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Bypass tunnels to route sediment around dams

Robert M. Boes, M. Müller-Hagmann, C. Auel, M. Facchini, I. Albayrak, A. Siviglia

Sediment Management in channel networks: from measurements to best practices

Bozen-Bolzano, 8 November 2018

Laboratory of Hydraulics, Hydrology and Glaciology

Content

Bypass tunnels (SBTs) to route sediment around dams

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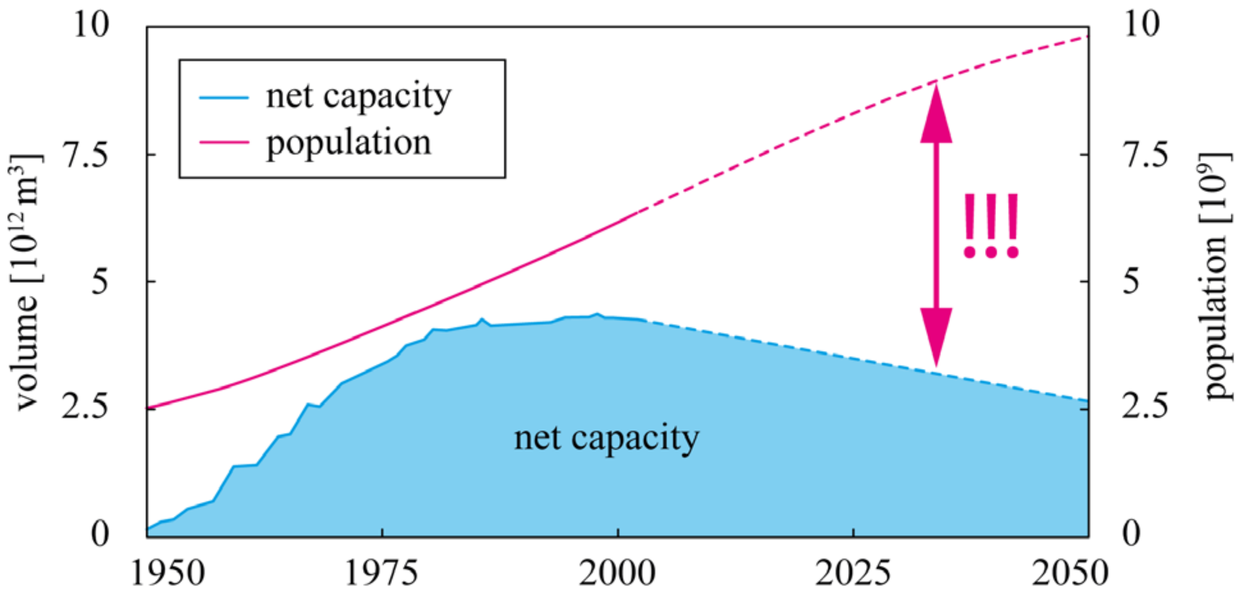
1. MOTIVATION

Photo: D. Ehrbar, VAW

Aggradation pattern in *Gries reservoir*, Switzerland, with lowered reservoir level during refurbishment works at the dam on 2 July 2015

Reservoir sedimentation



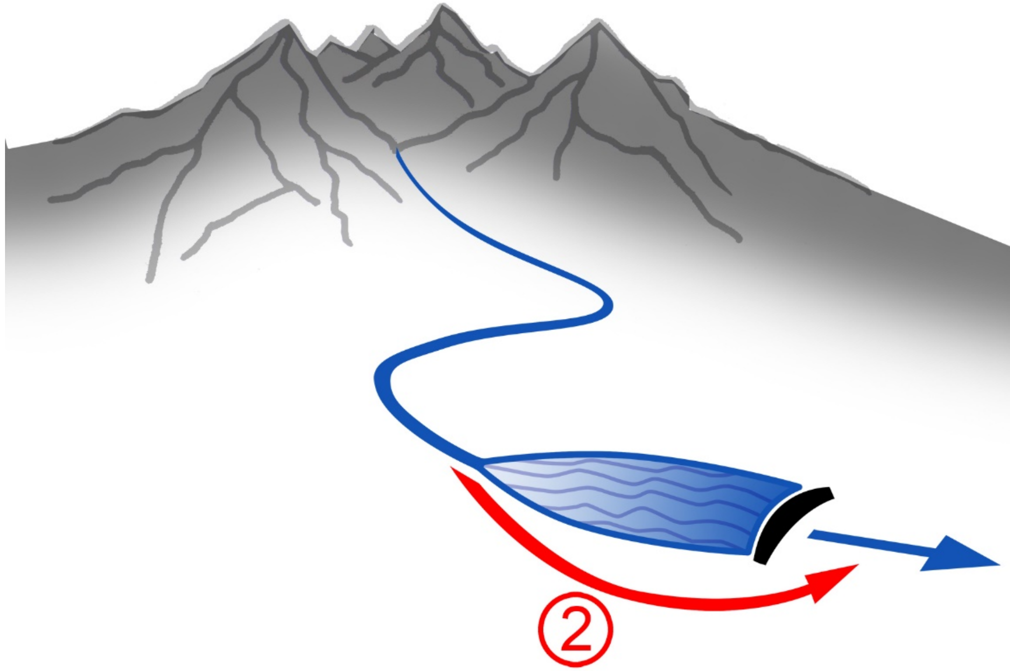
Based on White (2001), ICOLD (2009) and Annandale (2013)

- Increasing demand vs. decreasing capacity
- Sediment deficit in the downstream

→ Sustainable use of reservoirs requires efficient sediment management

Sediment management to counter reservoir sedimentation

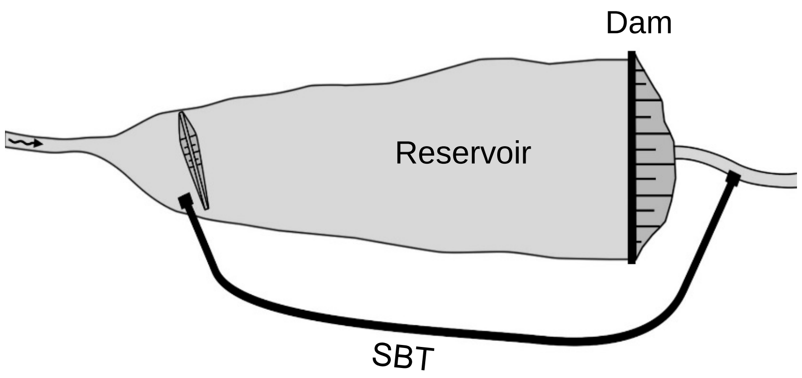
1. Sediment yield reduction in the catchment
2. **Sediment routing**
3. Sediment removal
4. Optimized reservoir and dam layout and location

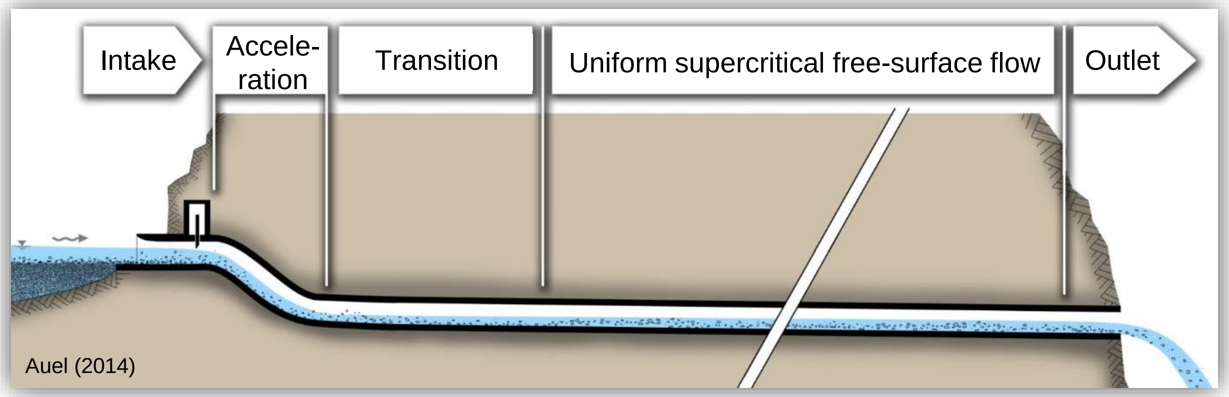


② Sediment Bypassing

2. CHARACTERISTICS AND HYDRAULICS OF SBTs

Characteristics of Sediment Bypass Tunnels (SBTs)





Auel (2014)

Effects:

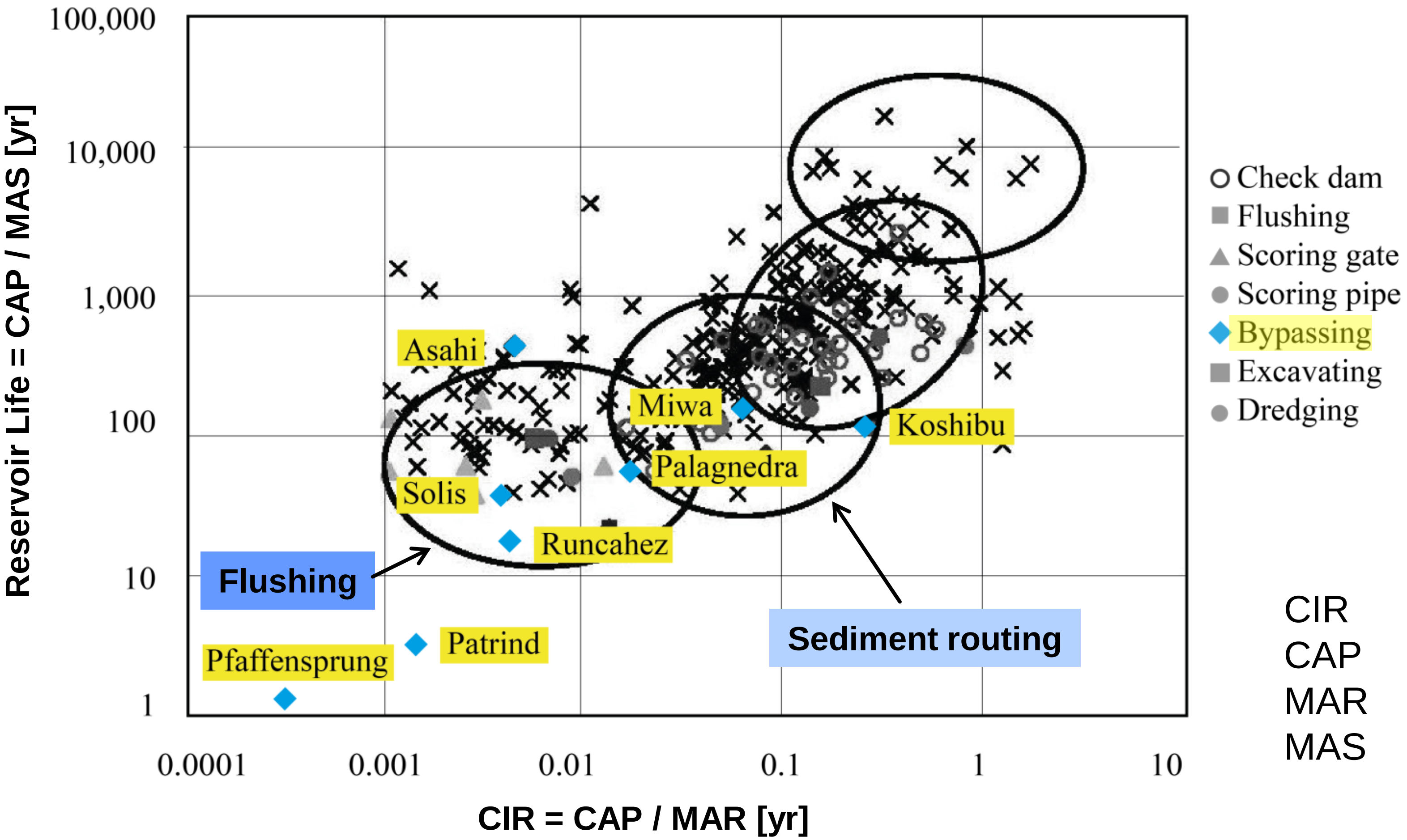
- Reduce reservoir sedimentation
- (partly) restore pre-dam sediment transport
- Recover downstream reach from sediment deficit

Operating conditions:

- High-velocity flow
- High sediment transport rates

→ Hydro-abrasion

Typical application range of SBTs



Source: adapted from Sumi (2005)

Sediment bypassing:
CIR < 0.3 … 0.4

CIR	Capacity Inflow Ratio [yr]
CAP	CAPacity of reservoir [Mm^3]
MAR	Mean Annaul Runoff [Mm^3/yr]
MAS	Mean Annaul Sedimentation [Mm^3/yr]

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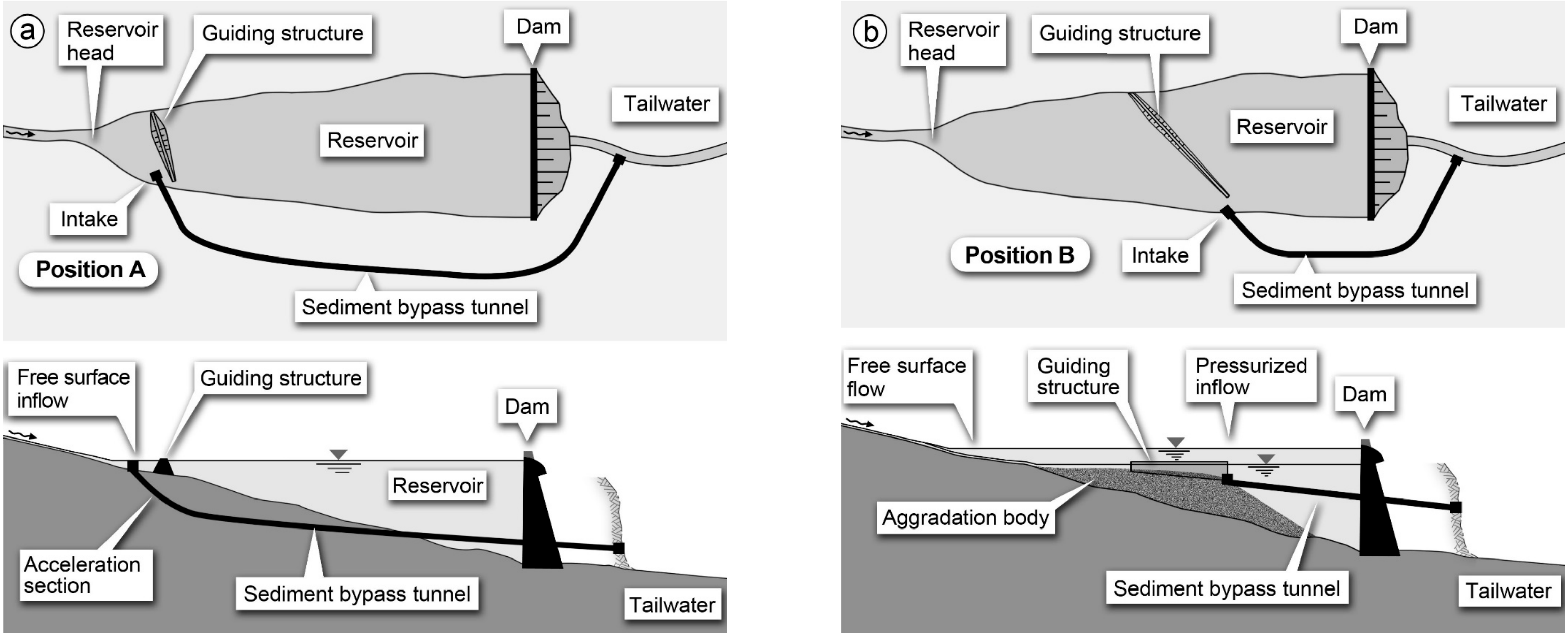
Location of intake structure

typically requires partial reservoir drawdown



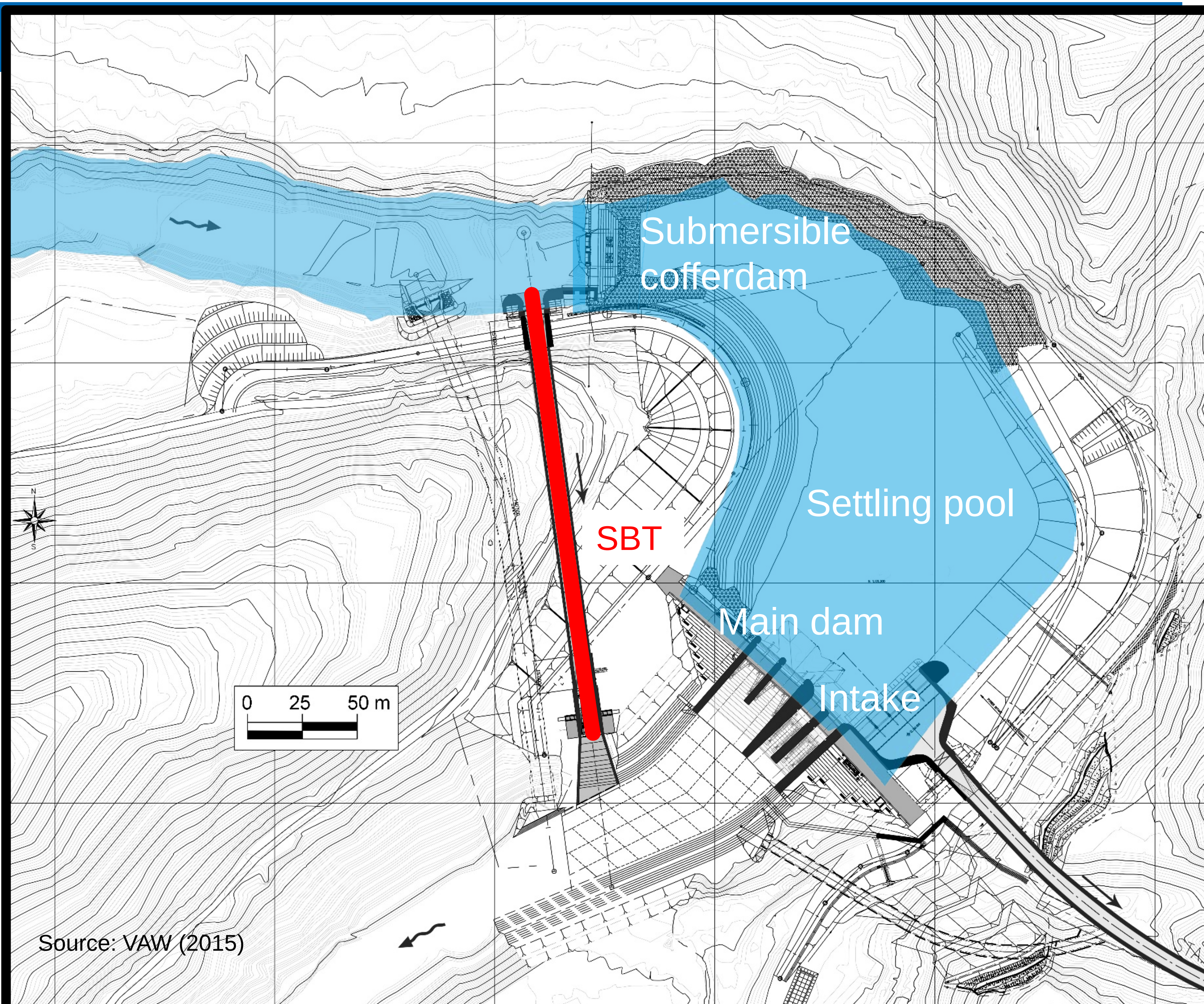
Source: Auel & Boes (2011)

Examples of SBTs

SBT Patrind, Pakistan

SBT particularly apt for smaller reservoirs, where

- **delta formation by coarse material (bed load)** is dominant
- **deposition of fines (suspended load) is rather small** due to short resident times
- **tunnel length** is **short**
- **water availability** is **high**

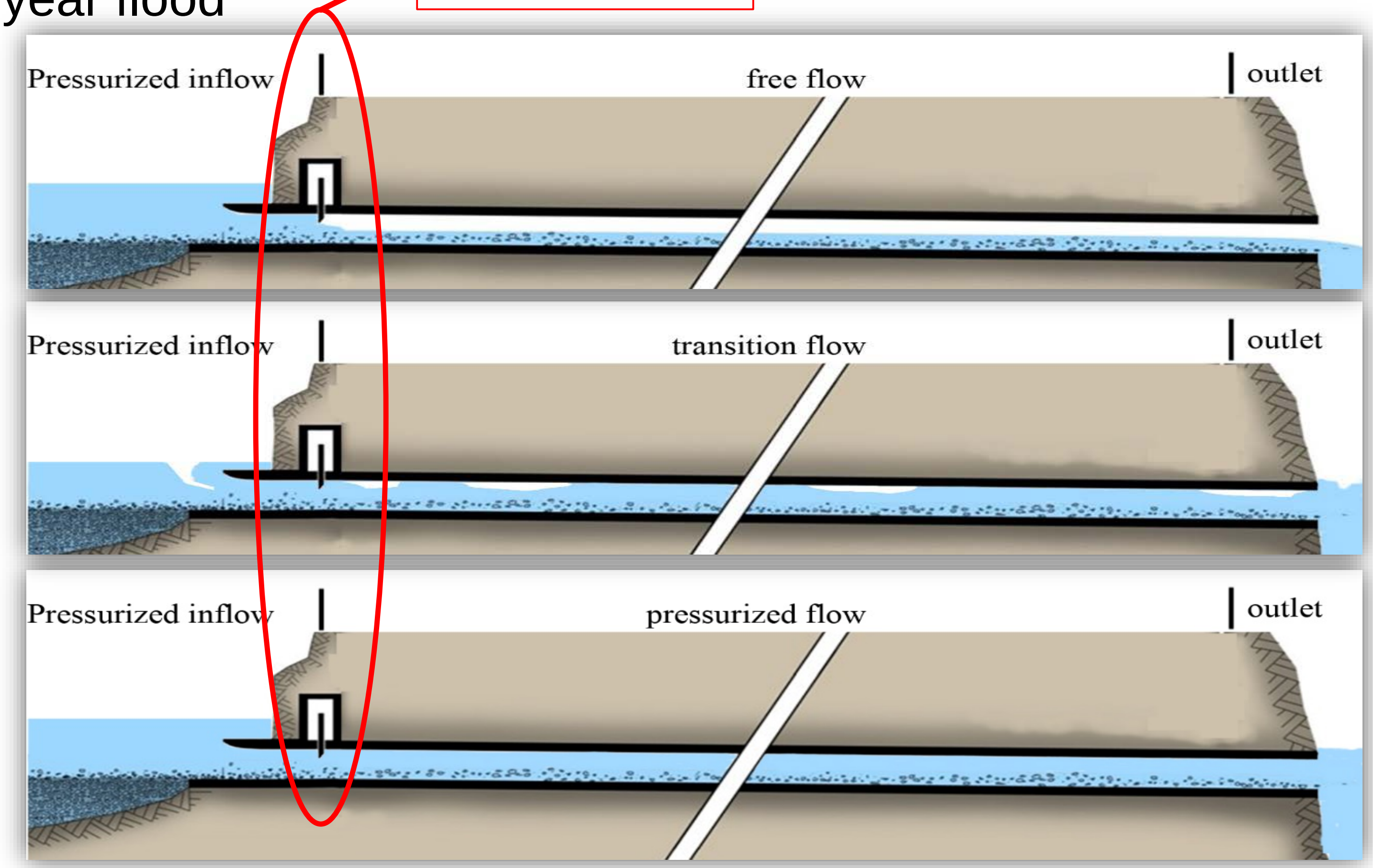


Source: VAW (2015)

Hydraulic characteristics of SBTs

- Free-surface, transition or pressurized flow
- **Supercritical flow**, typically with $\mathbf{F}_d$ < 3.2 at design flow Q_d (Auel 2015)
- **Significant sediment transport**
- Typical **design flow capacity** 5- to 10-year flood

Hydraulic
control section



Free-surface flow for small *Q*

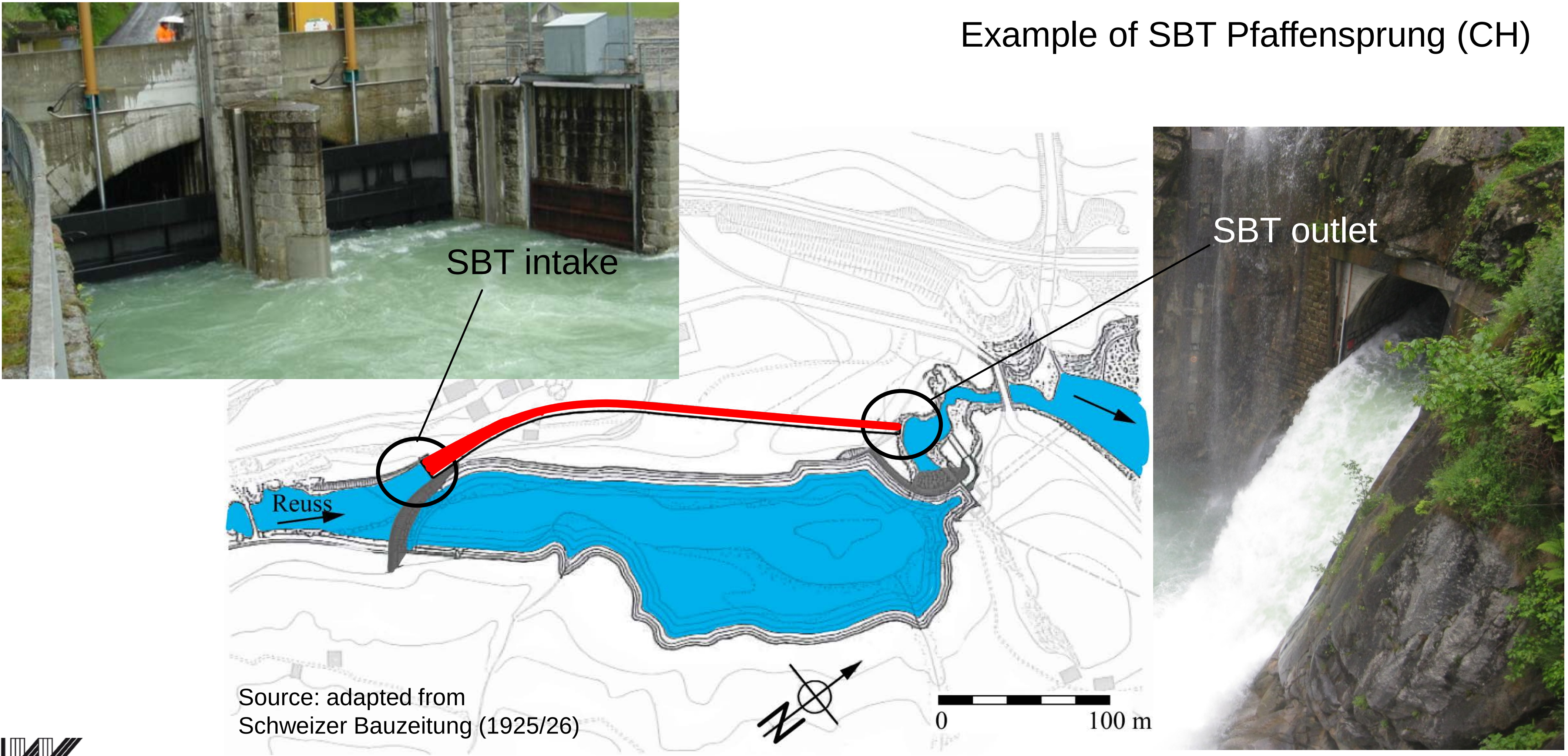
Possibly transition flow regime with increasing *Q*
- pulsations / pressure surges
→ requires proper tunnel lining design

Possibly pressurized flow for large *Q*:
→ generally decisive load case for
design of SBT diameter

Combination sediment routing / removal

bypassing */ flushing / mechanical dredging*

Example of SBT Pfaffensprung (CH)

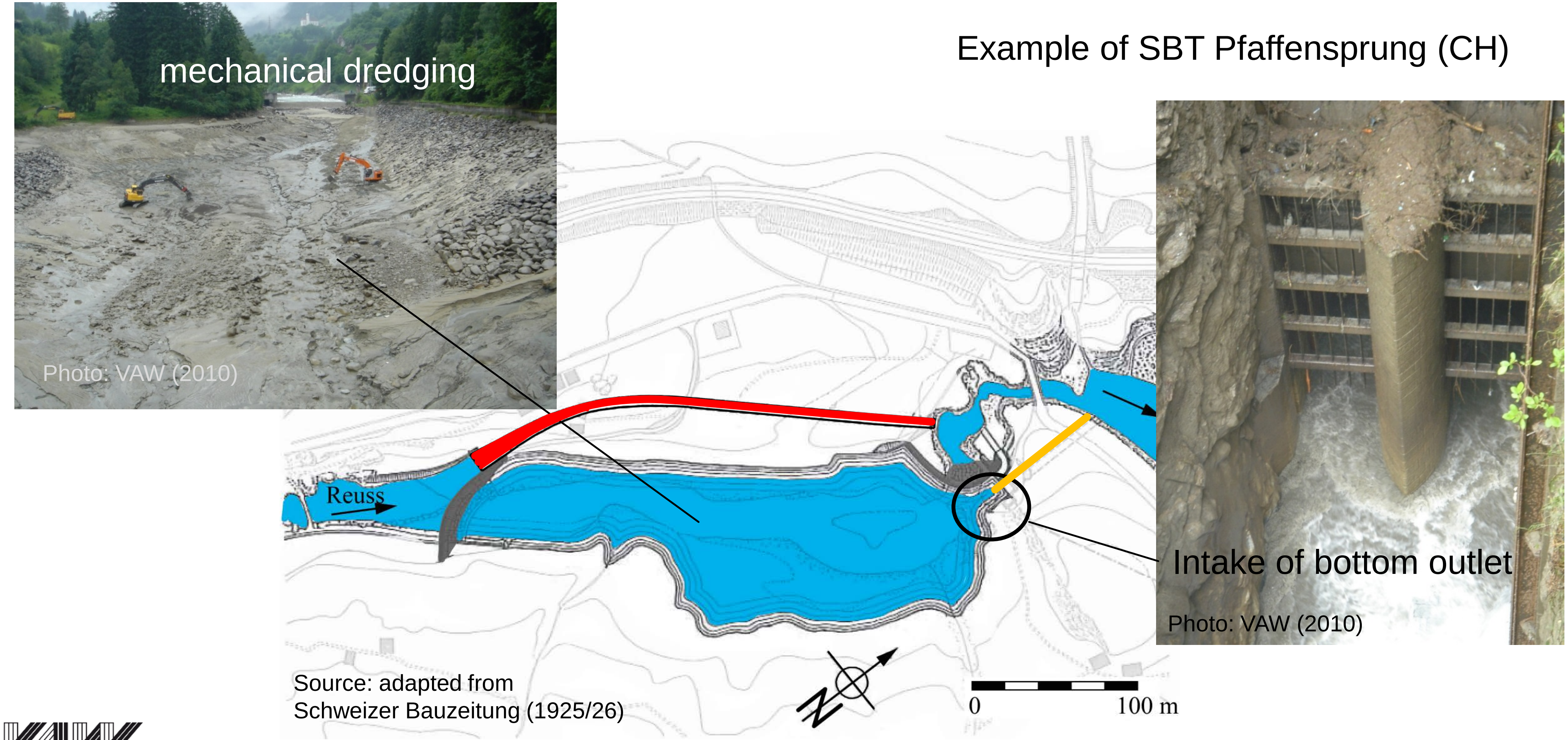


Source: adapted from
Schweizer Bauzeitung (1925/26)

Combination sediment routing / removal

*bypassing / **flushing / mechanical dredging***

Example of SBT Pfaffensprung (CH)



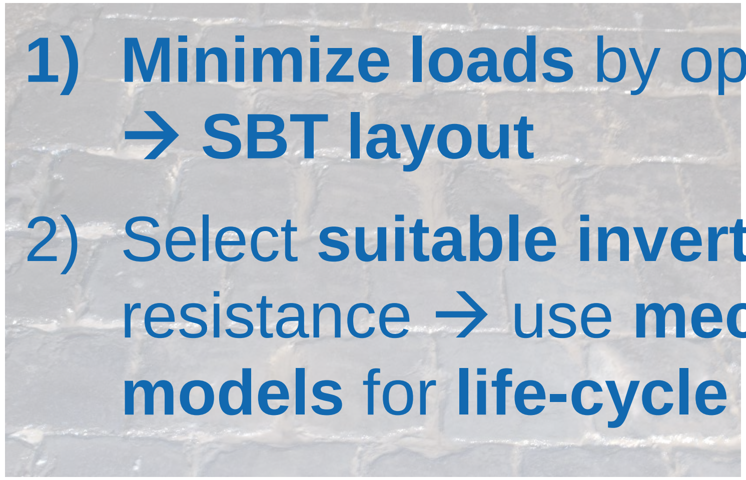
Source: adapted from
Schweizer Bauzeitung (1925/26)

3. HYDRO-ABRASION OF SBTs

Hydro-abrasion at Sediment Bypass Tunnels (SBTs)

Palagnedra (CH)
(Baumer and Radogna 2015)

Asahi (JP)
(Kansai Electric)



Pfaffensprung (CH)
(M. Müller-Hagmann)

Egschi (CH)
(sopr AG)

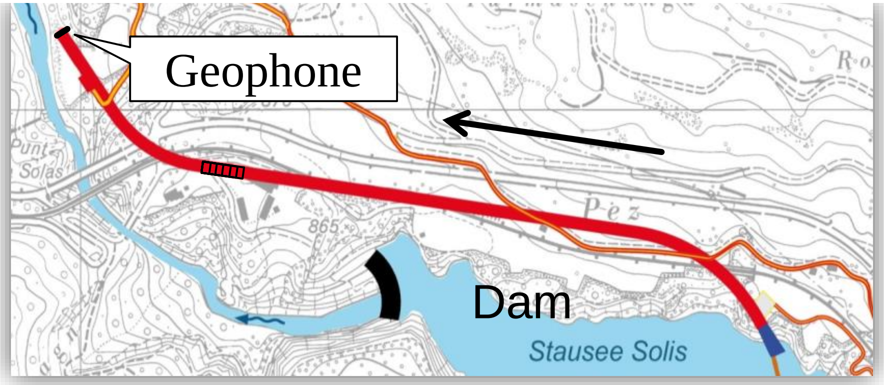
How to limit hydro-abrasion?

1) **Minimize loads** by optimized flow conditions → **SBT layout**

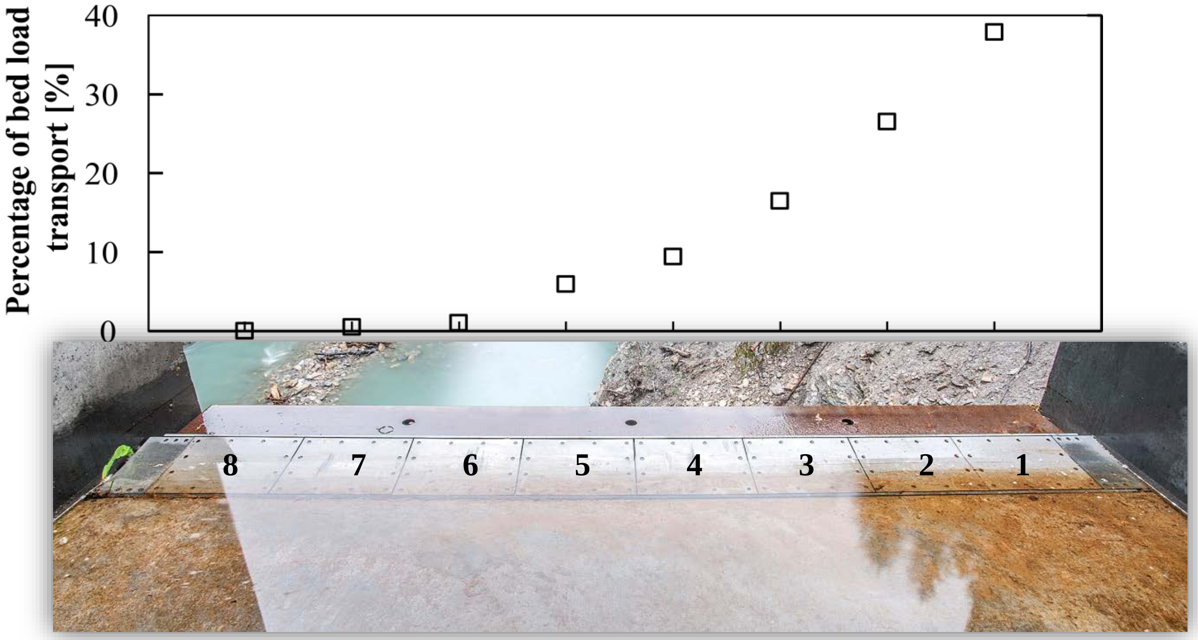
2) Select **suitable invert material** to maximize resistance → use **mechanistic abrasion models** for **life-cycle cost** approach

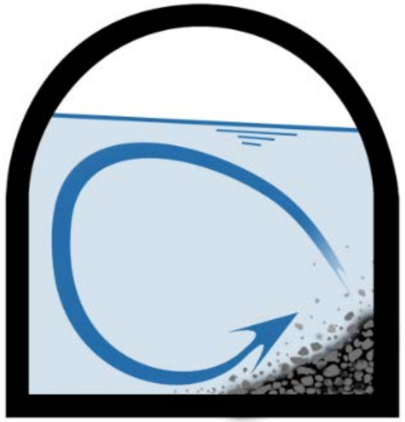
1) SBT design: tunnel layout in plan view

Effect of SBT alignment in plan view



→ Avoid bends if possible



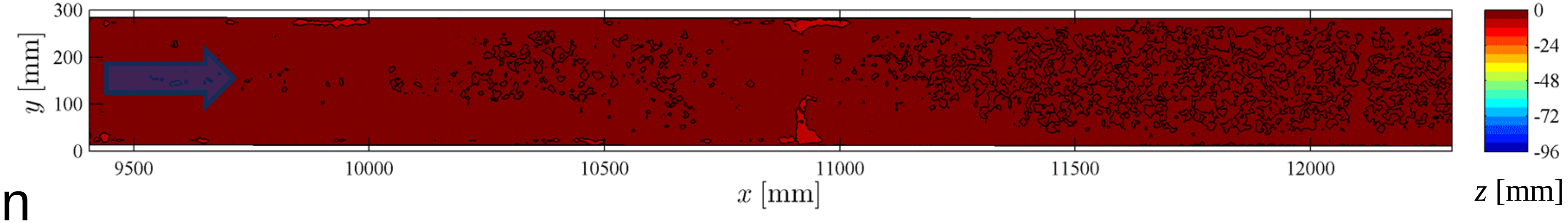


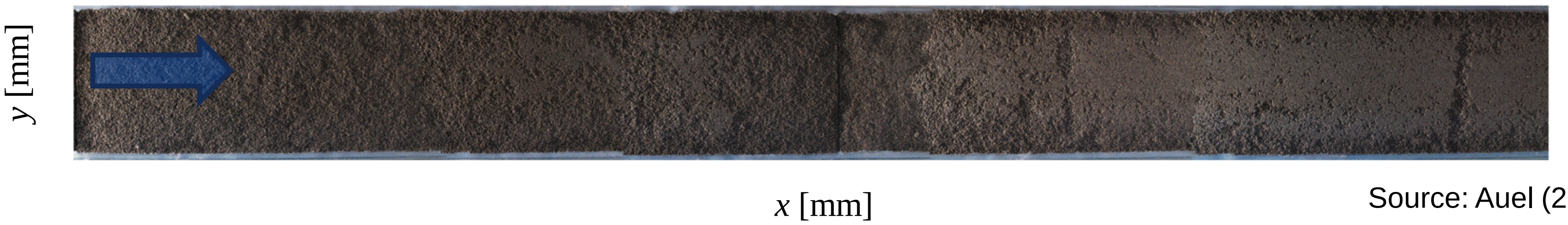
1) SBT design: tunnel layout in cross section

Effect of SBT cross section – 2D vs. 3D flow

Lab study

of invert abrasion





Source: Auel (2014)

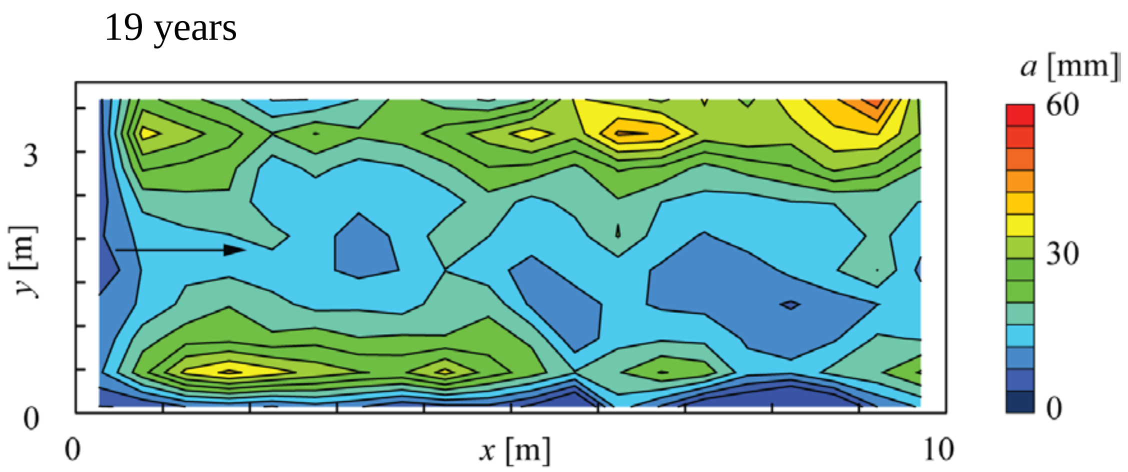
F = 1.8, h_o = 100 mm, S_b = 0.01, Q_S = 0.200 kg/s, D_b = 10.6 mm, t = 930 min

F	Froude number	S_b	Bed slope
h_o	Approach flow depth	D_b	Particle diameter
Q_S	Sediment transport rate [kg/s]	t	Test duration

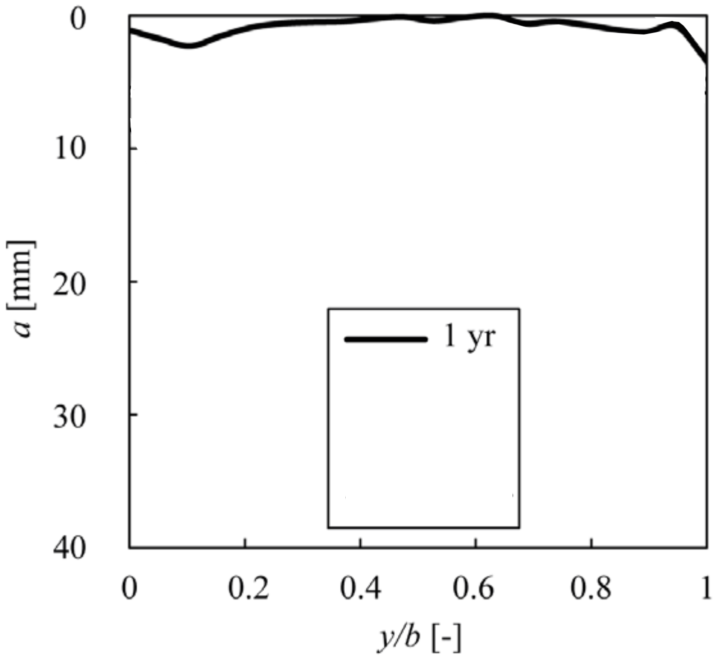
1) SBT design: tunnel layout in cross section

Effect of SBT cross section – 2D vs. 3D flow

Field study at SBT Runcahez – Invert Abrasion (1996 - 2014)



Silica fume concrete (SC)



- Incision channels along the tunnel walls

→ 3D-flow structures in narrow open channel flows

Source: Müller-Hagmann (2018)

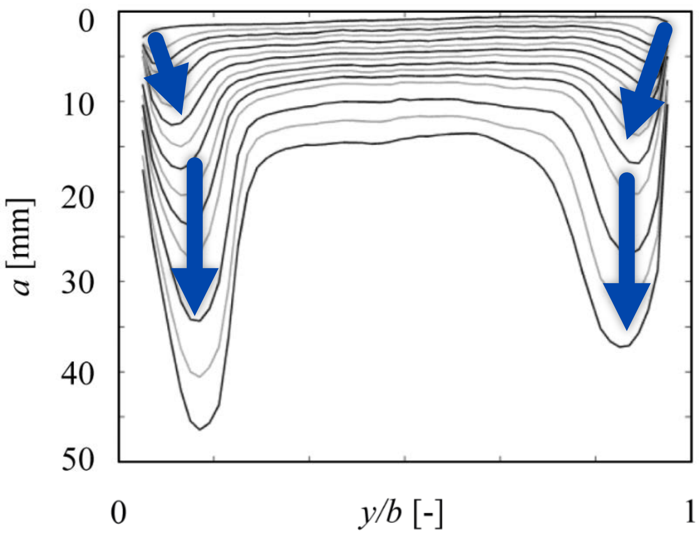
1) SBT design: tunnel layout in cross section

Effect of SBT cross section – 2D vs. 3D flow

lab study

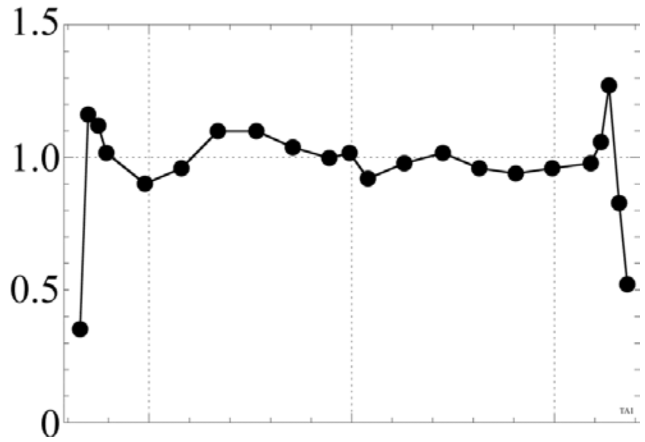
Source: Auel (2014)

- b/h = 2.8
- F = 1.8



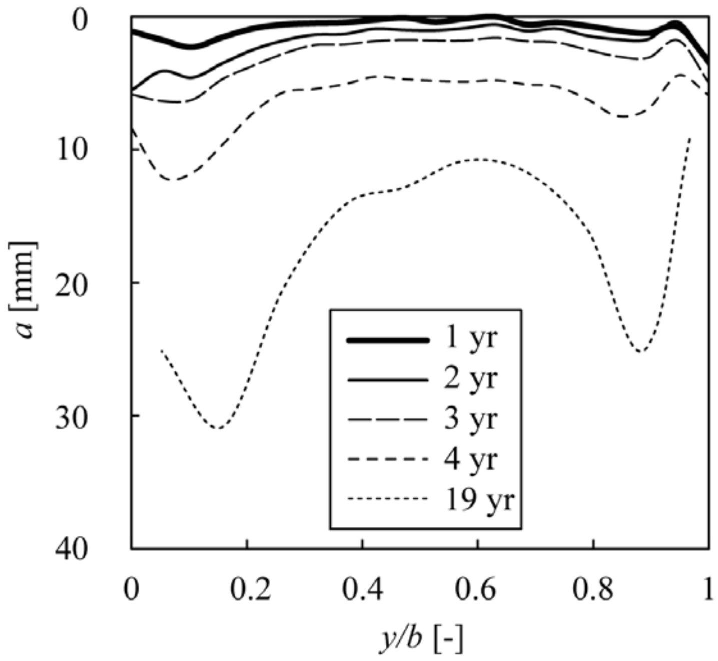
Normalized bed shear stress

$\tau/\overline{\tau}$



field study

Source:
Müller-Hagmann (2018)

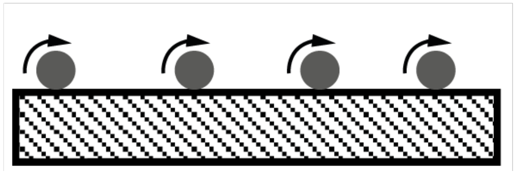


- b/h = 1.9
- F = 1.7

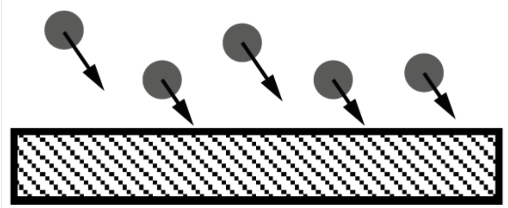
2) Mechanistic abrasion modelling

Transport mode and impact

sliding



rolling



saltation

Abrasion models

Saltation abrasion models

(bed load)

Sklar & Dietrich (2004)

Auel *et al*. (2017)

Total abrasion models

(bed load and suspended load)

Lamb *et al.* (2008)

2) Mechanistic abrasion modelling - Saltation Abrasion Model

Sklar and Dietrich (2004):

$$A_r = \frac{1}{\boxed{k_v}} \boxed{\frac{Y_M}{f_t^{2}}} \boxed{\frac{W_{im}^{2}}{L_p} q_s} \boxed{\left(1-\frac{q_s}{q_s^{*}}\right)}$$

$\boldsymbol{A_r}$ = **Abrasion rate [m/s]**
$\boldsymbol{k_v}$ = **Abrasion coefficient [-]**
Y_M = Young’s modulus
$\boldsymbol{f_t}$ = **Splitting tensile strength**
W_{im} = Vertical impact velocity
L_p = Particle hop length
q_s = Specific bedload transport rate
q_s^{*} = Specific bedload transport capacity

- 🟩 Abrasion coefficient
- ⬛ Material resistance
- 🟥 Energy flux term
- 🟦 Cover effect term

Auel *et al.* (2017)

$$A_r = \frac{Y_M}{k_v f_t^{2}} \cdot \boxed{\frac{\left(0.1(T^{*})^{0.39}\left[(s-1)gD\right]^{0.5}\right)^{2}}{2.3(T^{*})^{0.8} D} q_s} \left(1-\frac{q_s}{q_s^{*}}\right)$$

$$\approx \frac{Y_M}{k_v f_t^{2}} \cdot \boxed{\frac{(s-1)g}{230} q_s} \left(1-\frac{q_s}{q_s^{*}}\right)$$

2) Mechanistic abrasion modelling - Saltation Abrasion Model

Abrasion Coefficient

$$A_r = \frac{1}{\boxed{k_v}} \boxed{\frac{Y_M}{f_t^2}} \boxed{\frac{W_{im}^2}{L_p} q_s} \boxed{\left(1 - \frac{q_s}{q_s^*}\right)}$$

☐ Abrasion coefficient

☐ Material resistance

☐ Energy flux term

☐ Cover effect term

Sklar and Dietrich (2004):

- Laboratory experiments
- Mortars and rocks
- $k_v = (1.30 - 9.09) \cdot 10^6$

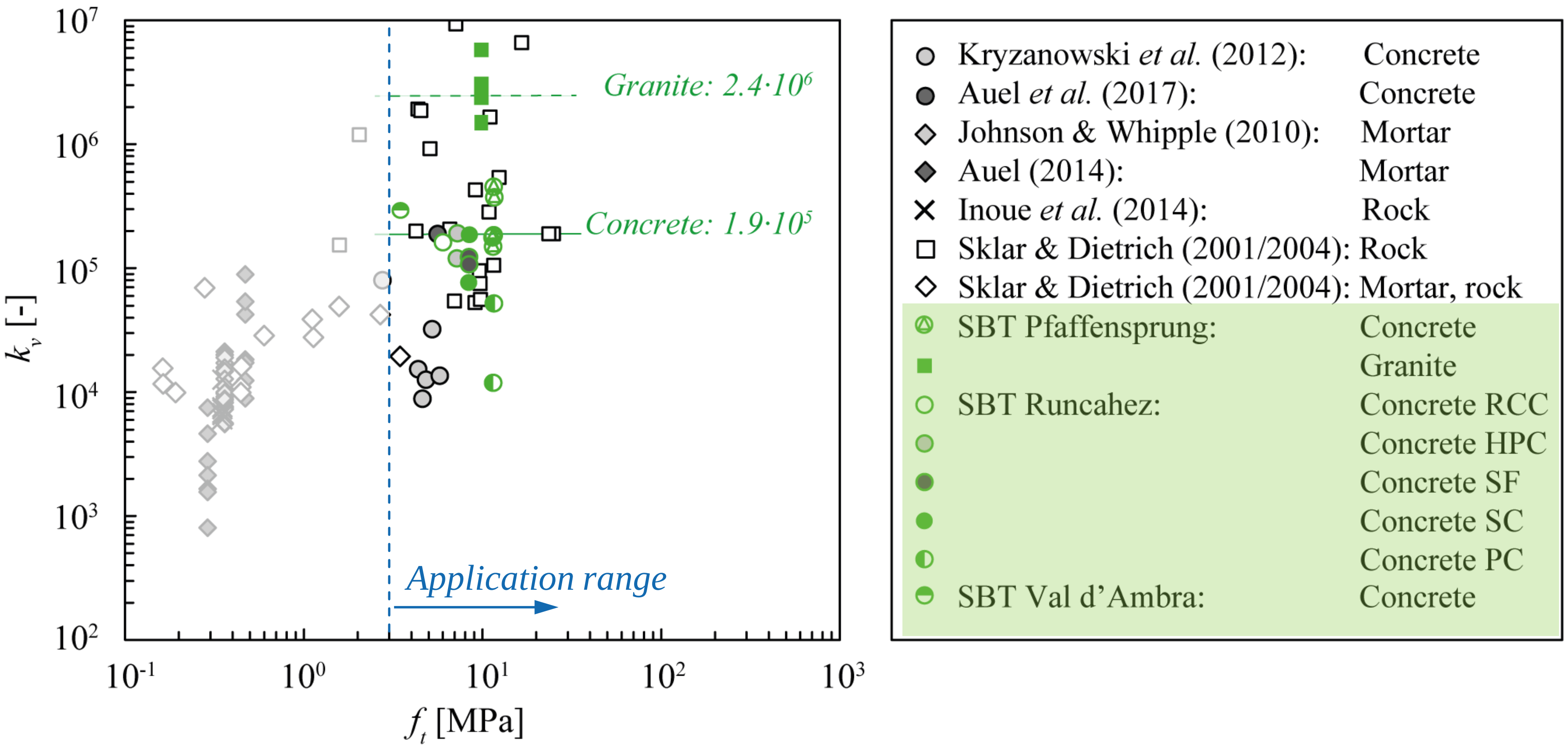
Auel *et al.* (2017):

- Japanese SBT Asahi
- Concrete f_c = 36/70 MPa
- $k_v = (1.9 \pm 0.7) \cdot 10^5$

→ Prototype data from 3 Swiss SBTs to validate and calibrate k_v

2) Mechanistic abrasion modelling

Abrasion Coefficient - Calibration



- k_v increases with f_t
- Material-specific k_v
- k_v: granite > concrete
- Scatter due to
  - measurement errors
  - model uncertainties
  - **abrasiveness of sediment not yet considered**

2) Select suitable invert material

Cost-Effectiveness Analysis - SBT Pfaffensprung field study

Net present value (*NPV*):

$$\boxed{NPV = \sum_{t=0}^{T} \frac{C_t}{(1+r)^t}}$$

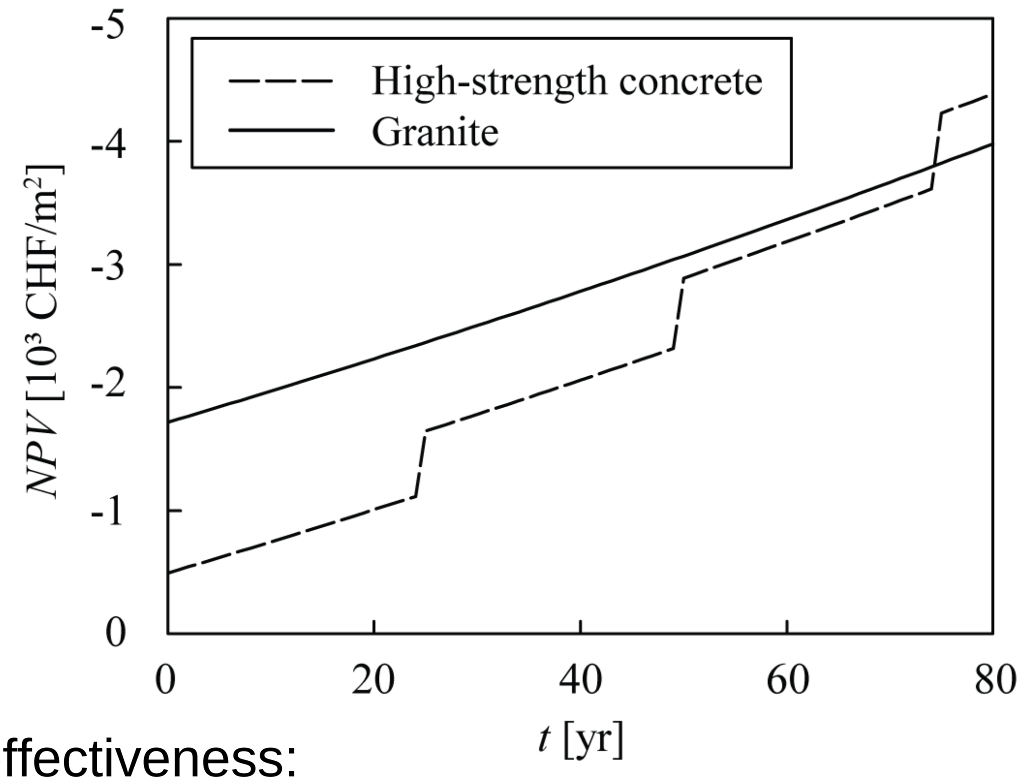
T = accounting period (here 80 yr)

C_t = net cash flow at time point *t*

r = interest rate (here 3%)

Input parameters / assumptions:

- Actual investment cost
- Maintenance costs: 25 CHF/(m²yr)
- Replacement at abrasion depths ≥ 20 cm
  → **mechanistic abrasion modelling**



Cost-effectiveness:

T < 75 yr: Concrete > granite

T ≥ 75 yr: Concrete < granite

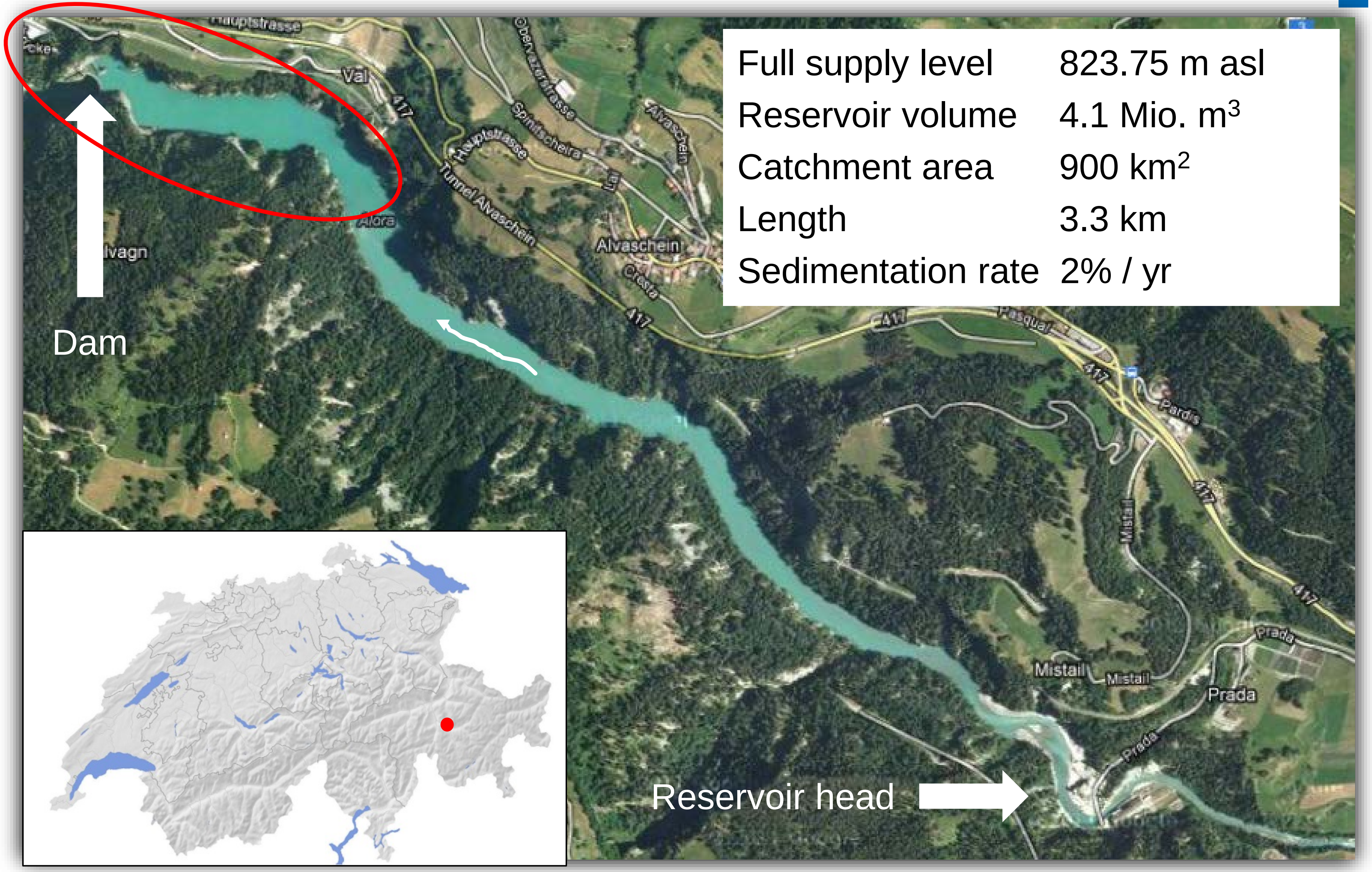
4. DOWNSTREAM MORPHOLOGICAL EFFECTS OF SBTs


River Albula

Photo: VAW

Test case Solis

Overview

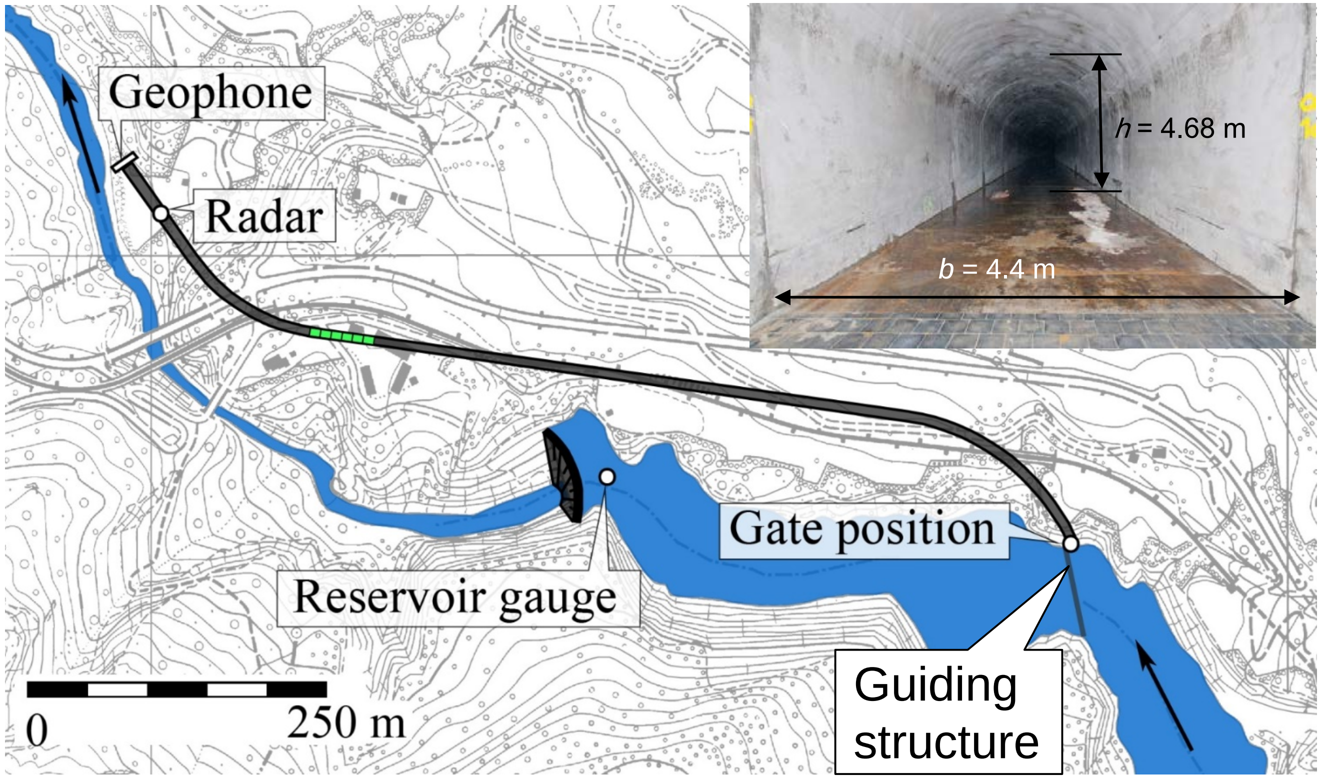


Full supply level	823.75 m asl
Reservoir volume	4.1 Mio. m^3
Catchment area	900 km^2
Length	3.3 km
Sedimentation rate	2% / yr

- Solis reservoir on Albula River (CH)

Test case Solis

SBT features

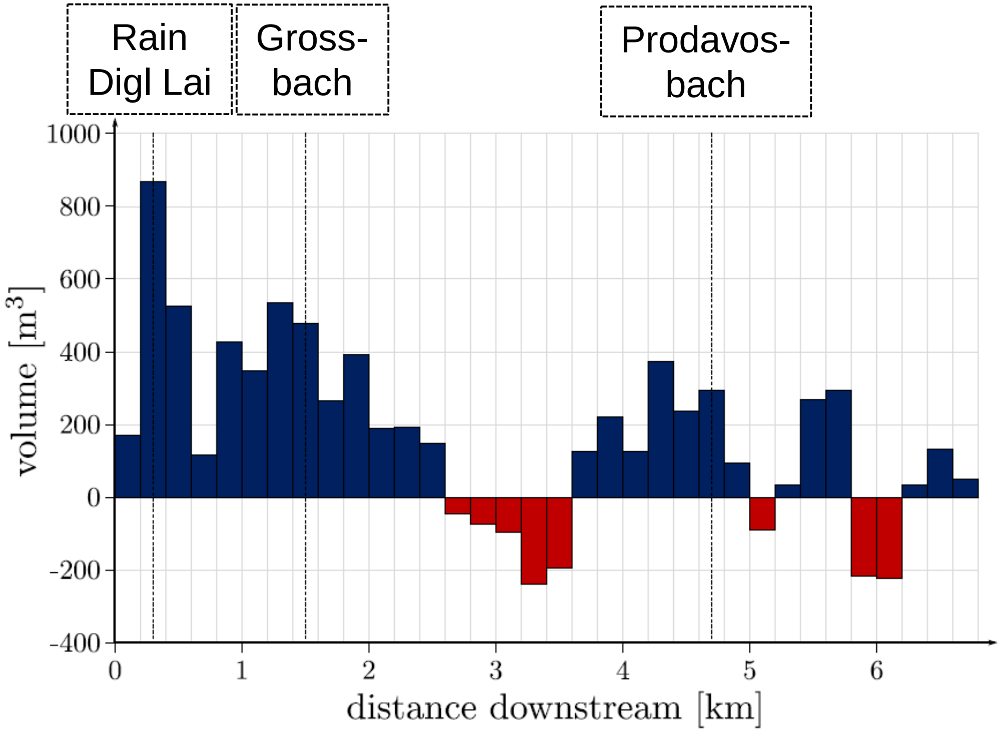


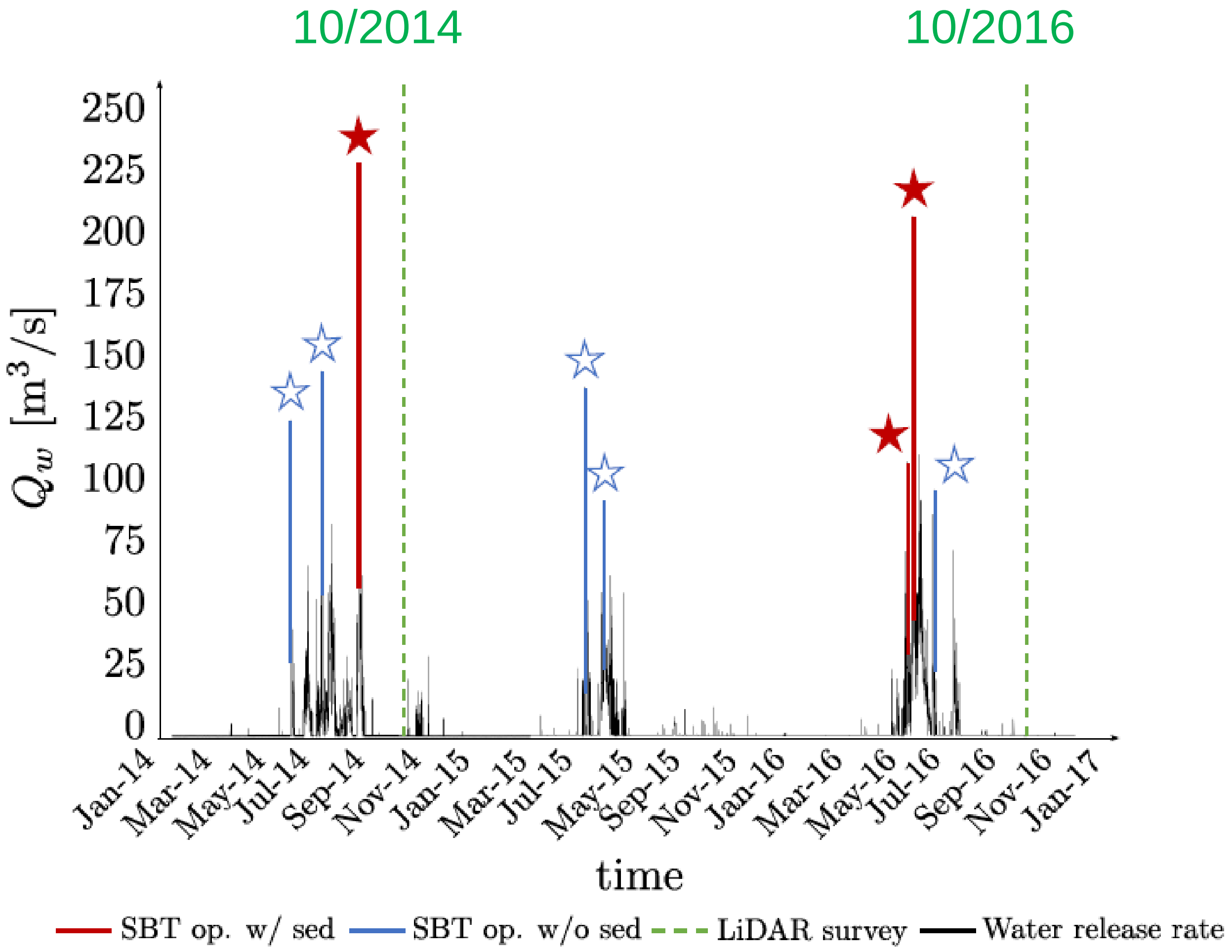
- Commissioned in 2012
- 973 m long, bed slope 1.9 %
- Max. discharge capacity 170 m^3/s
- **ca. 10 SBT operations during floods until now** (autumn 2018)
- **Largest events: 13-08-2014 and 16-06-2016**
  mean SBT discharge: 153 / 129 m^3/s, duration: 14 / 24 hours
  total bypassed sediment volume: ~22'000 / 23’000 m^3

Test case Solis

Morphological effects in Albula

- **deposition and erosion volumes** between 10/2014 and 10/2016 after 37 h of SBT operation with ~40’000 m³ of bypassed sediment

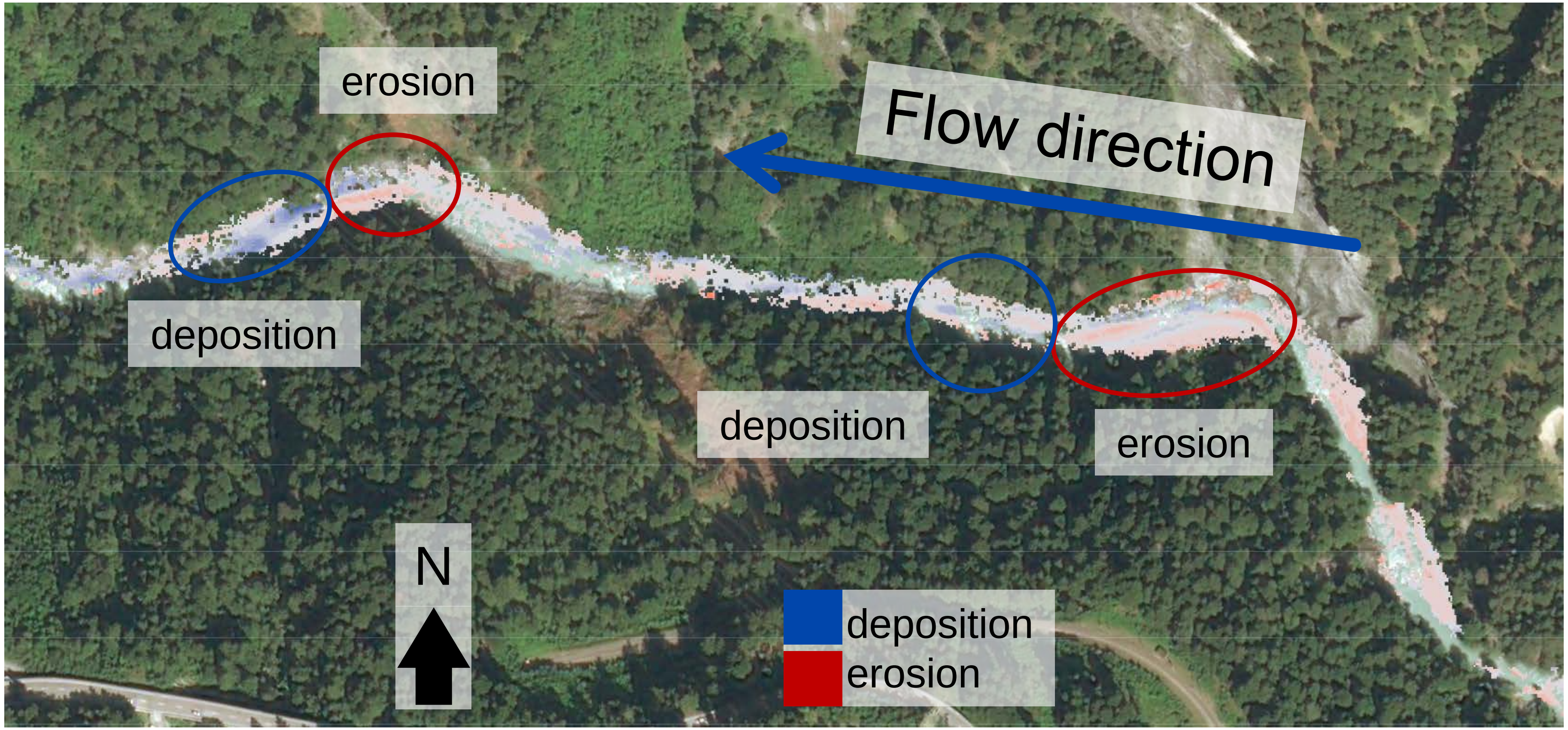




Source: Facchini (2017)

Sediment budget from DEM^2 of Difference

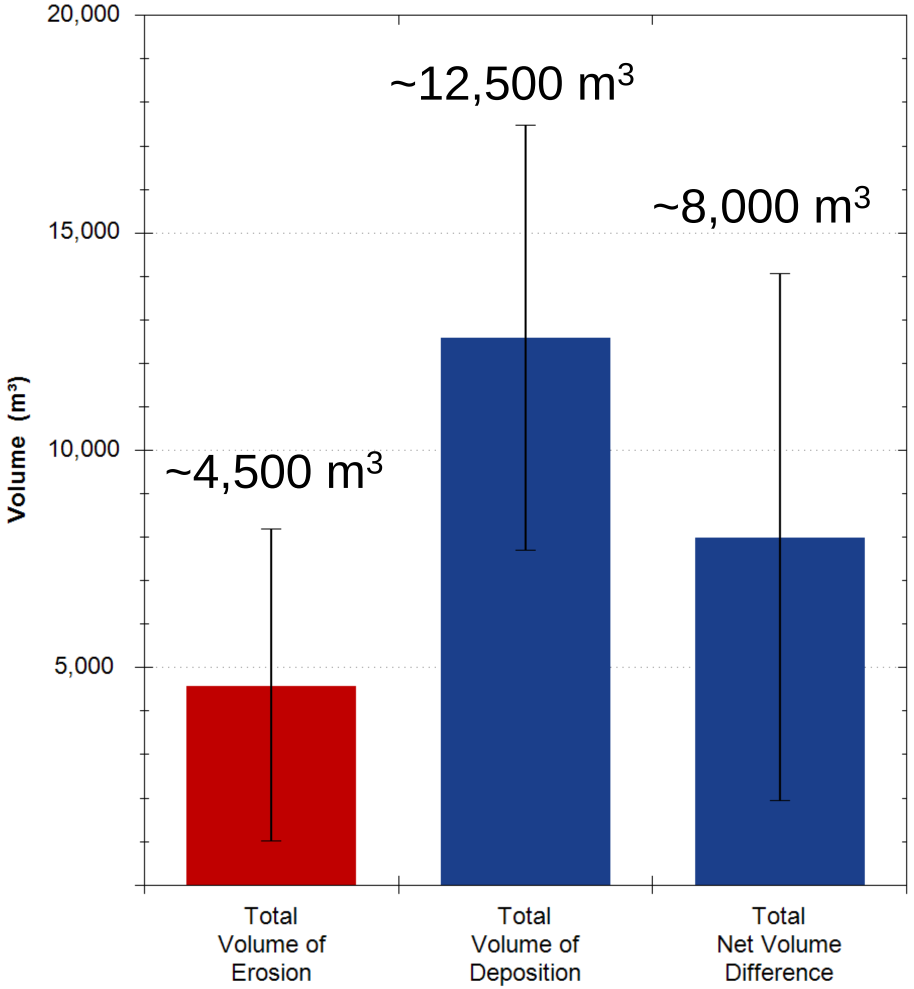
Example of erosion-deposition patterns

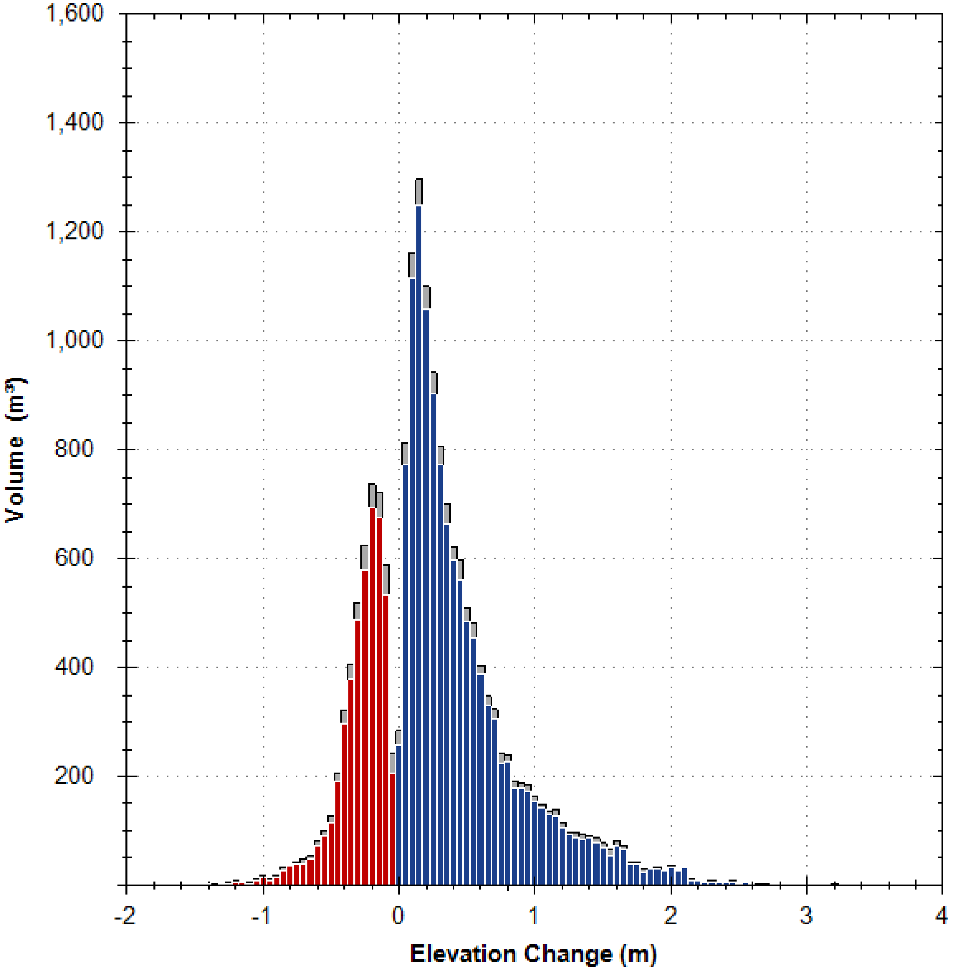


[2]DEM stands for Digital Elevation Model

Sediment budget from DEM of Difference

Volumes involved





Morphological effects of SBTs

- **sediment load to downstream is largely affected by**
  - location of intake structure
  - shape of reservoir and operation of reservoir level
  - extent of delta
- with increasing **operation duration** (decades to centuries) the downstream morphology (1D effect, i.e. river bed level) slowly approaches the pre-dam conditions (mobile-bed equilibrium)
- **reworking of bed material** (away from static armour towards mobile-bed composition) occurs much faster than adaptation of longitudinal slope
- **monitoring and continuous adaptation of operation needed** to avoid negative effects and promote sediment relocation with positive ecological effects


Foto: VAW

4. CONCLUSIONS

Conclusions

Bypass tunnels to route sediment around dams

- **SBTs** are a means to route sediment around dams **for CIR < 0.3…0.4**
- **optimal hydraulic and structural design** needed to minimize adverse effects
- **avoid bends** in plan view if possible
- **local invert strengthening is an option** to avoid abrasion concentration induced by 3D flow structures
- optimum **invert material** in terms of life-cycle cost can be selected based on abrasion predictions using **mechanistic models with adequate k_v values**
- SBTs help **improve morphology downstream of reservoirs** by
  - reworking of bed material within short time (few operations)
  - Adaptation of longitudinal slope (morphological 1D effect) over long periods (> decades)

THANK YOU FOR YOUR ATTENTION

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