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

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

(based on Wren et al., 2000)

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

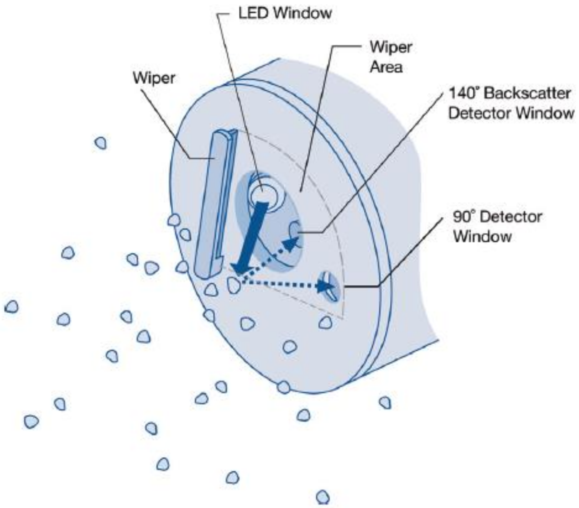
- Optical sensors:

Solitax ts-line

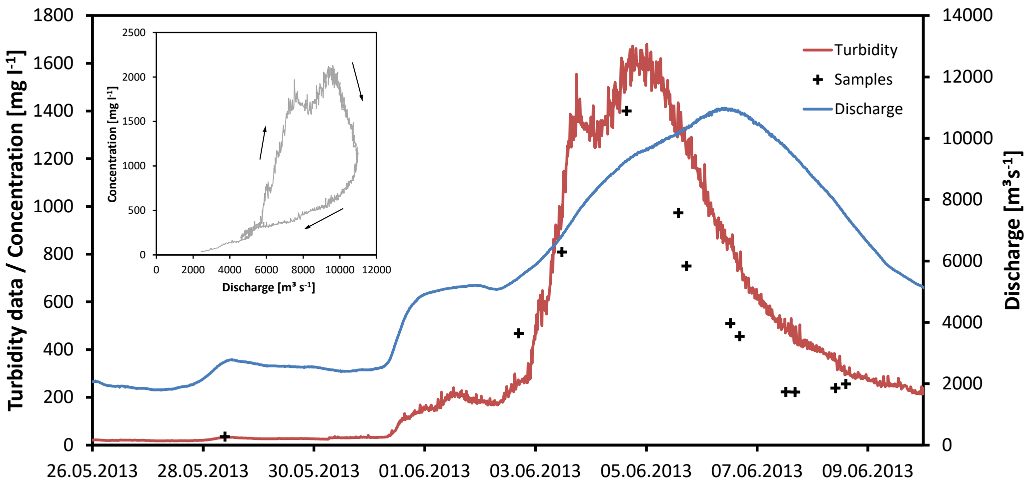
(https://at.hach.com)

S::can

(Bittner, 2008)



(https://at.hach.com/)



(Gmeiner et al., 2016, modified)

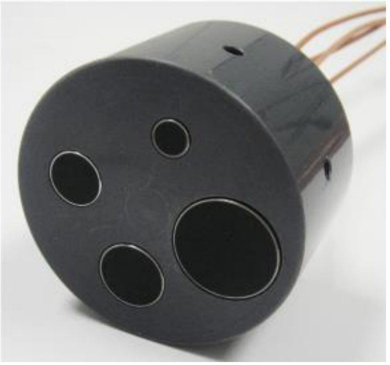
Suspended sediment monitoring techniques

- Acoustic devices:

Single frequency

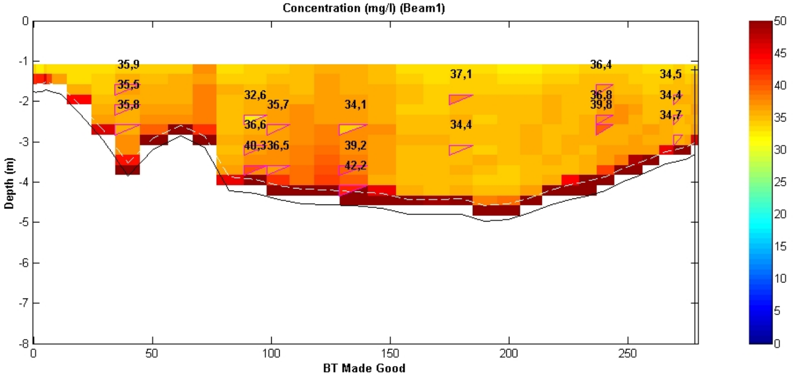
(https://www.sequoiasci.com)

Multi frequency



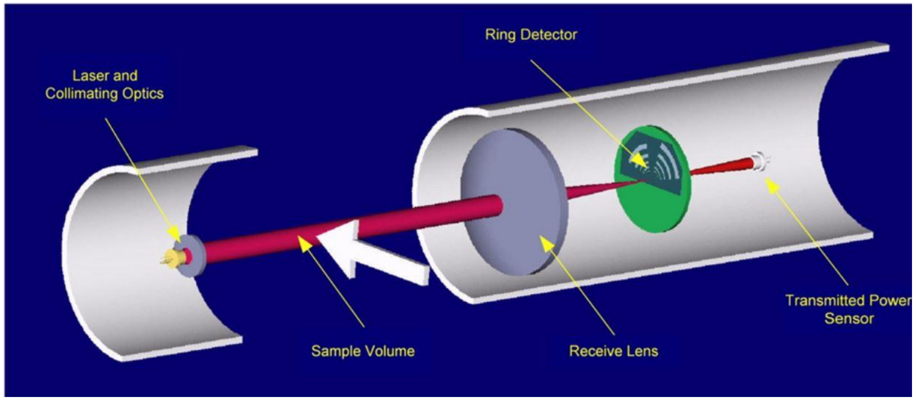
SediScat™ Pro

(http://www.hydrovision.de/)



Suspended sediment monitoring techniques

- Laser diffraction:



(https://www.sequoiasci.com)

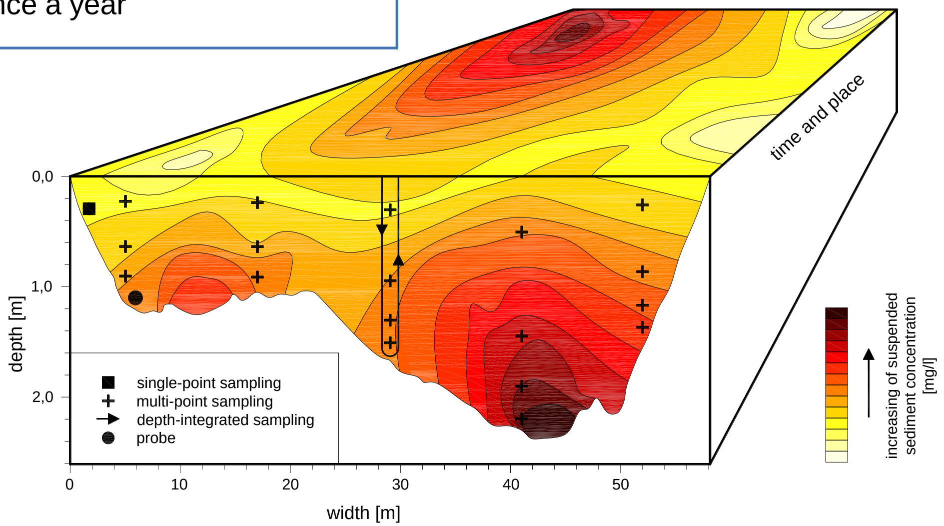
Refraction angle of laser incident on sediment particles is measured

Monitoring strategy

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

(BMLFUW, 2008; 2017)

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



(Haimann et al., 2014)

Data processing

Turbidity ← Probe characteristic $k_s = s_k / s_s$

Concentration close to the sensor ← Cross-sectional characteristic $k_p = s_m / s_k$

Mean concentration ← Discharge $Q_s = s_m \, Q$

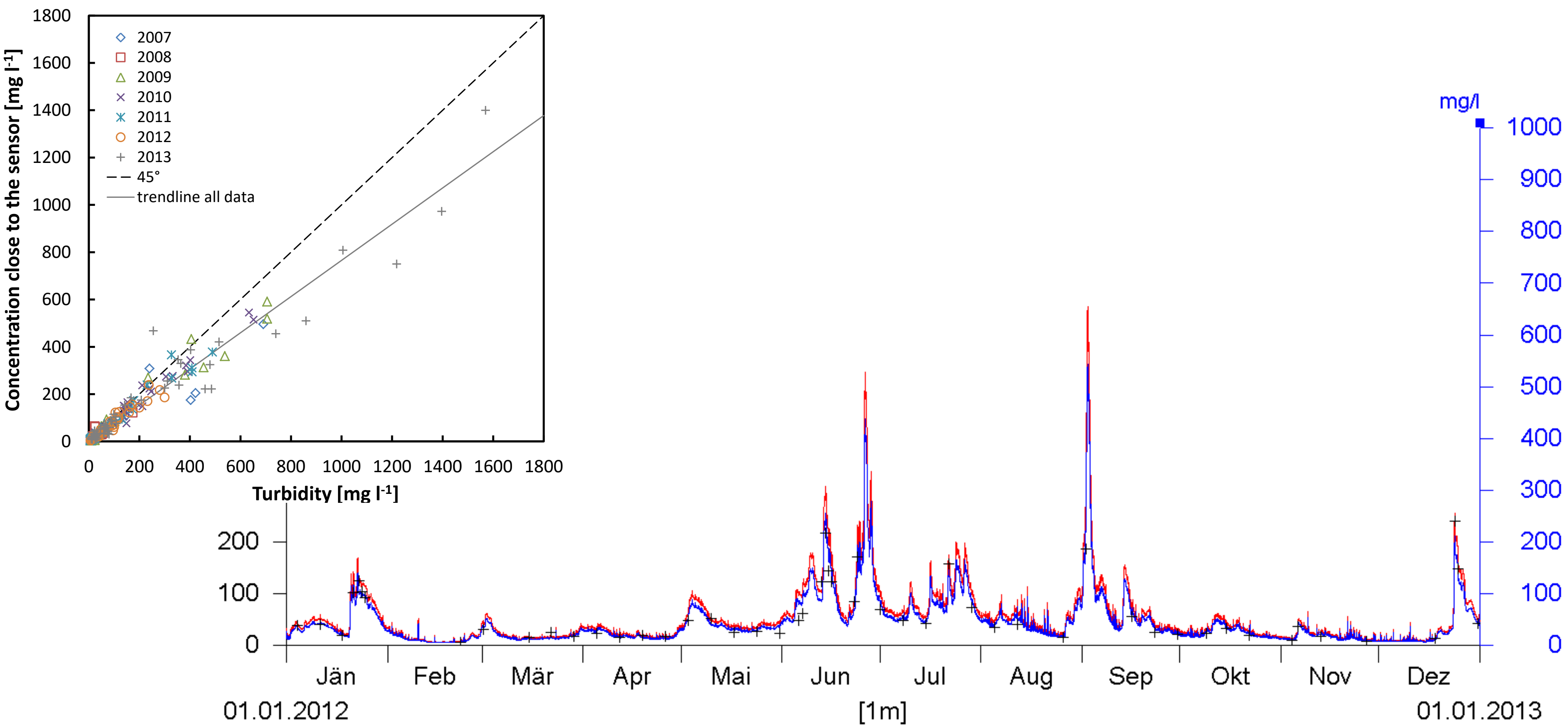
Suspended sediment transport ← Time $V_s = \int_{t_1}^{t_2} Q_s(t) \, dt$

Suspended sediment load

(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

↓ ← Probe characteristic $k_s = s_k / s_s$

Concentration close to the sensor

↓ ← **Cross-sectional characteristic $k_p = s_m / s_k$**

Mean concentration

↓ ← Discharge $Q_s = s_m \; Q$

Suspended sediment transport

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

Suspended sediment load

(Habersack et al., 2013)

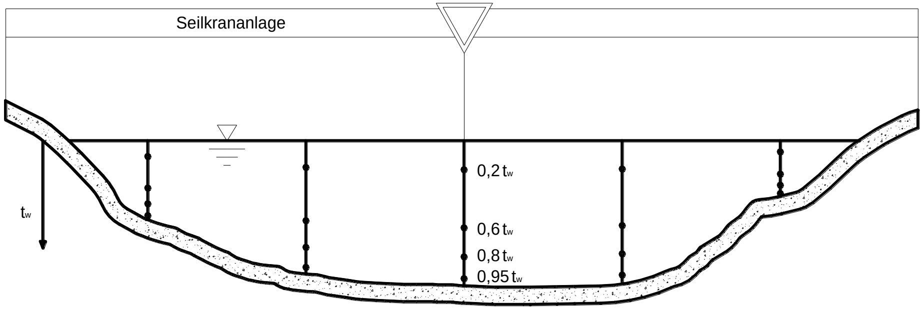
Cross-sectional measurements

- 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:

$$s_m = \frac{Q_s}{Q}$$



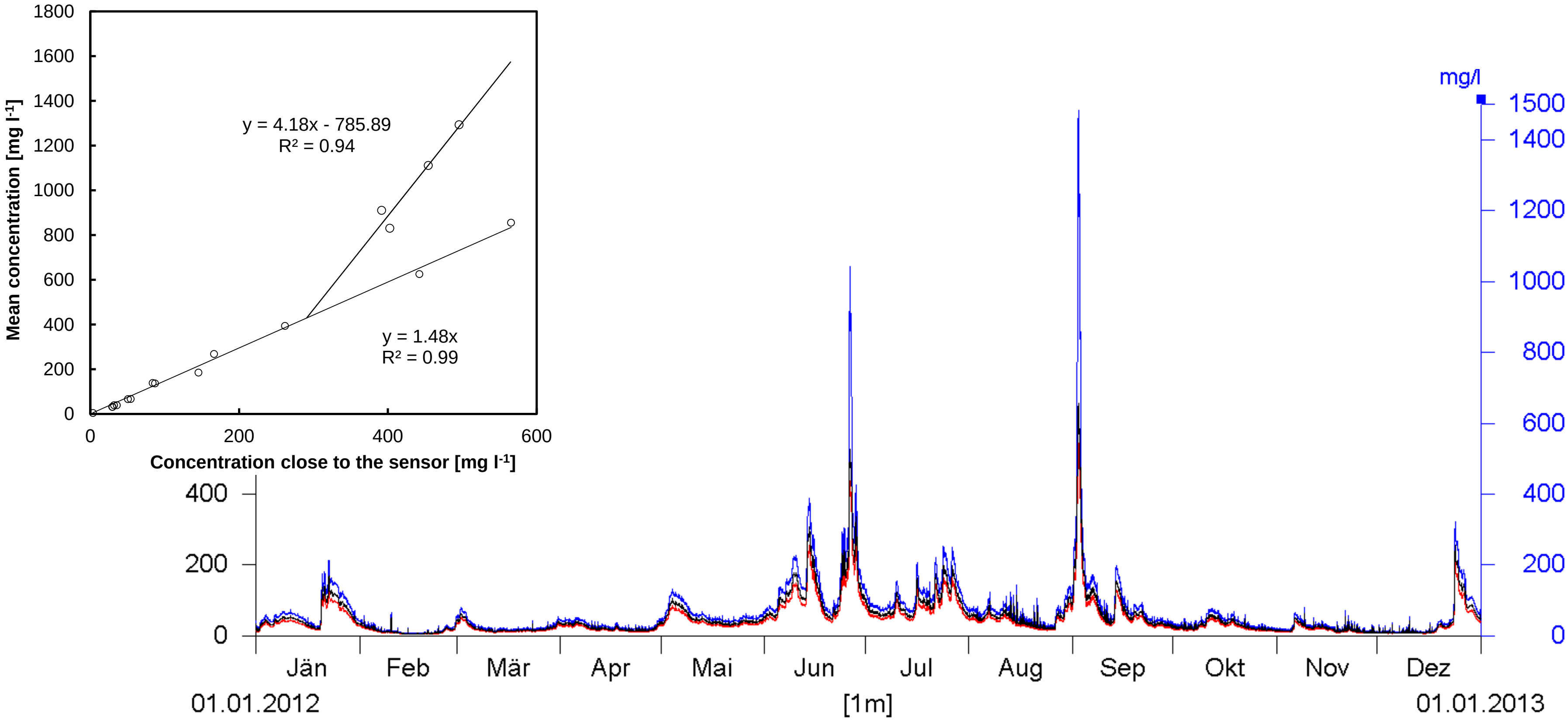
(BMLFUW, 2008; 2017)

determined by

- Multi-point sampling
- ADCP measurements combined with samples

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

↓ ← Probe characteristic $k_s = s_k / s_s$

Concentration close to the sensor

↓ ← Cross-sectional characteristic $k_p = s_m / s_k$

Mean concentration

↓ ← Discharge $Q_s = s_m \, Q$

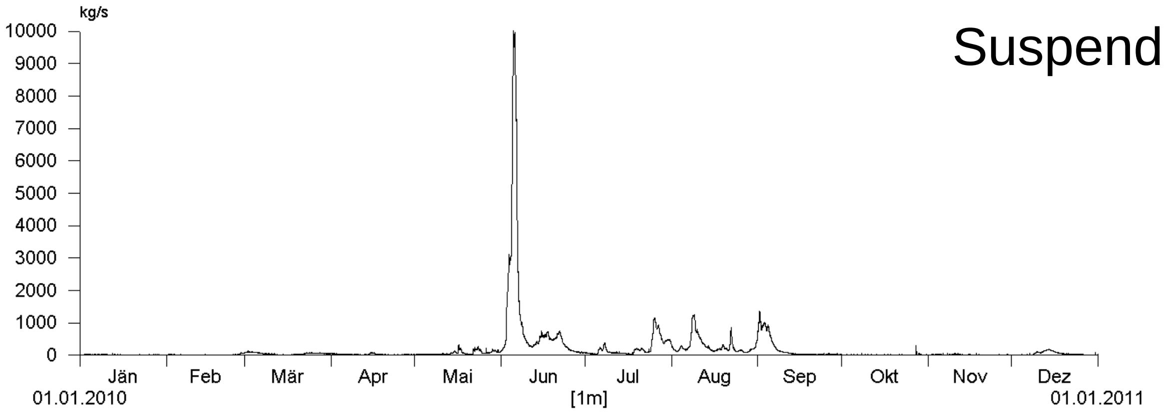
Suspended sediment transport

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

Suspended sediment load

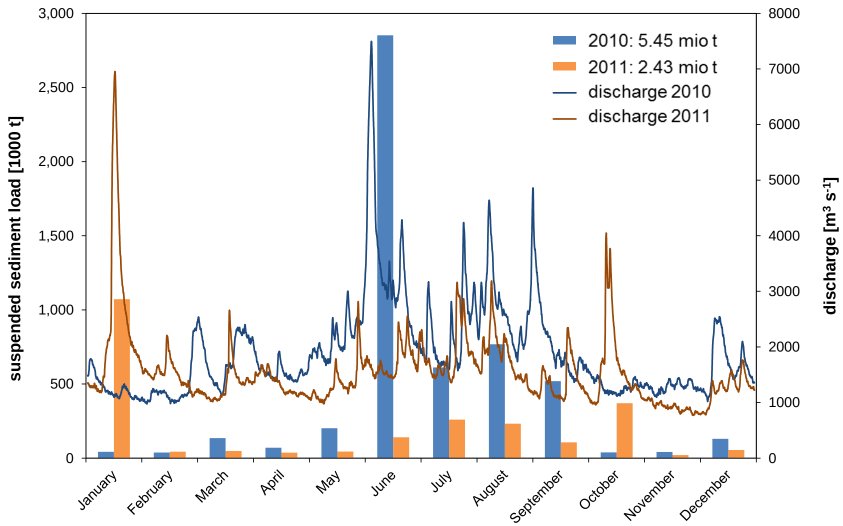
(Habersack et al., 2013)

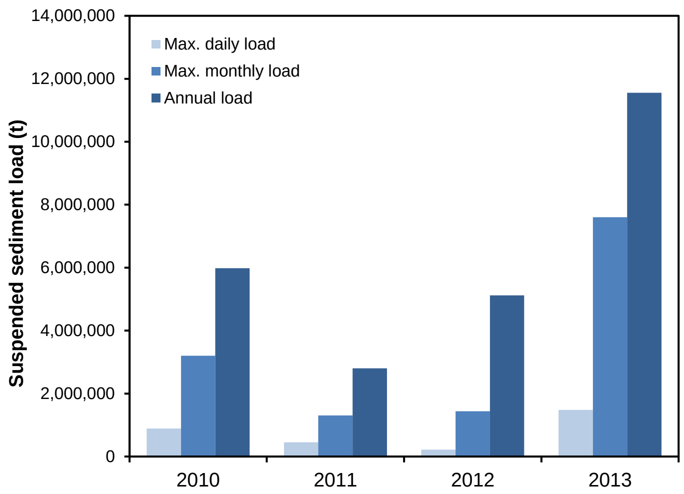
Data processing



Suspended sediment transport

Suspended sediment load





Suspended Sediment Monitoring

●●● highly suited for measuring this parameter
●● suited for measuring this parameter
● partially suited for measuring this parameter
- not suited to measure this parameter

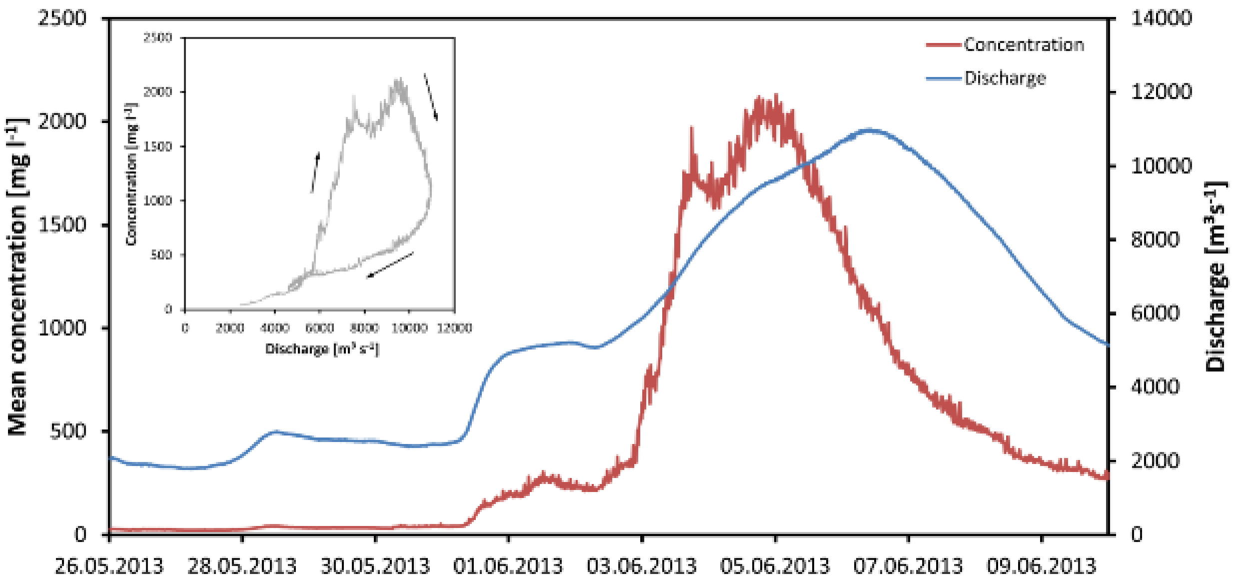
Suitability of monitoring methods – part of 1^{st} SedAlp milestone

Monitoring method / Parameter of Interest	Acoustic	Bottle sampling	Pump sampling	Focused beam reflectance	Laser diffraction	Nuclear	Optical	Remote spectral reflectance
Suspended sediment rate $[kg\ s^{-1}]$	●●	●	●●●	●	●	●	●●●	●
Total suspended sediment load [kg, t]	●●	●	●●●	●	●	●	●●●	●
Spatial variability of suspended load	●●	●	-	-	-	-	-	●●
Temporal variability of suspended load	●●	●	●	●	●	●	●●●	●●
Variation of sediment volume $[m, m^3]$	●●	●	●●	●	●	●	●●●	●
Initiation of motion $[m^3 s^{-1}]$	●●	-	-	●	●	-	●●●	-
Particle size distribution	●●●	●●	●●	-	-	●●	-	-

Habersack et al., 2015

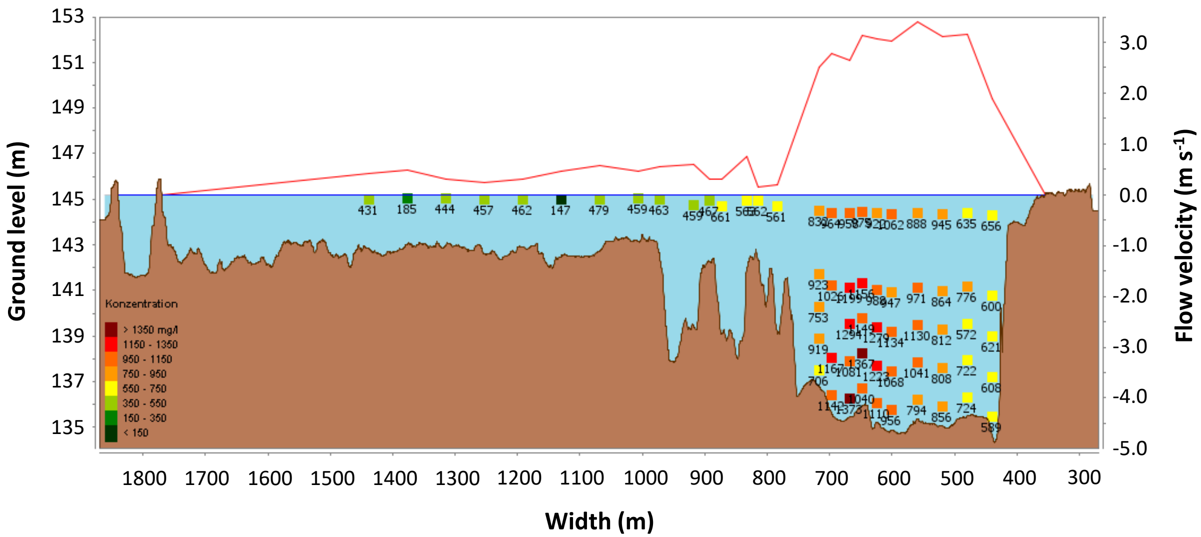
www.sedalp.eu

Suspended Sediments – Flood 2013



Habersack et al., 2015

Flood event June 2013

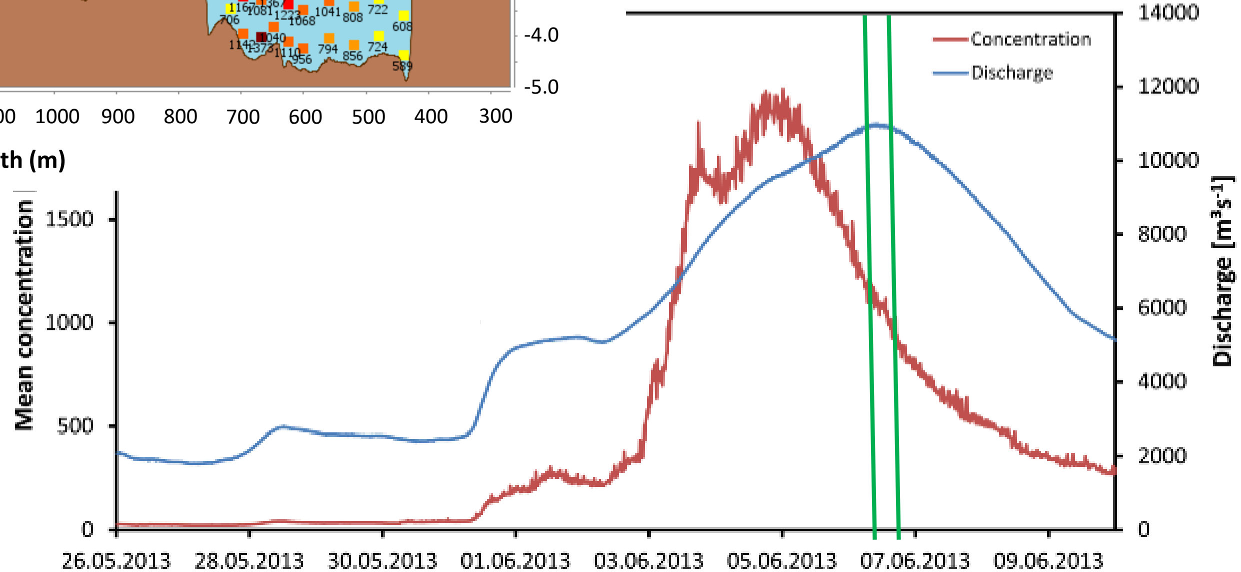


Multi-point measurement

$Q = 10{,}738\ m^3\ s^{-1}$

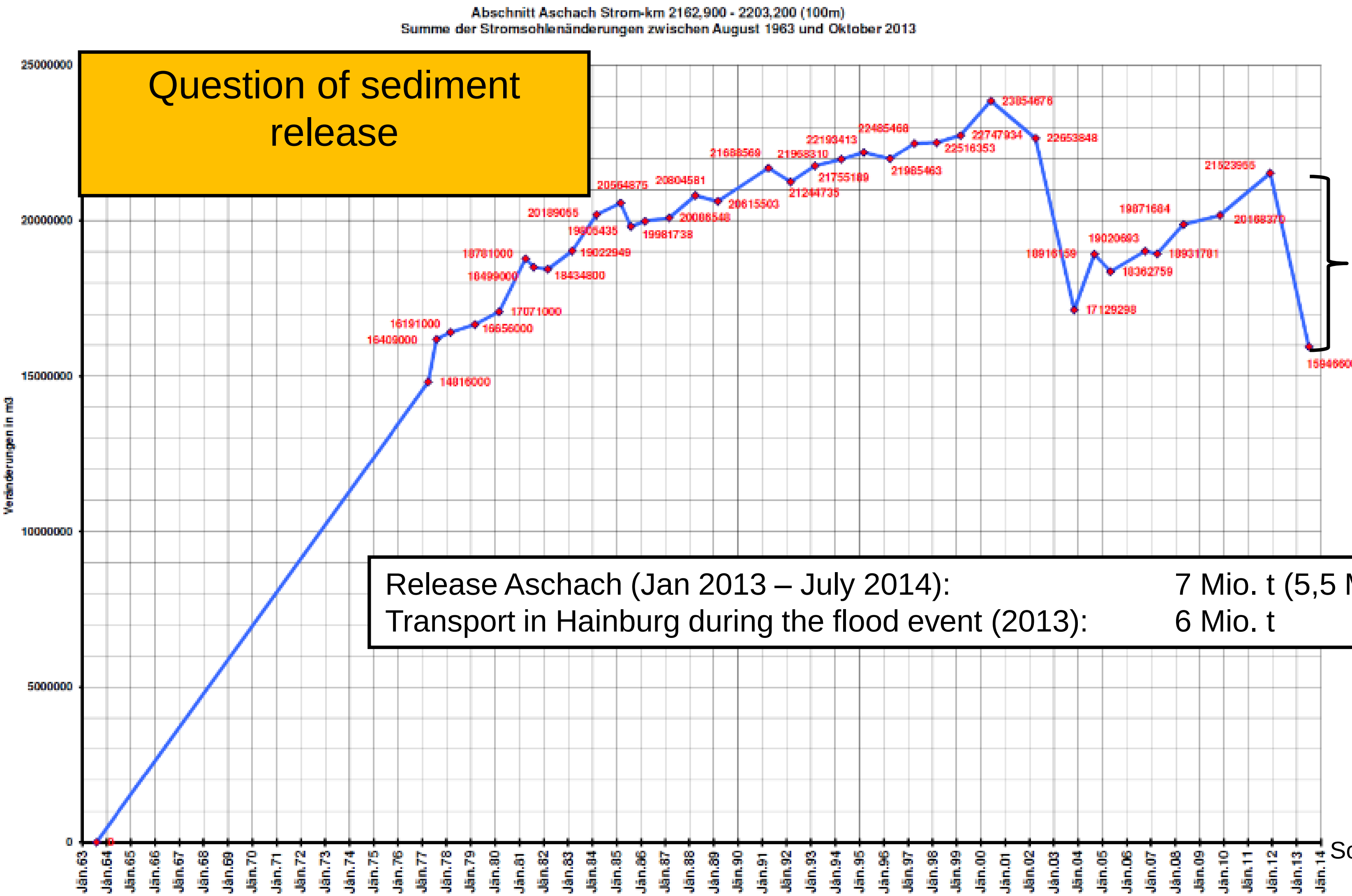
$s_m = 855.2\ mg\ l^{-1}$

$Q_s = 9{,}180\ kg\ s^{-1}$



Habersack et al., 2015

Remobilisation in a HPP reservoir



Question of sediment release

Release: 5,5 Mio. m^3

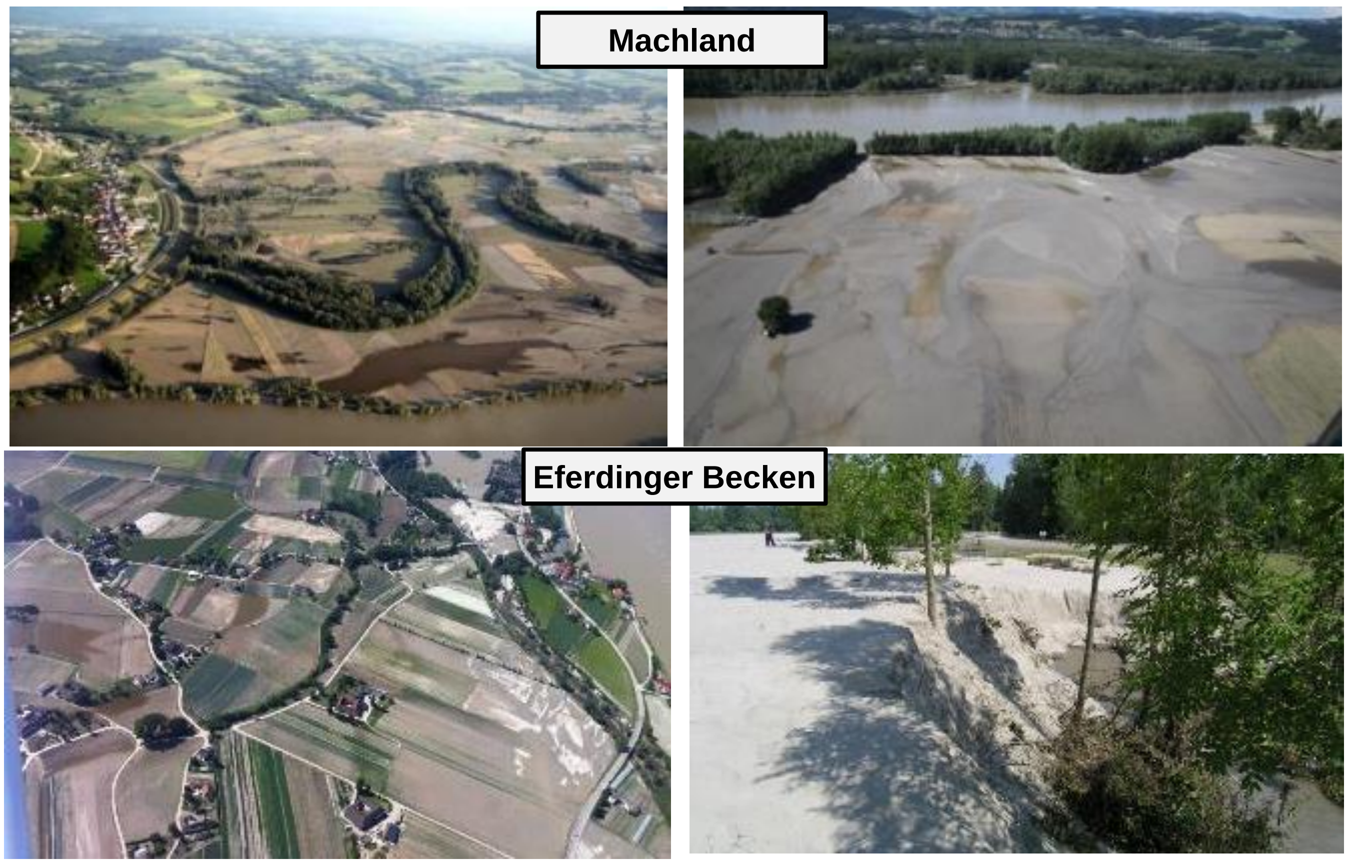
Release Aschach (Jan 2013 – July 2014): 7 Mio. t (5,5 Mio. m^3)
Transport in Hainburg during the flood event (2013): 6 Mio. t

Source: viadonau, verbund

Habersack et al., 2015

Sedimentation during flood 2013

Sediments: Deposion in floodplains



(Gmde Ardagger Markt, Pressl, 2013)

Verbund, Schmallfuss, 2013)

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*):

$$\frac{\partial c_i}{\partial t} + \frac{\partial (u_1 c_i)}{\partial x_1} + \frac{\partial (u_2 c_i)}{\partial x_2} + \left[\frac{\partial (u_3 c_i)}{\partial x_3}\right]$$
$$= \frac{\partial}{\partial x_1}\left(K_{t,1}\frac{\partial c_i}{\partial x_1}\right) + \frac{\partial}{\partial x_2}\left(K_{t,2}\frac{\partial c_i}{\partial x_2}\right) + \left[\frac{\partial}{\partial x_3}\left(K_{t,3}\frac{\partial c_i}{\partial x_3}\right)\right] + \left(s_{dep,i} - s_{ero,i}\right)$$

- 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):

$$s_{dep,i} = w_{ci} \frac{c_i}{F_i} \qquad F_i = \frac{\left(\frac{z_{0i}}{h}\right)^{Z_i^{*'}} - \left(\frac{z_{0i}}{h}\right)^{\beta_n}}{\left(1 - \frac{z_{0i}}{h}\right)^{Z_i^{*'}} \left(\beta_n - Z_i^{*'}\right)}$$

- Erosion flux following Garcia and Parker (1991):

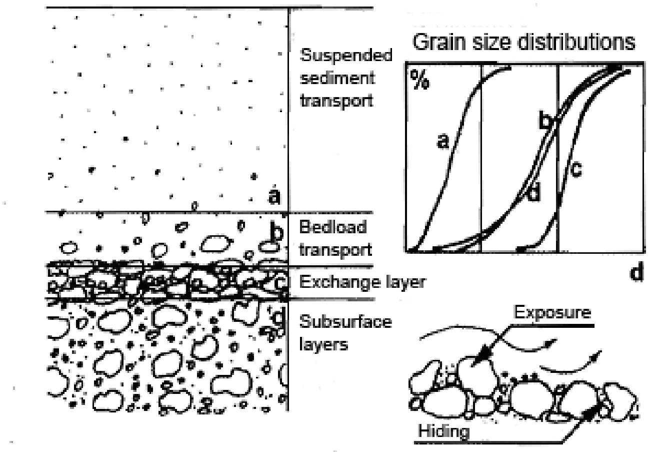
$$s_{ero,i} = w_{ci} p_i E_{sk,i} \qquad E_{sk,i} = \frac{A\left(\lambda Z_{mi}\right)^5}{1 + \frac{A}{0,3}\left(\lambda Z_{mi}\right)^5}$$

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:

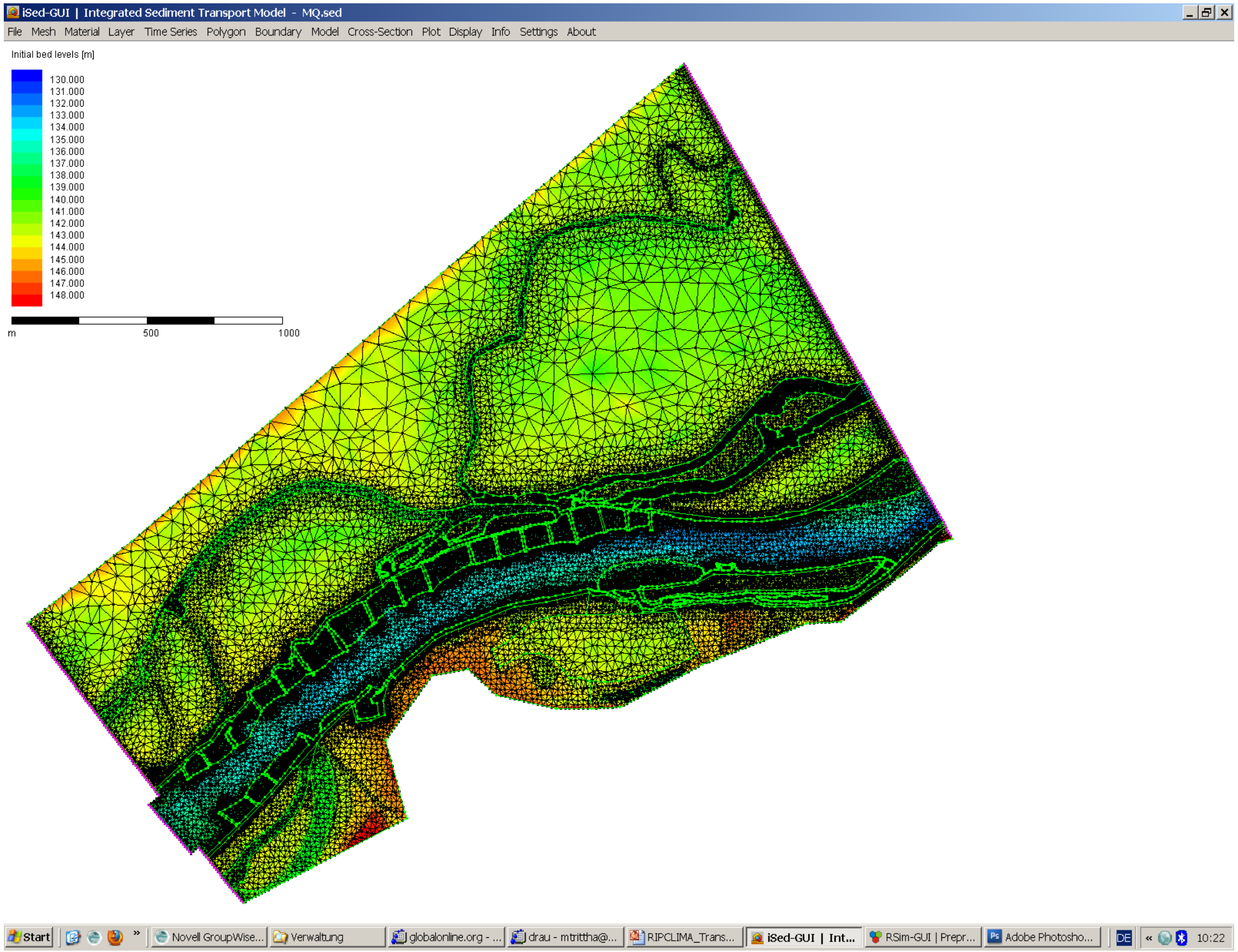


(modified after ATV-DVWK, 2003)

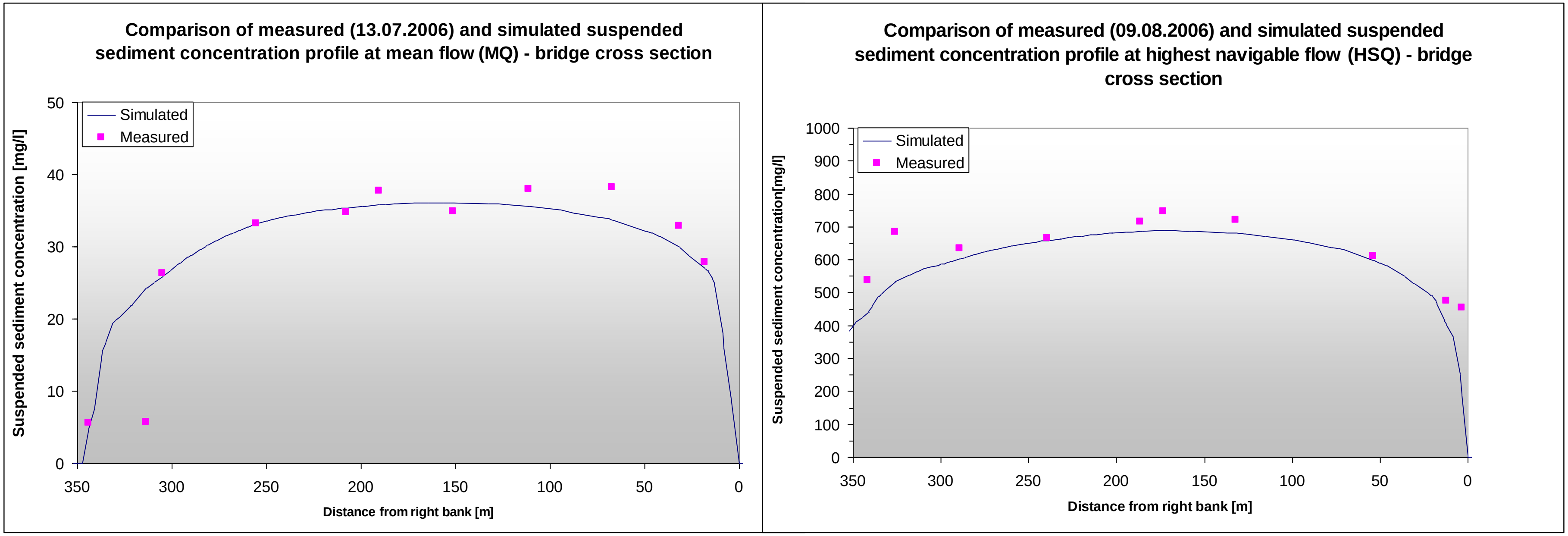
Modelling example #1 – Danube River

Upstream view (photo: courtesy National Park Donauauen)

Model setup: computation mesh



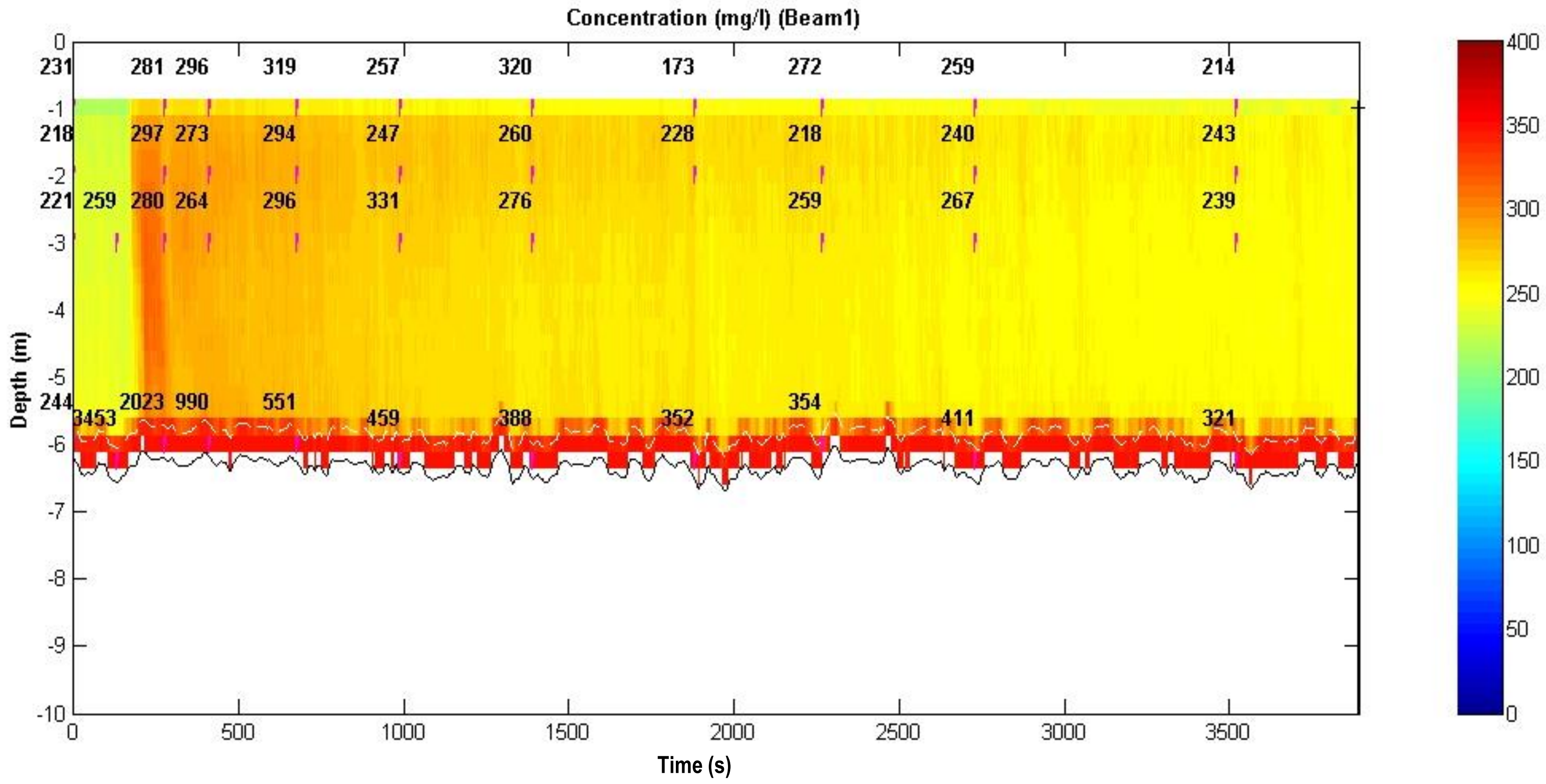
Validation of model results based on measurements



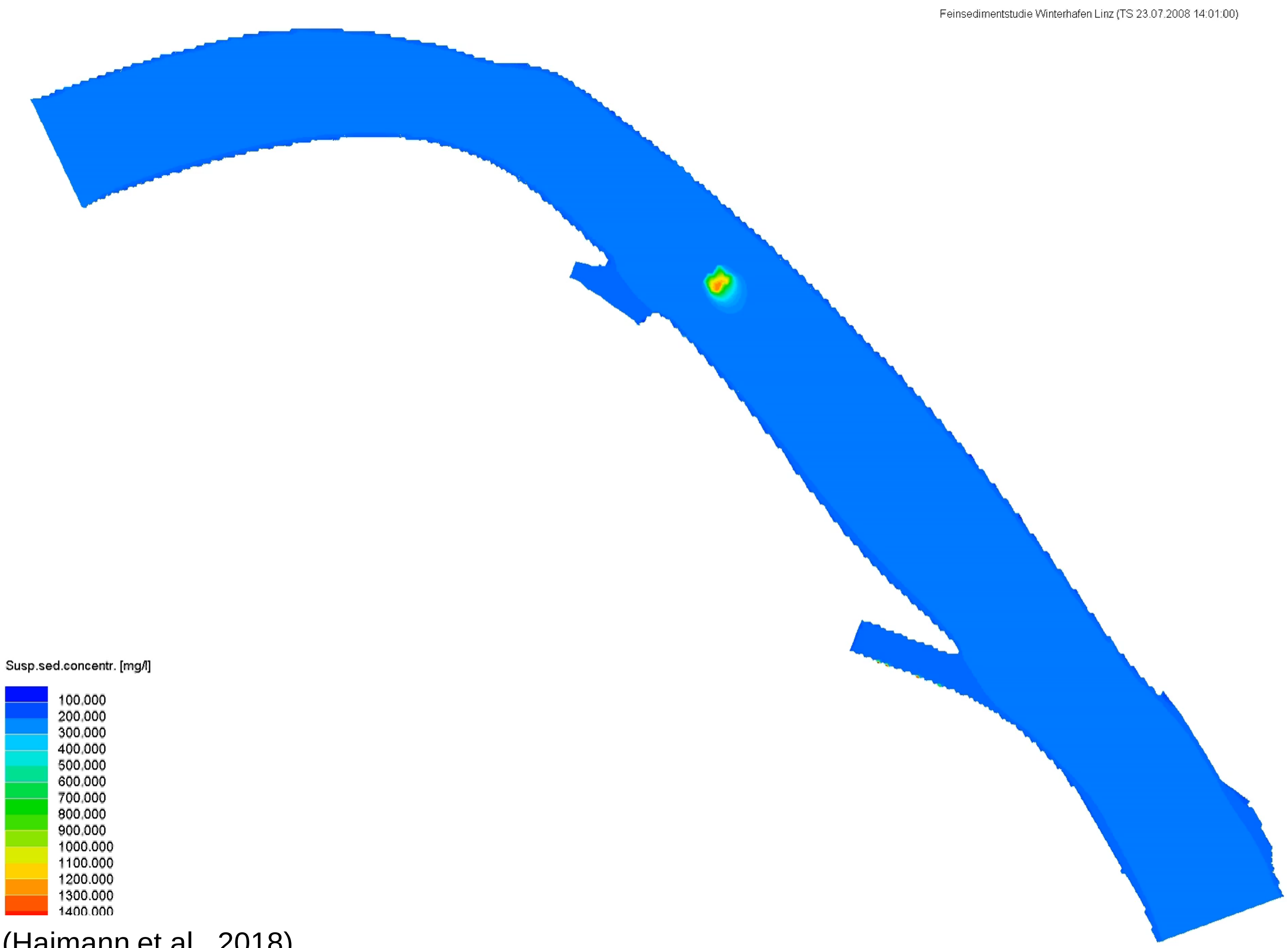
Suspended load: cross-section measurements using a US P-61-A sampler vs. simulation results

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 m³/s

(Haimann et al., 2018)

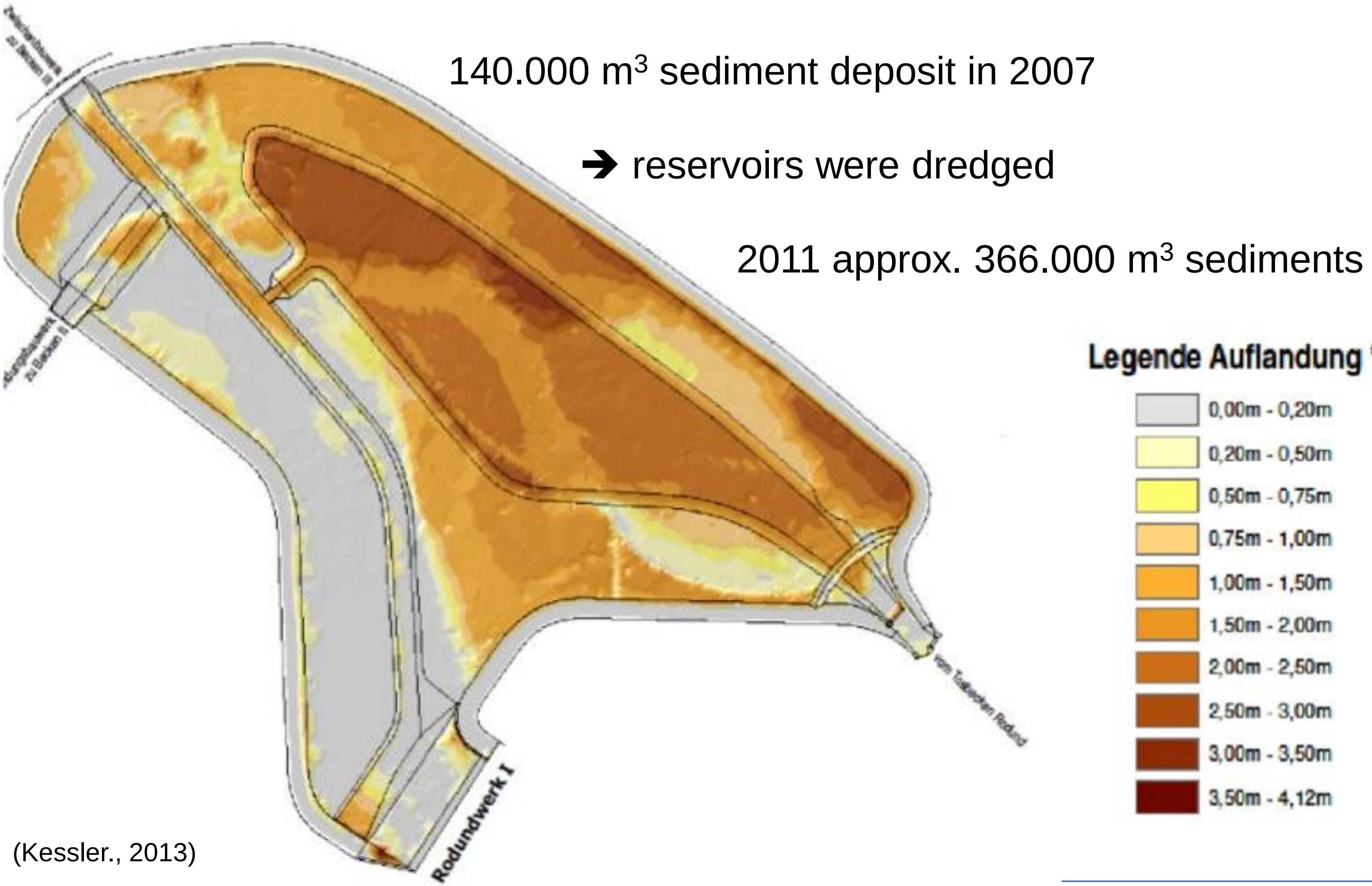
Modelling example #2: Rodund reservoir

Sedimentation in reservoir no. 1

140.000 m³ sediment deposit in 2007

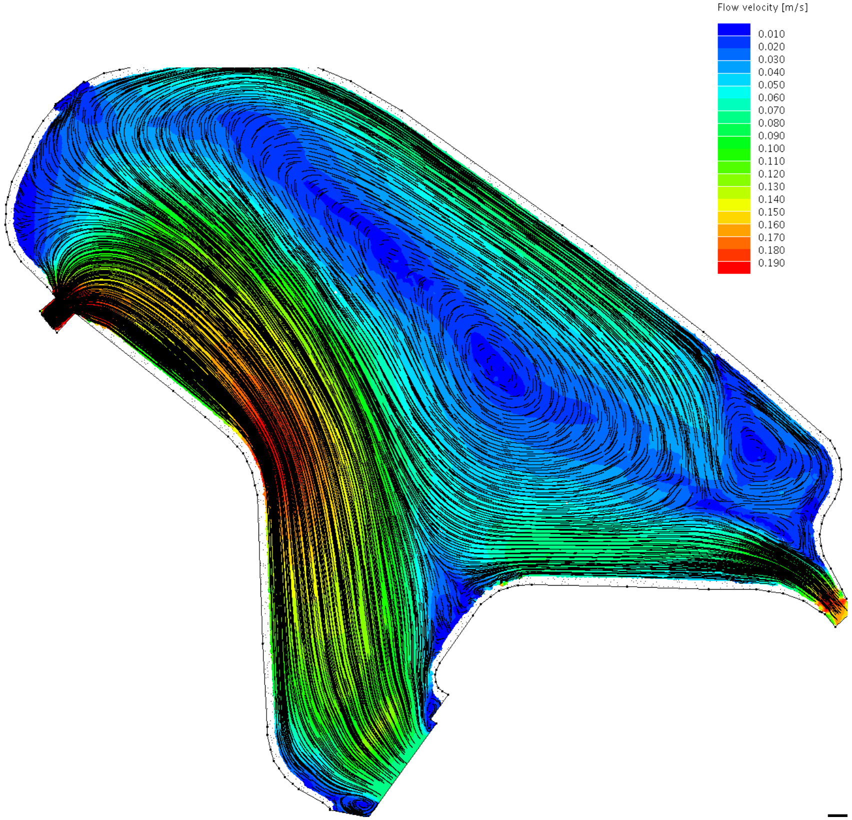
➔ reservoirs were dredged

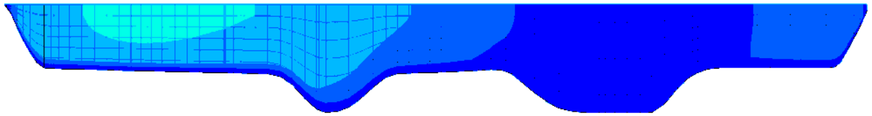
2011 approx. 366.000 m³ sediments

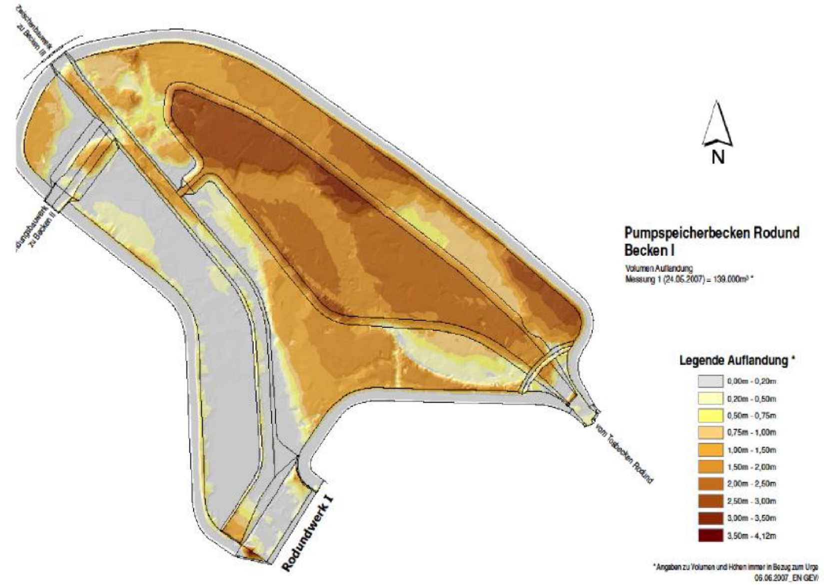


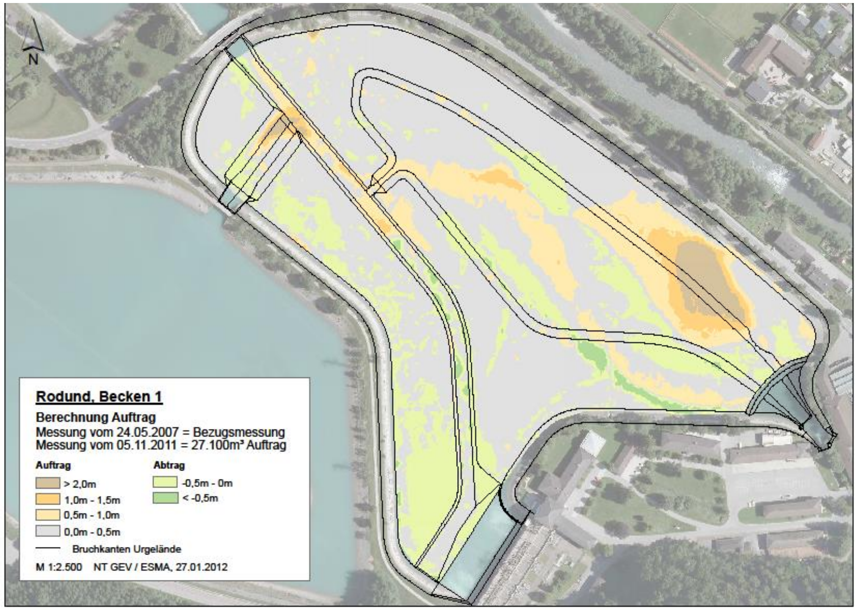
(Kessler., 2013)

Model calibration

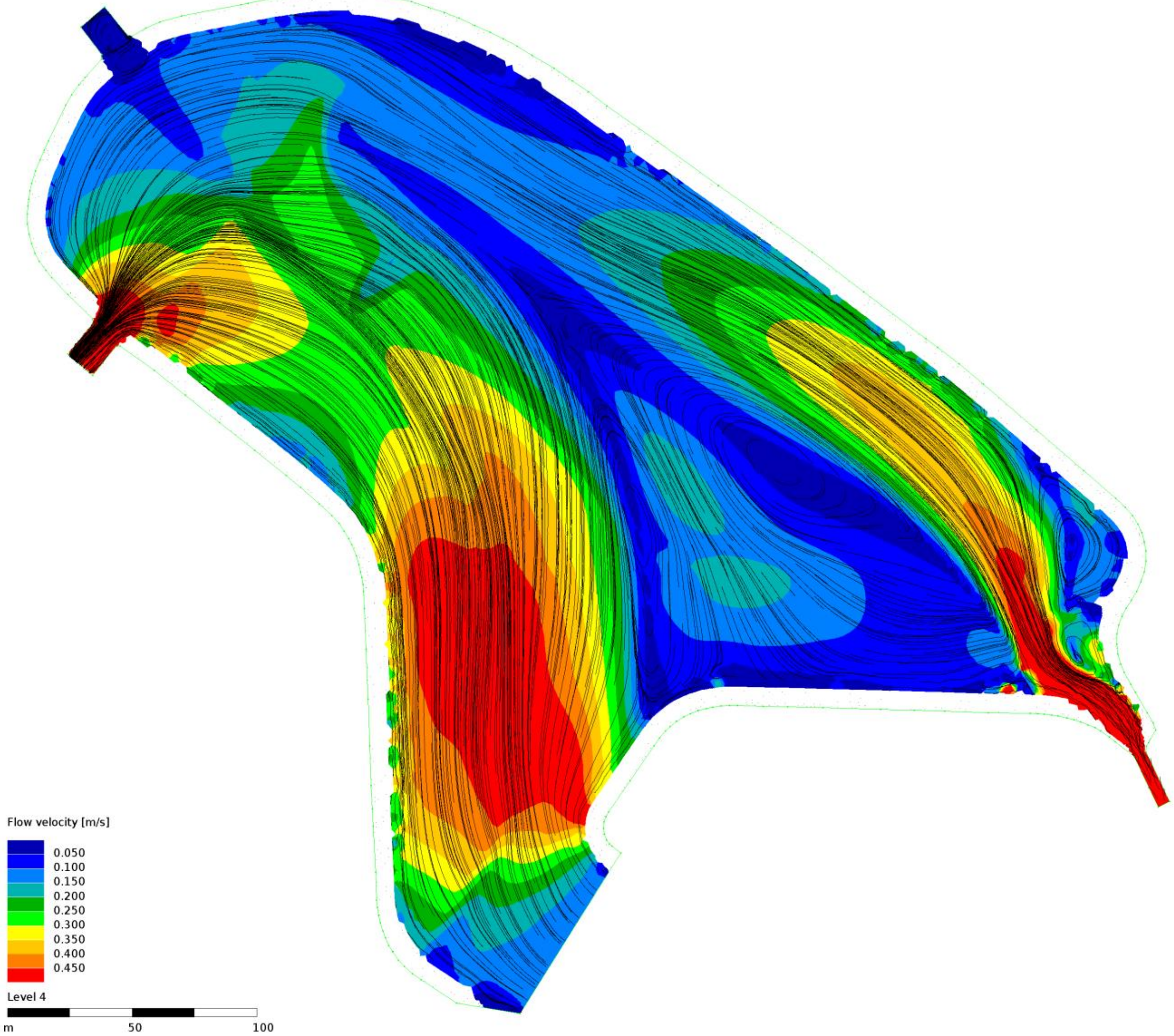




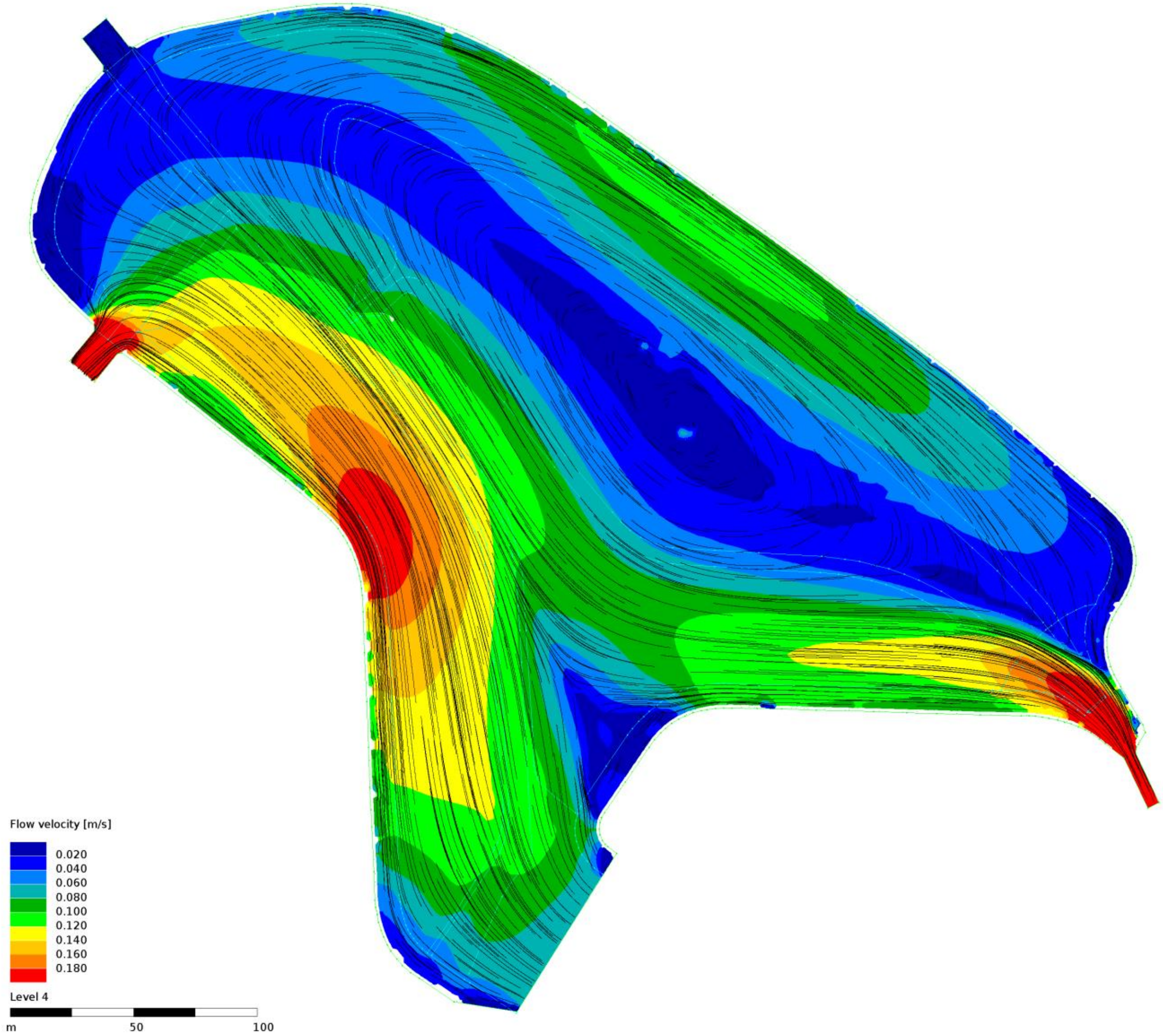




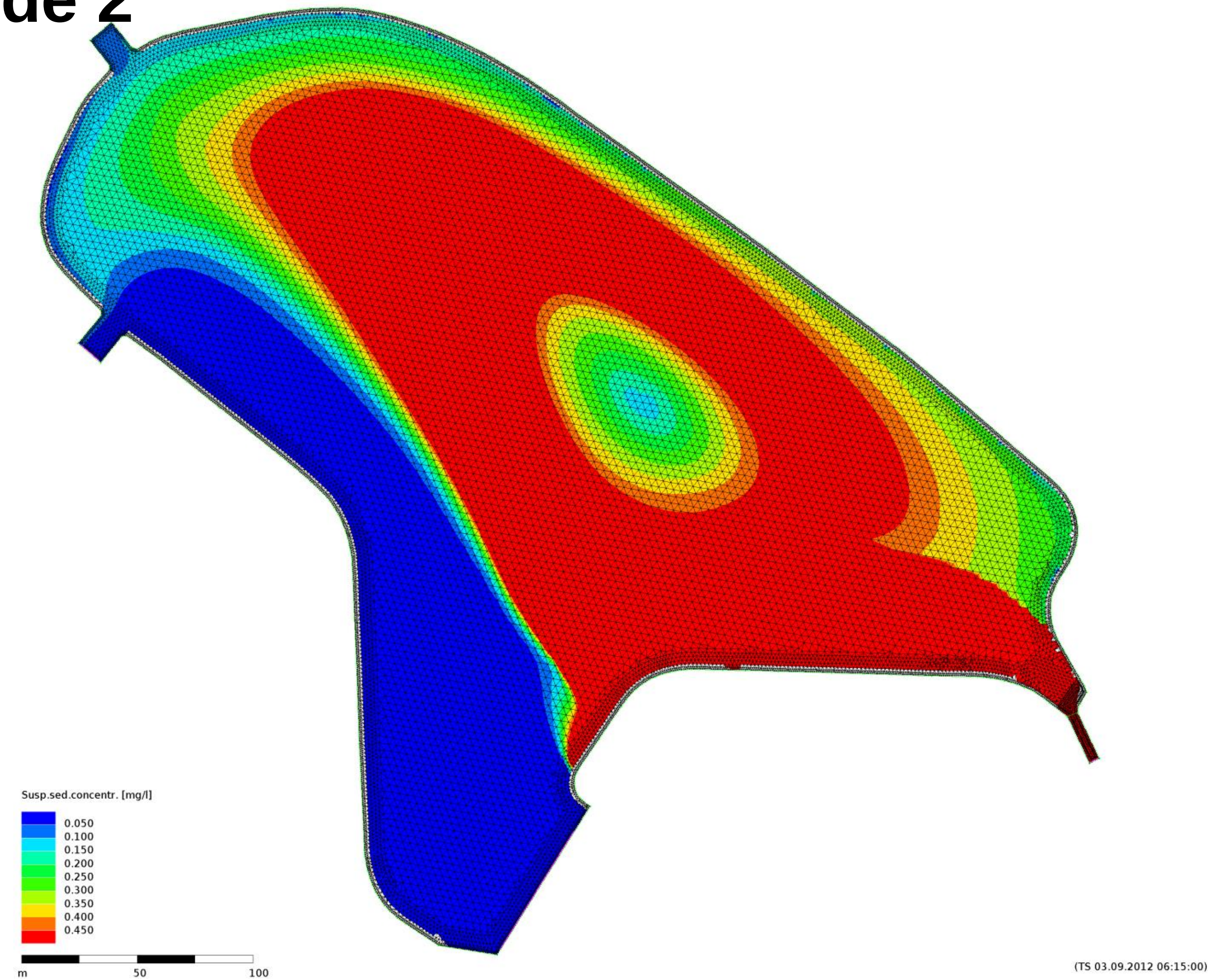
Flow field in operation mode 1 (pump operation)



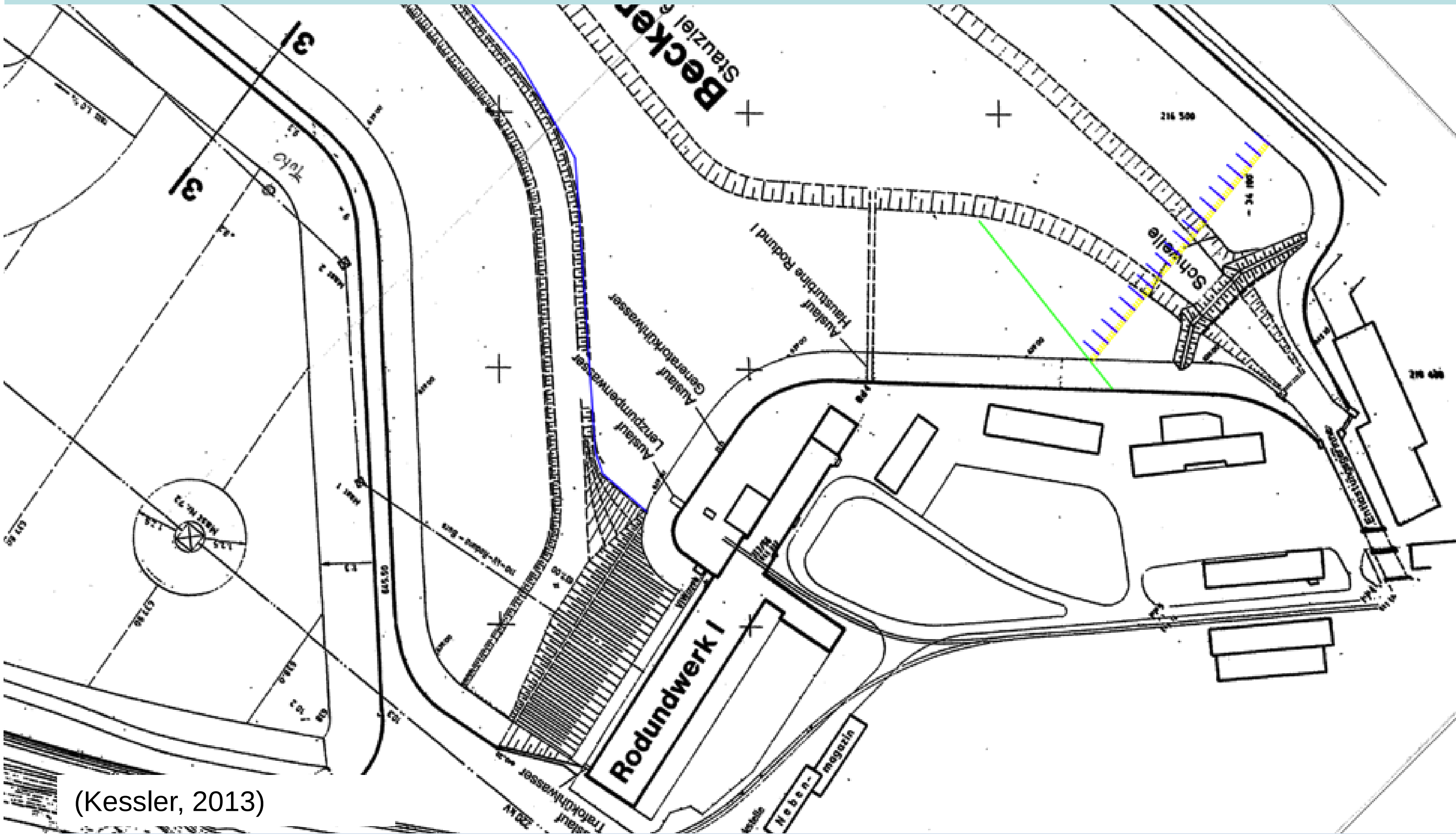
Flow field in operation mode 2 (turbine operation)



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

- Bittner G. (2008): Vergleich von Trübungssonden bei der Schwebstoffmessung unter definierten Laborbedingungen, Diplomarbeit, Universität für Bodenkultur, Wien.
- BMLFUW (2008; 2017): Schwebstoffe im Fließgewässer - Leitfaden zur Erfassung des Schwebstofftransports (Austrian Guideline of surveying suspended sediment transport) https://www.bmnt.gv.at/wasser/wasser-oesterreich/wasserkreislauf/Schwebstoffe_LF.html
- Gmeiner P., Liedermann M., Haimann M., Tritthart M., Habersack H. (2016): Grundlegende Prozesse betreffend Hydraulik, Sedimenttransport und Flussmorphologie an der Donau. Österreichische Wasser- und Abfallwirtschaft, 68, 208-216; ISSN 0945-358X
- Habersack H., Liedermann M., Tritthart M., Haimann M., Kreisler A. (2013): Innovative Approaches in Sediment Transport Monitoring and Modelling. In: IAHR, Proceedings of 2013 IAHR World Congress.
- Habersack, H., Aigner, J., Rindler, R., Blaumauer, B., Wagner, B., et al., 2015. Sediment Transport Monitoring, Final Report WP5, Alpine Space Project SedAlp (Sediment Management in Alpine Basins: Integrating Sediment Continuum, Risk Mitigation and Hydropower) (256 pp.).
- Haimann M., Liedermann M., Lalk P., Habersack H. (2014): An integrated suspended sediment transport monitoring and analysis concept. Int J Sediment Res.; 29(2): 135-148.
- 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.
- HYDROBIOLOGIA; 814(1): 89-107.
- 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.
- Tritthart M., Liedermann, M., Schober, B., Habersack, H. (2011): Non-uniformity and layering in sediment transport modelling 2: river application. Journal of Hydraulic Research; 49(3): 335-344.