resolution, allows remote deployment and data logging, relatively inexpensive</td>
<td>Exhibits strong particle-size dependency, flow intrusive, point measurement only, instrument fouling</td>
</tr>
<tr>
<td>Remote spectral reflectance</td>
<td>Light reflected and scattered from body of water is remotely measured.</td>
<td>Able to measure over broad areas</td>
<td>Poor resolution, poor applicability in fluvial environment, particle size dependency (based on Wren et al., 2000)</td>
</tr>
</tbody>
</table>
Suspended sediment monitoring techniques

- Bottle and pump sampling:

**Sampler requirements for multi-point sampling**
- to sample isocinetically
- to extract time integrated samples
- streamlined form
- weight
- to be valve controlled
Suspended sediment monitoring techniques

- Optical sensors:

S:can (Bittner, 2008)

Solitax ts-line (https://at.hach.com)

(Gmeiner et al., 2016, modified)
Suspended sediment monitoring techniques

- Acoustic devices:
  - Single frequency
    - LISST ABS
      (https://www.sequiasci.com)
  - Multi frequency
    - SediScat™ Pro
      (http://www.hydrovision.de/)
Suspended sediment monitoring techniques

- Laser diffraction:

Refraction angle of laser incident on sediment particles is measured

(https://www.sequoiasci.com)
# Monitoring strategy

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Method</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbidity</td>
<td>Turbidity sensor</td>
<td>Continously</td>
</tr>
<tr>
<td>Concentration of suspended sediments close to the sensor</td>
<td>Single point samples close to the sensor</td>
<td>High sediment discharge: min. daily Med. sediment discharge: min. 1-2 / week Low sediment discharge: rare</td>
</tr>
<tr>
<td>Distribution of the concentration of suspended sediments in a cross section</td>
<td>Selected point method, depth-integrated method ADCP+samples</td>
<td>2-4 times/year at different discharges</td>
</tr>
<tr>
<td>Grain size</td>
<td>Single or multi-point samples</td>
<td>At least once a year</td>
</tr>
</tbody>
</table>

- **Determination of the spatial and temporal variability**
- **Combination of direct and indirect methods**

(Haimann et al., 2014)
Data processing

Turbidity

Concentration close to the sensor

Mean concentration

Suspended sediment transport

Suspended sediment load

Probe characteristic $k_s = s_k / s_s$

Cross-sectional characteristic $k_p = s_m / s_k$

Discharge $Q_s = s_m Q$

Time $V_s = \int_{t_1}^{t_2} Q_s(t) \, dt$

(Habersack et al., 2013)
Data processing

Probe factor and concentration close to the sensor

Samples (black), Turbidity data (red) and suspended sediment concentration close to the sensor (blue)
Data processing

Turbidity

Mean concentration

Concentration close to the sensor

Suspension sediment transport

Suspension sediment load

Probe characteristic
\[ k_s = \frac{s_k}{s_s} \]

Cross-sectional characteristic
\[ k_p = \frac{s_m}{s_k} \]

Discharge
\[ Q_s = s_m \cdot Q \]

Time
\[ V_s = \int_{t_1}^{t_2} Q_s(t) \, dt \]

(Habersack et al., 2013)
Cross-sectional measurements

- Suspended sediment transport in a cross section:

\[ Q_s = \int_{0}^{b} \int_{0}^{t_w} s_0 v \, dt_w \, db \]

- Mean suspended sediment concentration in a cross section:

\[ s_m = \frac{Q_s}{Q} \]

determined by

- Multi-point sampling
- ADCP measurements combined with samples

(BMLFUW, 2008; 2017)
Data processing

Mean suspended sediment concentration

Turbidity data (black), suspended sediment concentration close to the sensor (red) and mean suspended sediment concentration (blue)
Data processing

Turbidity

Concentration close to the sensor

Mean concentration

Suspended sediment transport

Suspended sediment load

Probe characteristic $k_s = s_k / s_s$

Cross-sectional characteristic $k_p = s_m / s_k$

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(Habersack et al., 2013)
Data processing

Suspended sediment transport

Suspended sediment load
Suspended Sediment Monitoring

Suitability of monitoring methods – part of 1st SedAlp milestone

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<th>Nuclear</th>
<th>Optical</th>
<th>Remote spectral reflectance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Suspended sediment rate [kg s⁻¹]</td>
<td>⚫⚫⚫</td>
<td>⚫</td>
<td>⚫⚫⚫</td>
<td>⚫</td>
<td>⚫</td>
<td>⚫</td>
<td>⚫</td>
<td>⚫</td>
</tr>
<tr>
<td>Total suspended sediment load [kg, t]</td>
<td>⚫⚫⚫</td>
<td>⚫</td>
<td>⚫⚫⚫</td>
<td>⚫</td>
<td>⚫</td>
<td>⚫</td>
<td>⚫</td>
<td>⚫</td>
</tr>
<tr>
<td>Spatial variability of suspended load</td>
<td>⚫⚫⚫</td>
<td>⚫</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Temporal variability of suspended load</td>
<td>⚫⚫⚫</td>
<td>⚫</td>
<td>⚫</td>
<td>⚫</td>
<td>⚫</td>
<td>⚫</td>
<td>⚫</td>
<td>⚫</td>
</tr>
<tr>
<td>Variation of sediment volume [m, m³]</td>
<td>⚫⚫⚫</td>
<td>⚫</td>
<td>⚫⚫</td>
<td>⚫</td>
<td>⚫</td>
<td>⚫</td>
<td>⚫</td>
<td>⚫</td>
</tr>
<tr>
<td>Initiation of motion [m³s⁻¹]</td>
<td>⚫⚫⚫</td>
<td>-</td>
<td>-</td>
<td>⚫</td>
<td>⚫</td>
<td>-</td>
<td>⚫</td>
<td>⚫</td>
</tr>
<tr>
<td>Particle size distribution</td>
<td>⚫⚫⚫</td>
<td>⚫</td>
<td>⚫</td>
<td>-</td>
<td>-</td>
<td>⚫</td>
<td>-</td>
<td>-</td>
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Habersack et al., 2015

www.sedalp.eu
Suspended Sediments – Flood 2013

Habersack et al., 2015

Suspended sediment transport monitoring and modelling: state of the art | Habersack H., Haimann M., Tritthart M.
Flood event June 2013

Q = 10,738 m$^3$ s$^{-1}$
$s_{m} = 855.2$ mg l$^{-1}$
$Q_s = 9,180$ kg s$^{-1}$

Habersack et al., 2015
Remobilisation in a HPP reservoir

Question of sediment release

Release:
5,5 Mio. m³

7 Mio. t (5,5 Mio. m³)

Transport in Hainburg during the flood event (2013):
6 Mio. t

Source: viadonau, verbund

Habersack et al., 2015
Sedimentation during flood 2013

Sediments: Deposition in floodplains

Machland

Eferdinger Becken

Habersack et al., 2015
Suspended sediment transport modelling
(as implemented in the iSed model)

- Important to consider different suspended sediment size fractions
- Transport governed by advection-diffusion equation (evaluated for every size fraction $i$):
  \[
  \frac{\partial c_i}{\partial t} + \frac{\partial (u_1 c_i)}{\partial x_1} + \frac{\partial (u_2 c_i)}{\partial x_2} + \left[ \frac{\partial (u_3 c_i)}{\partial x_3} \right] = \frac{\partial}{\partial x_1} \left( K_{t,1} \frac{\partial c_i}{\partial x_1} \right) + \frac{\partial}{\partial x_2} \left( K_{t,2} \frac{\partial c_i}{\partial x_2} \right) + \left[ \frac{\partial}{\partial x_3} \left( K_{t,3} \frac{\partial c_i}{\partial x_3} \right) \right] + (s_{dep,i} - s_{ero,i})
  \]

- Solution e.g. by applying a generalized Finite Volume Method on control volumes
- Exchange with river/channel bed modelled by sedimentation and erosion fluxes (source/sink terms)

(Tritthart et al., 2011)
Deposition and erosion fluxes
(examples as implemented in the iSed model)

- Deposition flux according to van Rijn (1984):

\[ S_{dep,i} = w_{ci} \frac{c_i}{F_i} \]

\[ F_i = \frac{\left( \frac{z_{0i}}{h} \right)^{Z^*'} - \left( \frac{z_{0i}}{h} \right)^{\beta_n}}{1 - \frac{z_{0i}}{h}} \left( \beta_n - Z_i^{*'} \right) \]

- Erosion flux following Garcia and Parker (1991):

\[ s_{ero,i} = w_{ci} p_i E_{sk,i} \]

\[ E_{sk,i} = \frac{A(\lambda Z_{mi})^5}{1 + 0.3 \left( \frac{A}{0.3} \left( \lambda Z_{mi} \right) \right)^5} \]
Bed evolution and bed schematization

- Exner equation for bed evolution, including bedload and suspended load:

\[
(1 - n_p) \frac{\partial z_i}{\partial t} + \frac{\partial q_{si,x}}{\partial x} + \frac{\partial q_{si,y}}{\partial y} = s_{dep,i} - s_{ero,i}
\]

- Sorting processes – exchange layer concept:

(modified after ATV-DVWK, 2003)
Modelling example #1 – Danube River

Upstream view (photo: courtesy National Park Donauauen)
Model setup: computation mesh
Validation of model results based on measurements

Comparison of measured (13.07.2006) and simulated suspended sediment concentration profile at mean flow (MQ) - bridge cross section

Comparison of measured (09.08.2006) and simulated suspended sediment concentration profile at highest navigable flow (HSQ) - bridge cross section

Suspended load: cross-section measurements using a US P-61-A sampler vs. simulation results
Application Danube: monitoring and modelling of spatio temporal variability of dredging and dumping fine material
ADCP-Measurements + calibration probes
Results of a 3D numerical suspended sediment modelling during dumping of dredged material

\[ Q = 2375 \text{ m}^3/\text{s} \]

(Haimann et al., 2018)
Modelling example #2: Rodund reservoir
Sedimentation in reservoir no. 1

140,000 m$^3$ sediment deposit in 2007

- reservoirs were dredged

2011 approx. 366,000 m$^3$ sediments

(Kessler., 2013)
Model calibration
Flow field in operation mode 1 (pump operation)
Flow field in operation mode 2 (turbine operation)
Suspended sediment concentrations in operation mode 2
Synthesis: Proposal of measures to achieve concentrated sedimentation patches for reduced dredging effort

(Kessler, 2013)
Conclusions

Monitoring

- Determination of the spatial and temporal variability by combining direct and indirect methods
- Continuous monitoring with OBS (or ABS) sensors mounted on the river bank (If possible, automatized and connected to online monitoring system)
- Calibration of sensors with samples taken close to the sensor
- Cross-sectional calibration several times a year at different water flows, with a special attention to flood events

Modelling

- Type of numerical modelling depends on spatio-temporal variability and study aims
- Monitoring data are a prerequisite for modelling (calibration, validation, input data, boundary conditions)
- Consideration of suspended sediment size fractions is important to achieve good agreement with measurement data
- Valuable tool for analysis of suspended sediment transport in rivers, reservoir sedimentation, flushing, turbidity currents and proposal of structural measures
Thank you for your attention!

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References

- Haimann, M; Hauer, C; Tritthart, M; Prenner, D; Leitner, P; Moog, O; Habersack, H (2018): Monitoring and modelling concept for ecological optimized harbour dredging and fine sediment disposal in large rivers.
- Kessler Ch. (2013): Variantenuntersuchung der Verlandungsprozesse von Speicherseen der Vorarlberger Illwerke basierend auf numerischer Modellierung. Masterarbeit - Institut für Wasserwirtschaft, Hydrologie und konstruktiver Wasserbau (IWHW), BOKU-Universität für Bodenkultur, 159 S.