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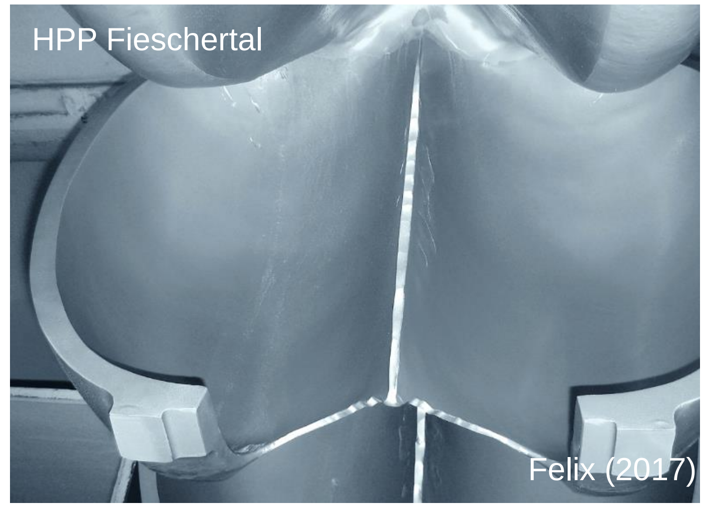

Fine sediment management at hydropower schemes considering turbine erosion

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ETH zürich

SCCER-SoE Annual Conference
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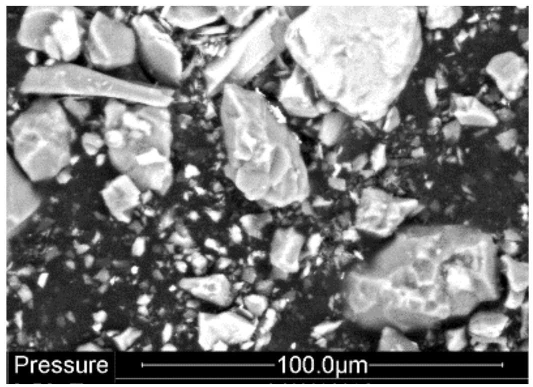
Versuchsanstalt für Wasserbau,
Hydrologie und Glaziologie

Outline

- **Sediment problems** at hydropower plants
- **Reducing the sediment load** in the turbine water of run-of-river HPPs by temporary shutdowns
- **Increasing the fine sediment load** in the turbine water of storage HPPs to reduce reservoir sedimentation
- **Estimating erosion** in Pelton turbines
- Conclusions

Variability of sediment transport

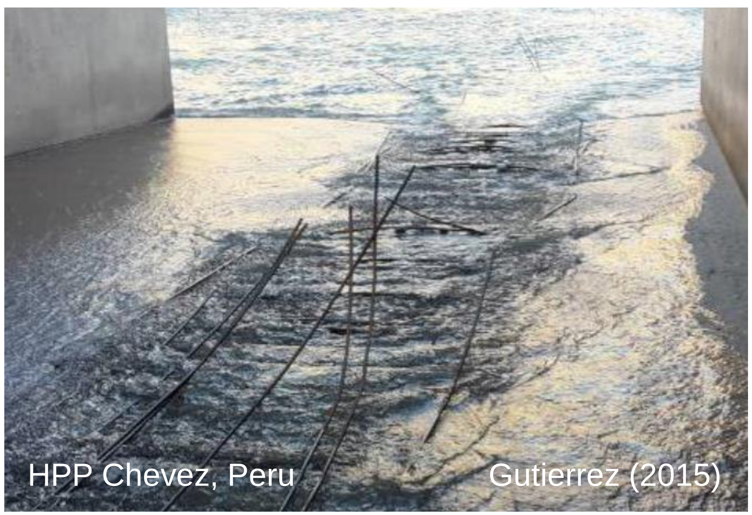
Wysswasser (downstream
of Fieschergletscher)



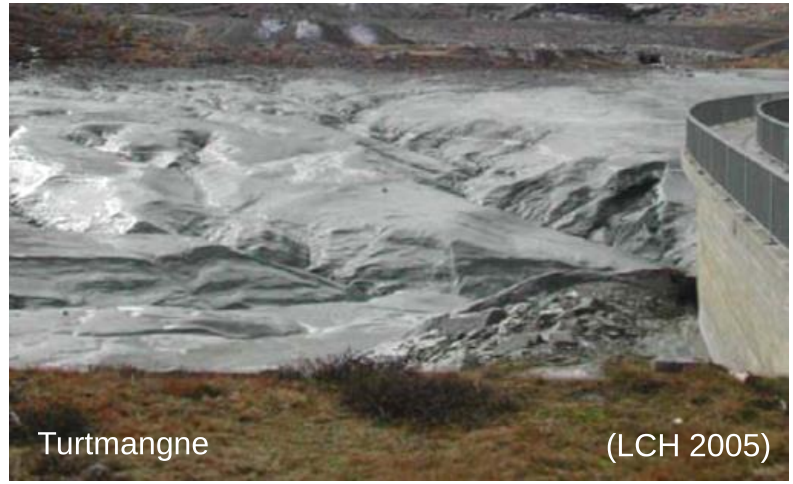
Sediment problems at HPPs

Blockage of intakes, outlets, etc.

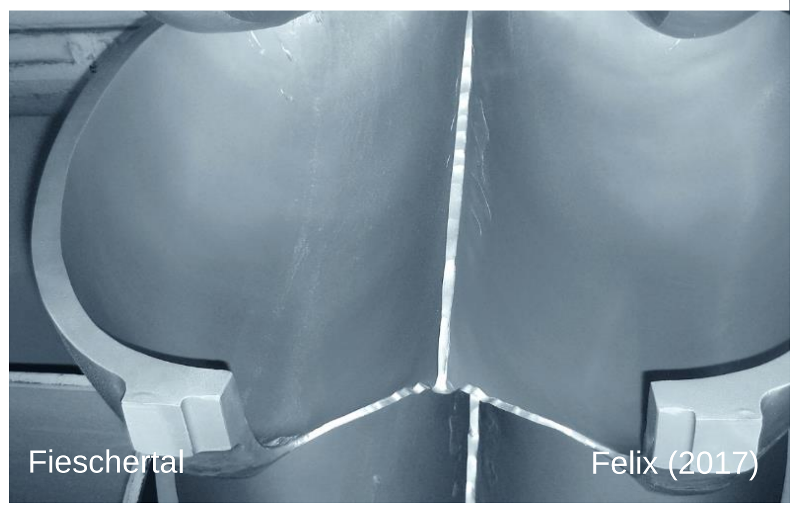
Erosion on hydraulic structures



Reservoir sedimentation



Erosion on hydraulic machinery



- Sediment problems at hydropower plants
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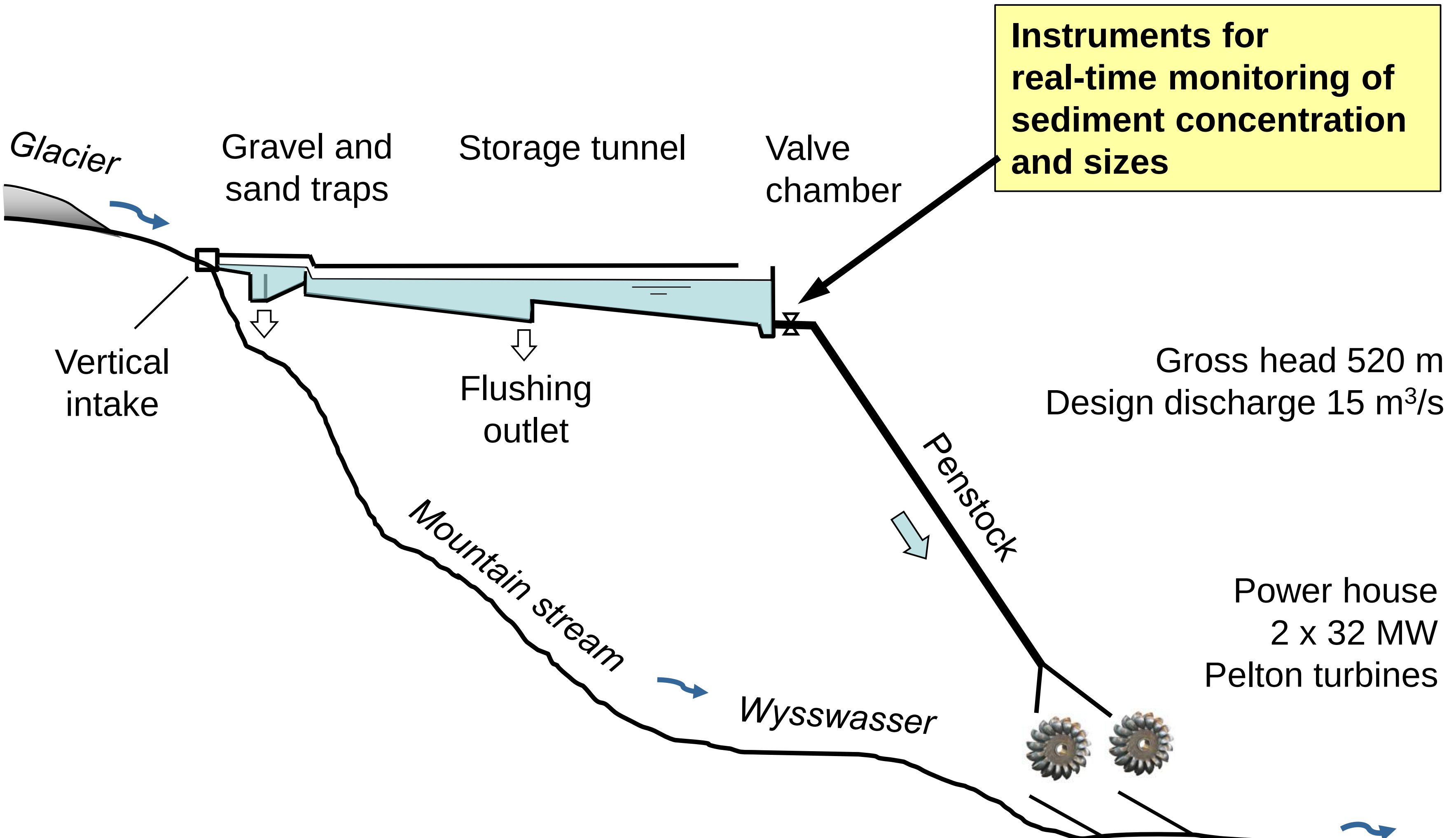
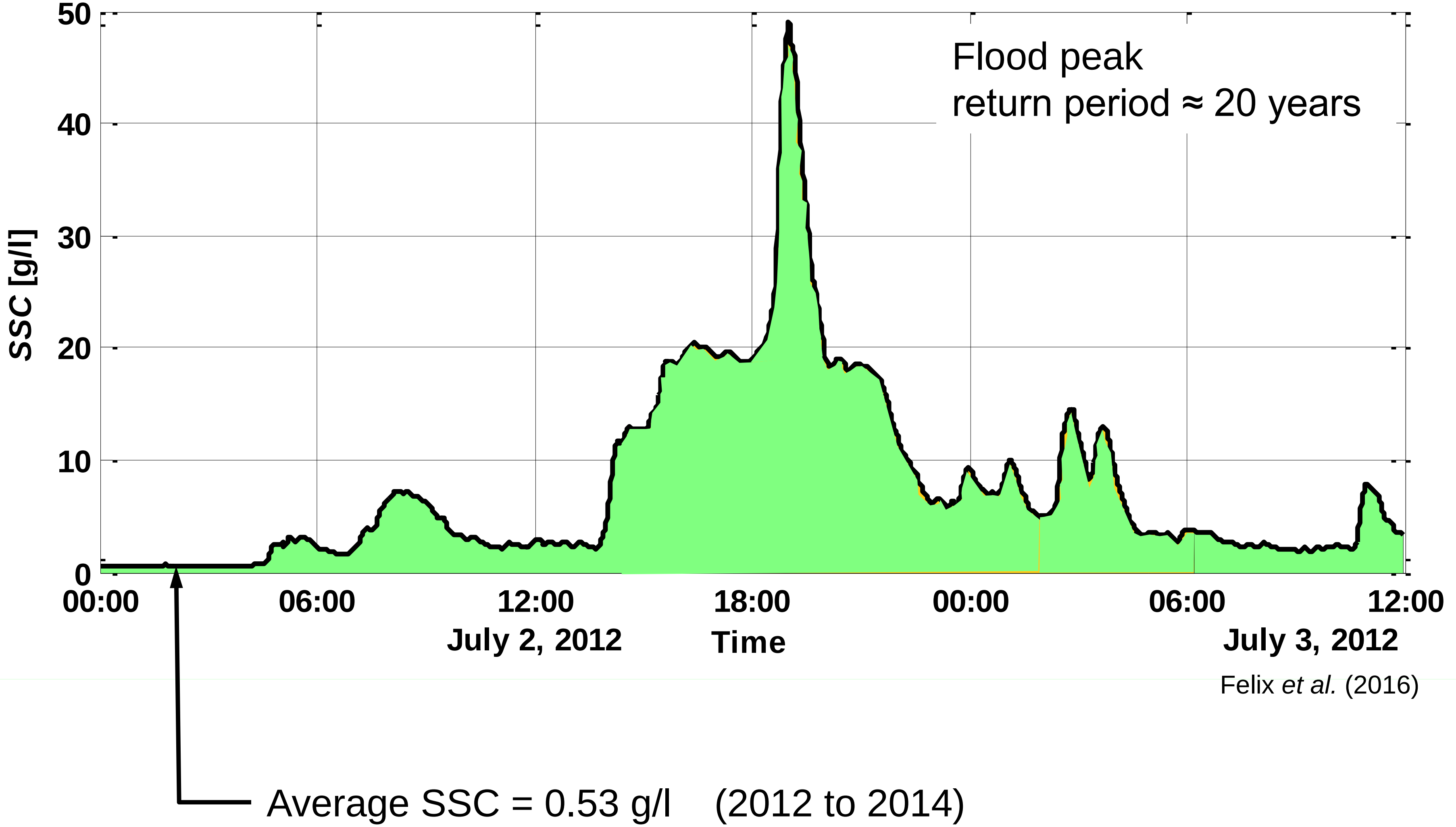
Longitudinal profile of HPP Fieschertal

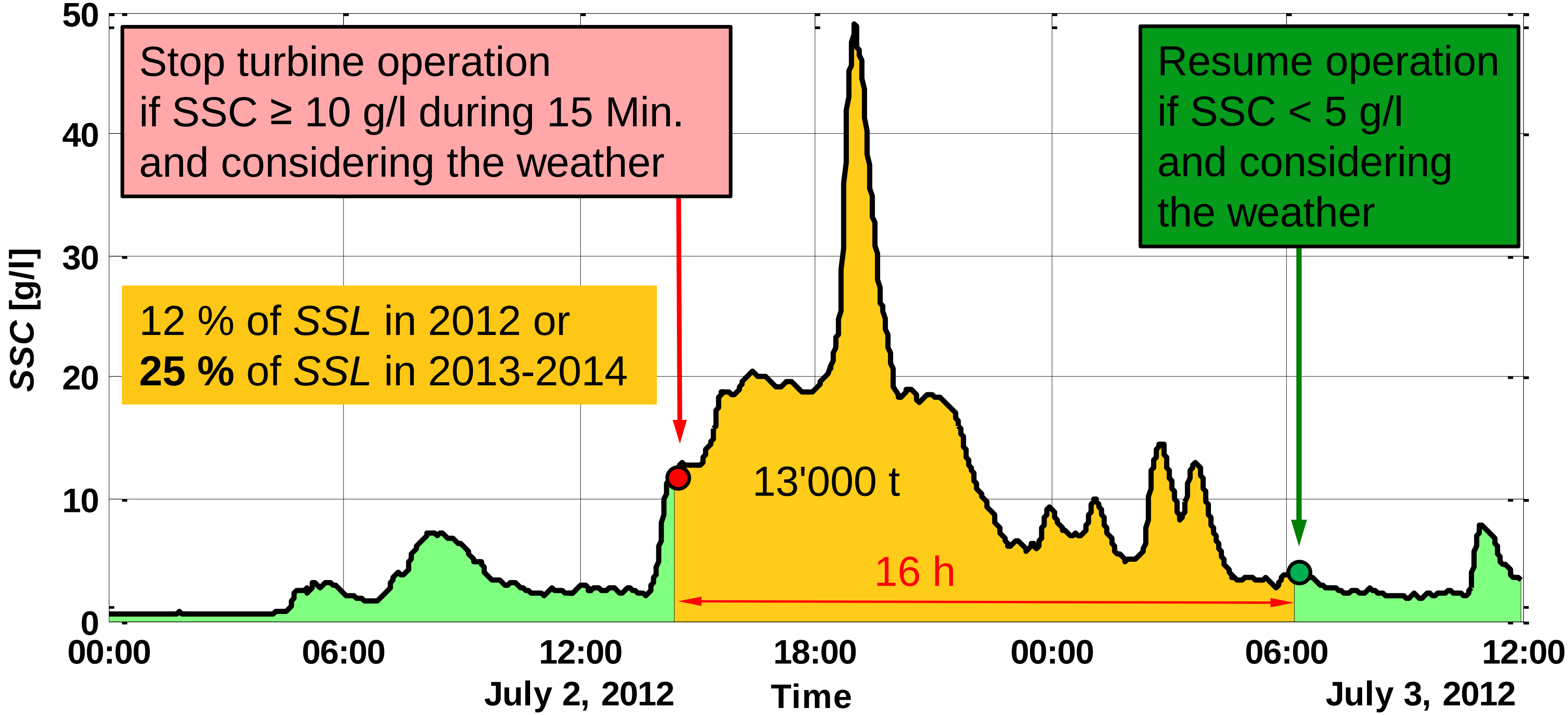


modified from Felix *et al.* (2016)

Sediment concentration during a flood



Shutdown scenario during flood



Felix *et al.* (2016)

−	50 000 CHF	**Production loss due to standstill (2 turbines)**
+	200 000 CHF	**Avoided repair costs** (rough estimate)
+	50 000 CHF	**Avoided future production losses** (estimate)
+	**200 000 CHF**	**Net benefit** corresponding to **2.7% of annual revenue**

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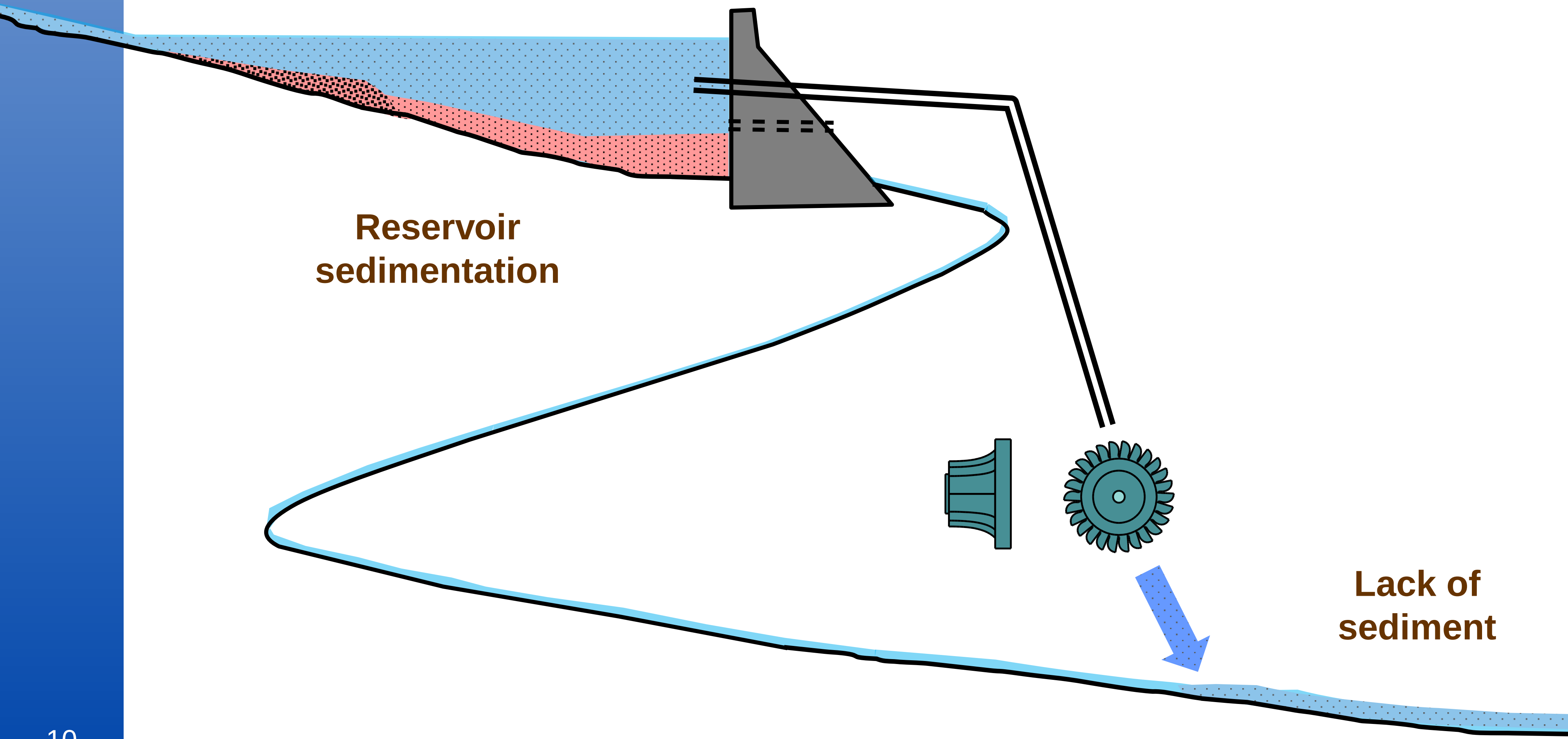
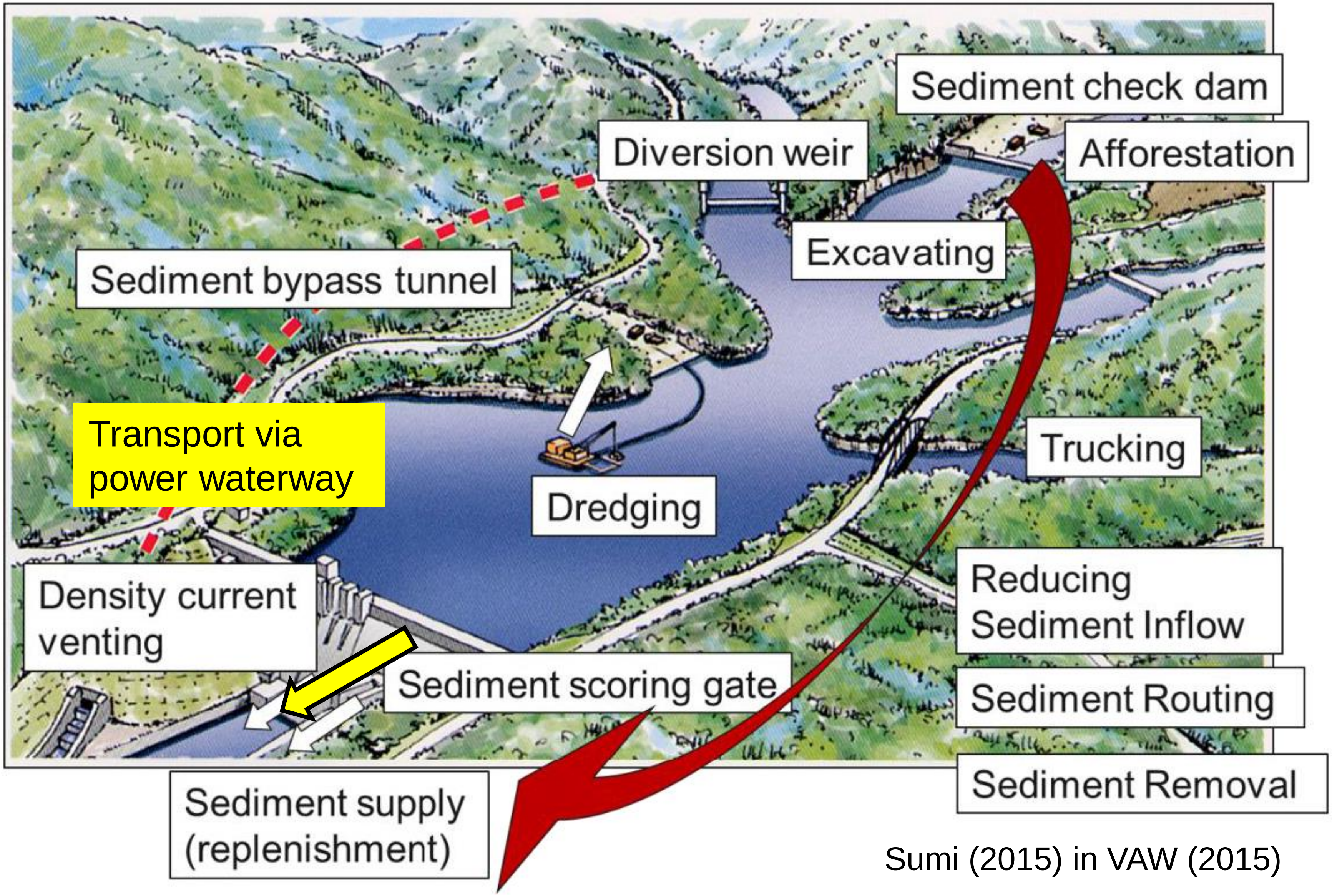
Reservoir sedimentation

High sediment trap efficiency



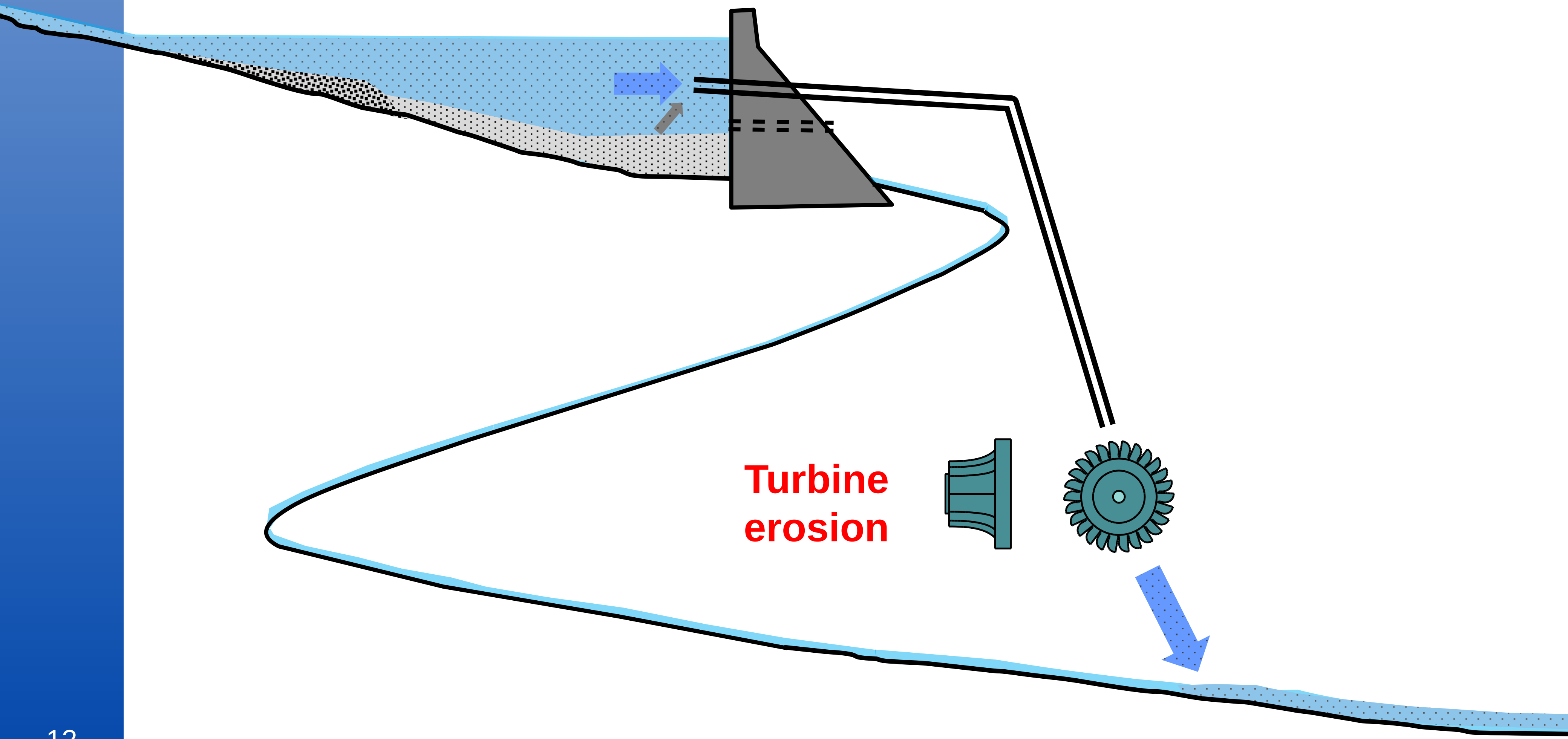
Options to reduce reservoir sedimentation



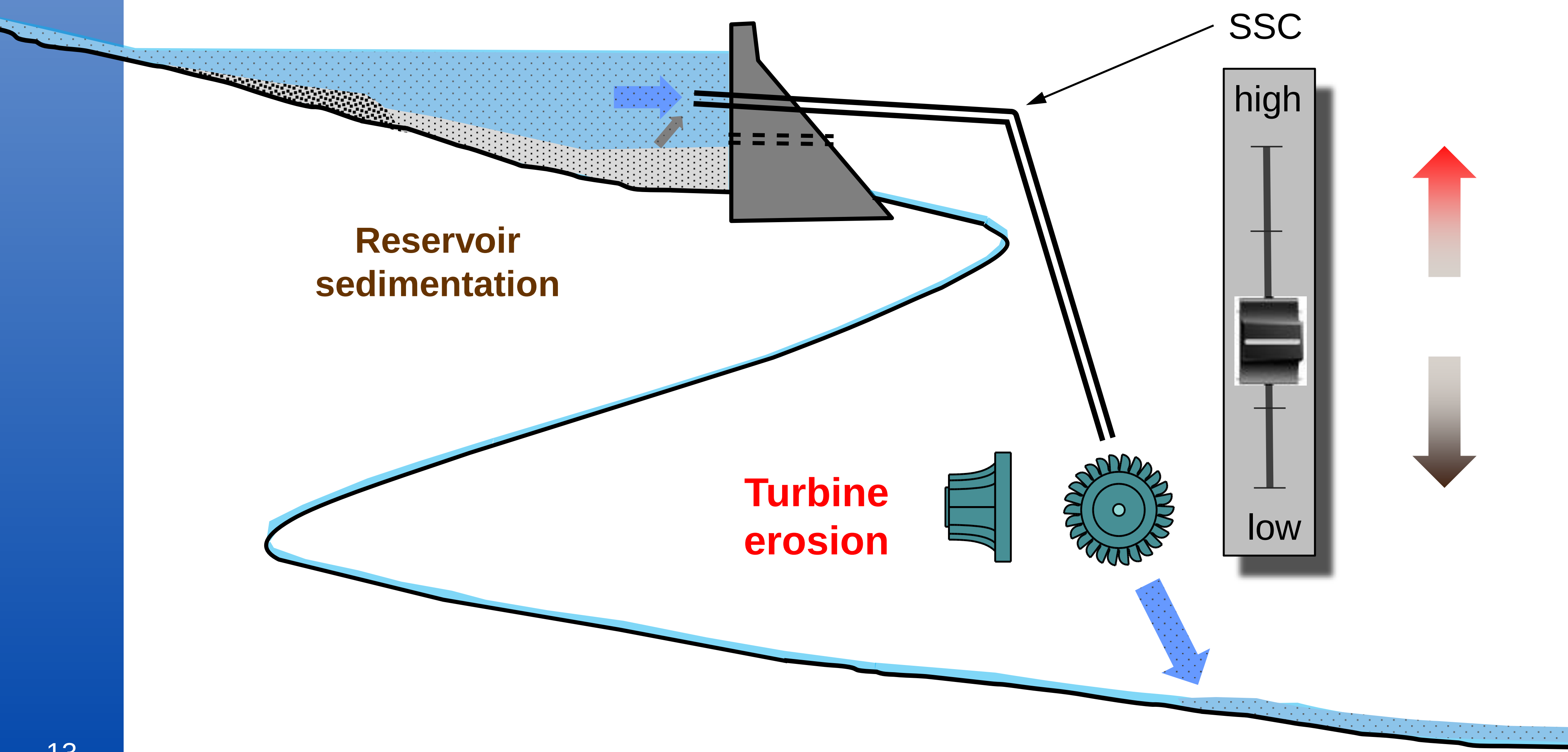
Sumi (2015) in VAW (2015)

Fine sediment transport via power waterway

- Reduce settling (e.g. with jet-induced turbulence -> Demonstrator ‘Sedmix’)
- Sediment re-mobilisation by hydro-suction / air lift etc.



Fine sediment transport via power waterway



- Sediment problems at hydropower plants
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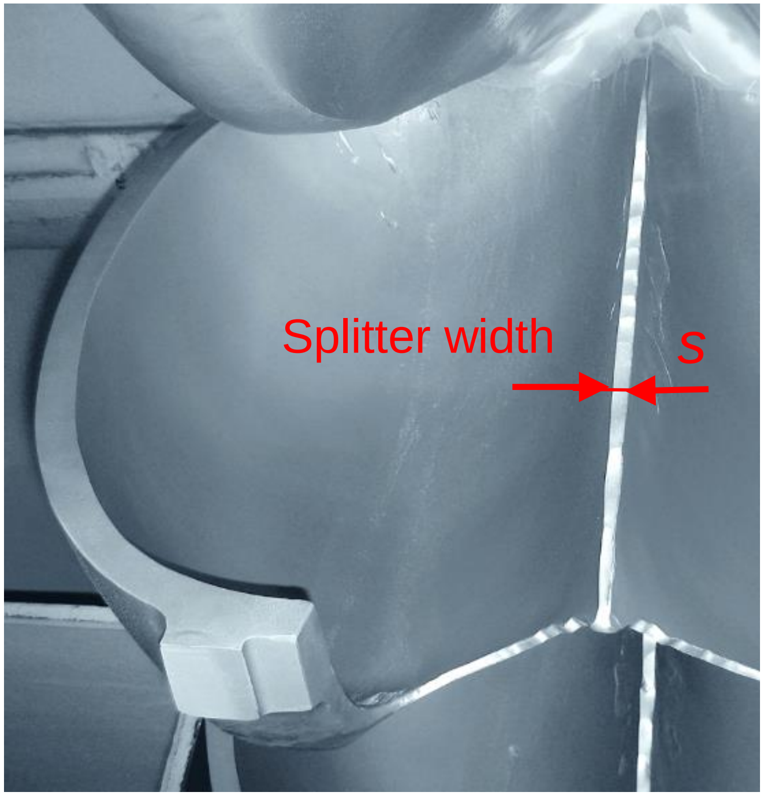
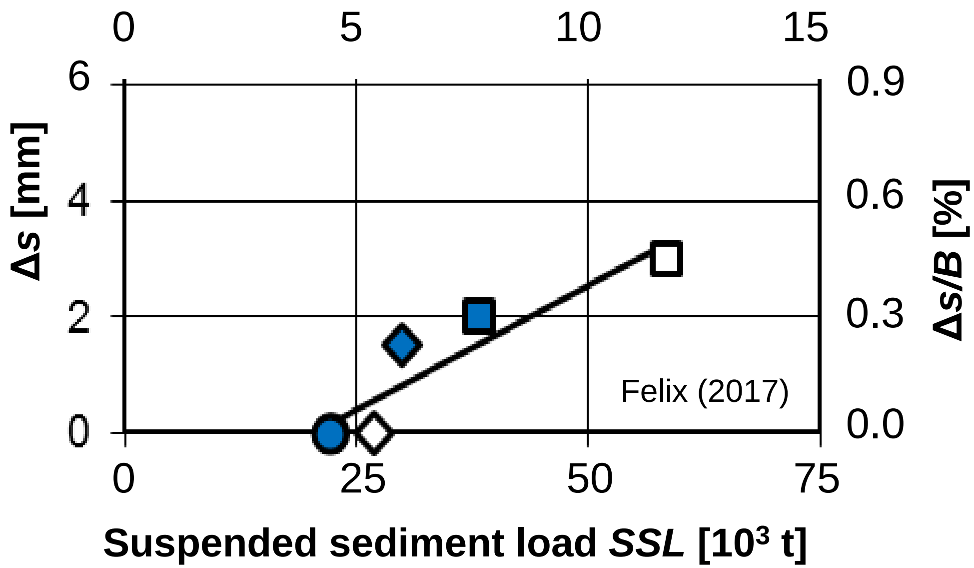
Estimating turbine erosion

Bucket of a Pelton runner
(fully coated at the beginnings
of the seasons)





Increase of splitter width Δ*s* of the runners of turbine 1 and 2 (empty and full markers) of HPP Fieschertal
in 2012 (□), 2013 (◇) und 2014 (○)

$$\Delta s(t) = K_{f,s}\, K_m\, w^3 PL_b(t)$$

Felix *et al.* (2016), Felix (2017), VAW-Mitteilung 238

Conclusions

- Various **options** to cope with sediment at HPPs
- At medium- and high-head run-of-river HPPs: **temporary** closing of intakes and **turbine shutdowns** (at high SSCs)
- At storage HPPs if no other option is suitable: **fine sediment transport through turbines** (with low SSCs)
- **Site-specific** optimizations based on monitoring data and economic analysis

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Model for hydro-abrasive erosion in turbines

According to a guideline of the International Electrotechnical Commission IEC 62364 (2013), adapted for erosion in **Pelton buckets**

Based on a comprehensive literature review (e.g. Meng & Ludema 1995)

Erosion depth

Effects of the "flow field" (impact angle) and the bucket size [...]

Relative erosion resistance of the eroded material [-]

Relative velocity [m/s] $w = 0.5\sqrt{2\,g\,h_n}$

$$\Delta d_e(t) = K_{f,s}\, K_m\, w^3\, PL_b(t)$$

"Particle Load" per bucket [h · g/l]

Number of jets (nozzles in operation) [-]

$$PL_b(t) = \int \frac{z_0}{z_2}\, SSC\, k_{size}\, k_{shape}\, k_{hardness}\, \mathrm{d}t$$

Factors for particle properties [-]

Time [h]

Number of buckets [-]

Suspended sediment concentration [g/l]

Model for hydro-abrasive erosion in turbines

- Properties of the HPP (green)
- Operation data (blue)
- Measurements (constant) (yellow)
- Measurements (variable in time) (red)

$$\Delta d_e(t) = K_{f,s}\, K_m\, w^3\, PL_b(t)$$

- Erosion depth
- $K_{f,s}$: Effects of the "flow field" (impact angle) and the bucket size [...]
- K_m: Relative erosion resistance of the eroded material [-]
- w: Relative velocity [m/s] $w = 0.5\sqrt{2\,g\,h_n}$
- $PL_b(t)$: "Particle Load" per bucket [h · g/l]

?

$$PL_b(t) = \int \frac{z_0}{z_2}\, SSC\, k_{size}\, k_{shape}\, k_{hardness}\, \mathrm{d}t$$

- z_0: Number of jets (nozzles in operation) [-]
- z_2: Number of buckets [-]
- SSC: Suspended sediment concentration [g/l]
- $k_{size}\, k_{shape}\, k_{hardness}$: Factors for particle properties [-]
- t: Time [h]

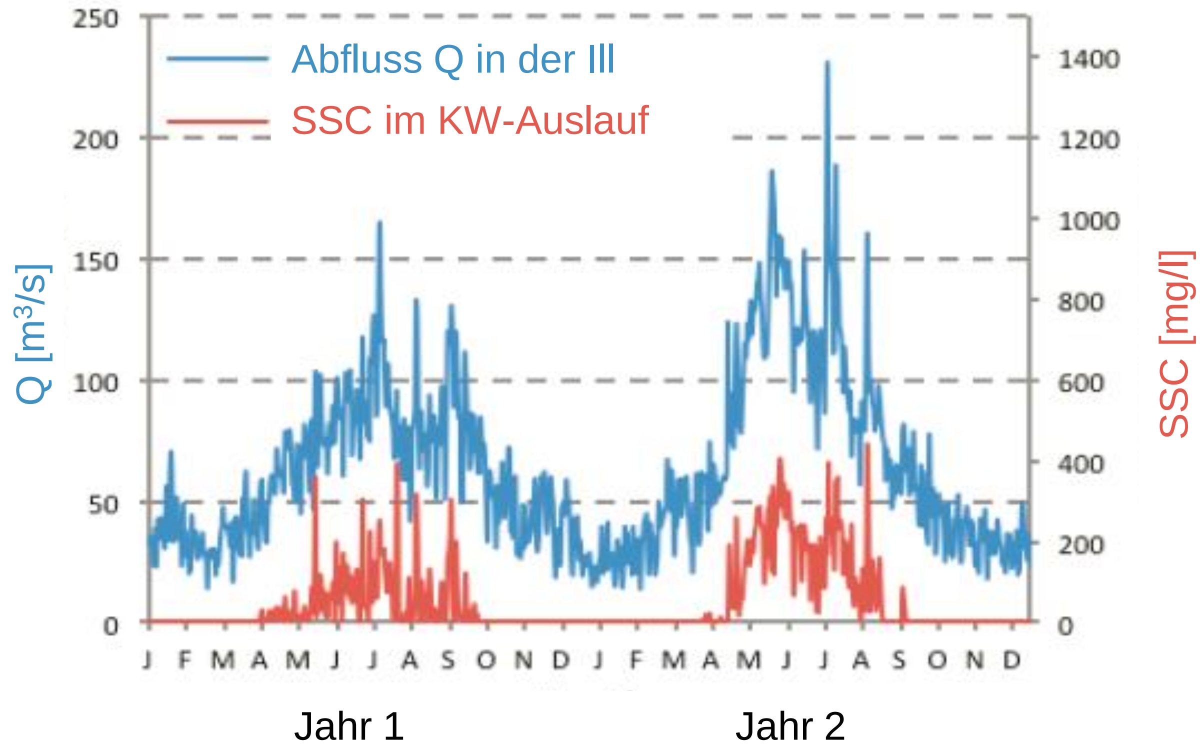
(II) Feinsedimente lösen, fördern und durchleiten

Fallbeispiel Walgauwerk, Österreich

Randbedingungen:

a) Sedimentrückgabe von April bis September

b) Keine Rückgabe von Sandfraktionen → Verwendung als Baustoff



c) Zulässige Erhöhungen der Schwebstoffkonzentration (SSC) in Abhängigkeit der SSC_{us} im Fluss oberstrom der Wasserrückgabe:

0	für $SSC_{us} \leq 0.05$ g/l
0.2 g/l	für 0.05 g/l < SSC_{us} < 0.2 g/l
1.5 * SSC_{us}	für $SSC_{us} \geq 0.2$ g/l

Quelle: nach Sollerer & Matt (2013)

(II) Feinsedimente lösen, fördern und durchleiten

Übersicht zu praktizierten Fallbeispielen an Speicherkraftwerken

WKA (Fluss) und Speichername, Land (Referenz)	Brutto Fall-höhe	Turbinen-ausbau-abfluss Q_d	Zulässiger Anstieg der SSC im Vorfluter	Zulässige Sedimentrück-gaberate Q_S
WKA Kubel (Sitter), Gübsensee, Schweiz (De Cesare et al. 2009)	97 m	16 m³/s	0 im Winter, 0.2 g/l sonst	270 t/d
WKA Walgauwerk (Ill), Ausgleichsbecken Rodund, Österreich (Sollerer & Matt 2013, Sollerer & Gökler 2016)	162 m	68 m³/s	0 für $SSC_{us} \leq 0.05$ g/l, 0.2 g/l für $0.05 < SSC_{us} < 0.2$ g/l, 1.5* SSC_{us} für $SSC_{us} \geq 0.2$ g/l	1170 t/d ≤ 4800 t/d
WKA Langenegg, Bolgenachspeicher, Österreich (DWA 2006)	280 m	ca. 30 m³/s	Praktizierte Rückgabe mit 0.02 g/l bis 0.2 g/l (vor allem bei hohen natürl. Q) lag unter der Grenz-SSC	praktiziert ≤ 500 t/d (80 000 t/a)

mit Francisturbinen

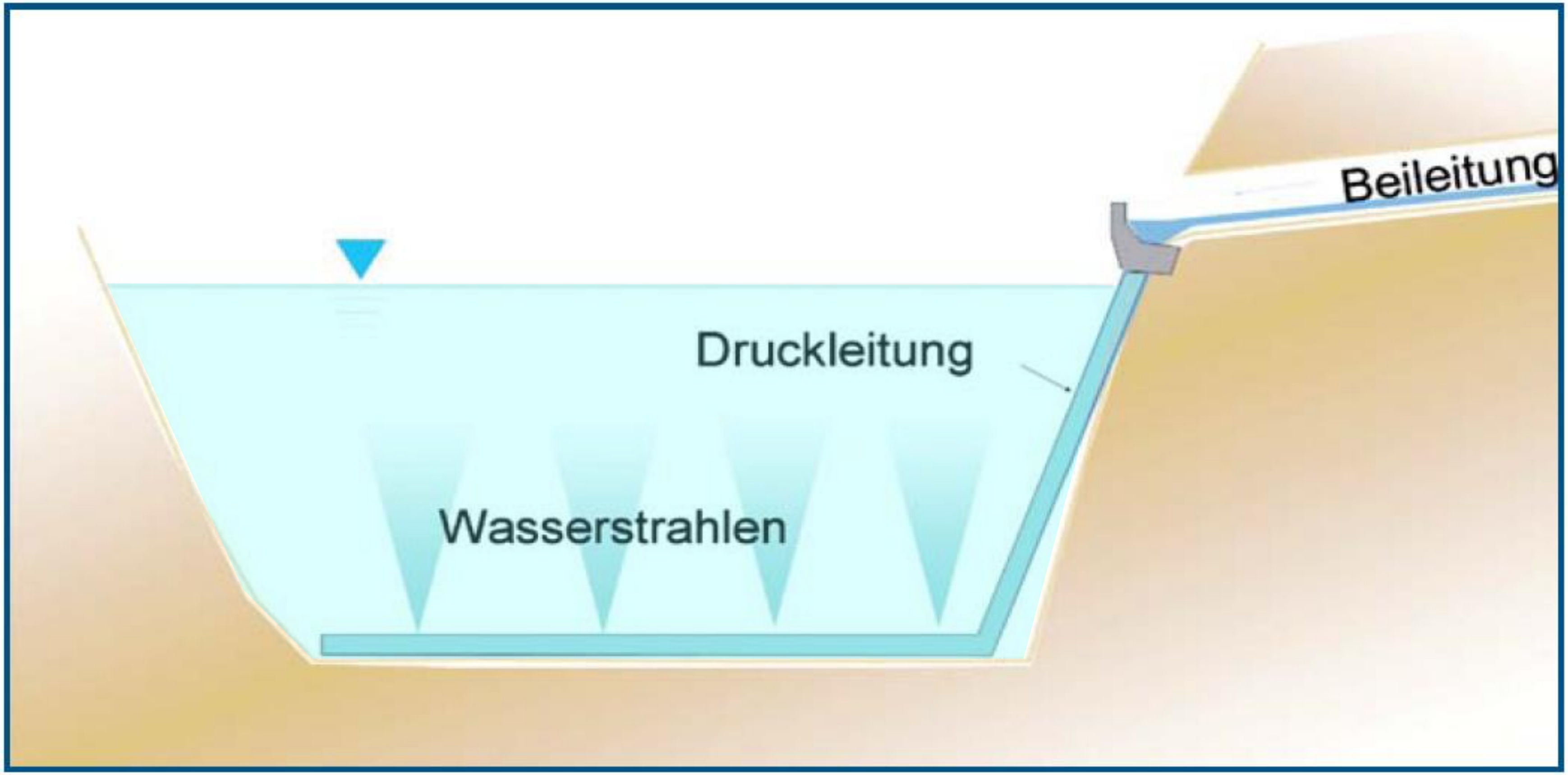
Quelle: nach Felix *et al.* (2016)

Vor-/Nachteile der Feinsedimentableitung

- \+ Wegen Verdünnungseffekt mit grossen Wasservolumina relativ geringe SSC im Unterwasser
- \+ Naturnahe SSC im Unterwasser («dynamische» Dotierung möglich)
- \+ Keine Erhöhung der SSC in der Restwasserstrecke
- \+ Keine Entwässerung und Deponierung der Sedimente erforderlich
- \+ Keine Spülwasserverluste

- – Erhöhter Verschleiss und Unterhalt an elektro-mechanischen Anlagenteilen (Laufräder, Düsen, Dichtungen, …)
- – Reduktion des Absetzens der Feinsedimente benötigt Strömungs-turbulenz (z.B. mittels Blasenschleier oder Wasserstrahlen; «Abflusskanal» in kleineren Speichern)
- – ggf. Remobilisierung von bereits abgesetzten Feinsedimenten (in der Regel kohäsiv) mittels Saugbagger bzw. Pumpen erforderlich
- – Erfordert ggf. Anpassungen am Einlaufbauwerk und im Maschinenhaus (z.B. Turbinenbeschichtungen, Anpassung des Kühlwassersystems)

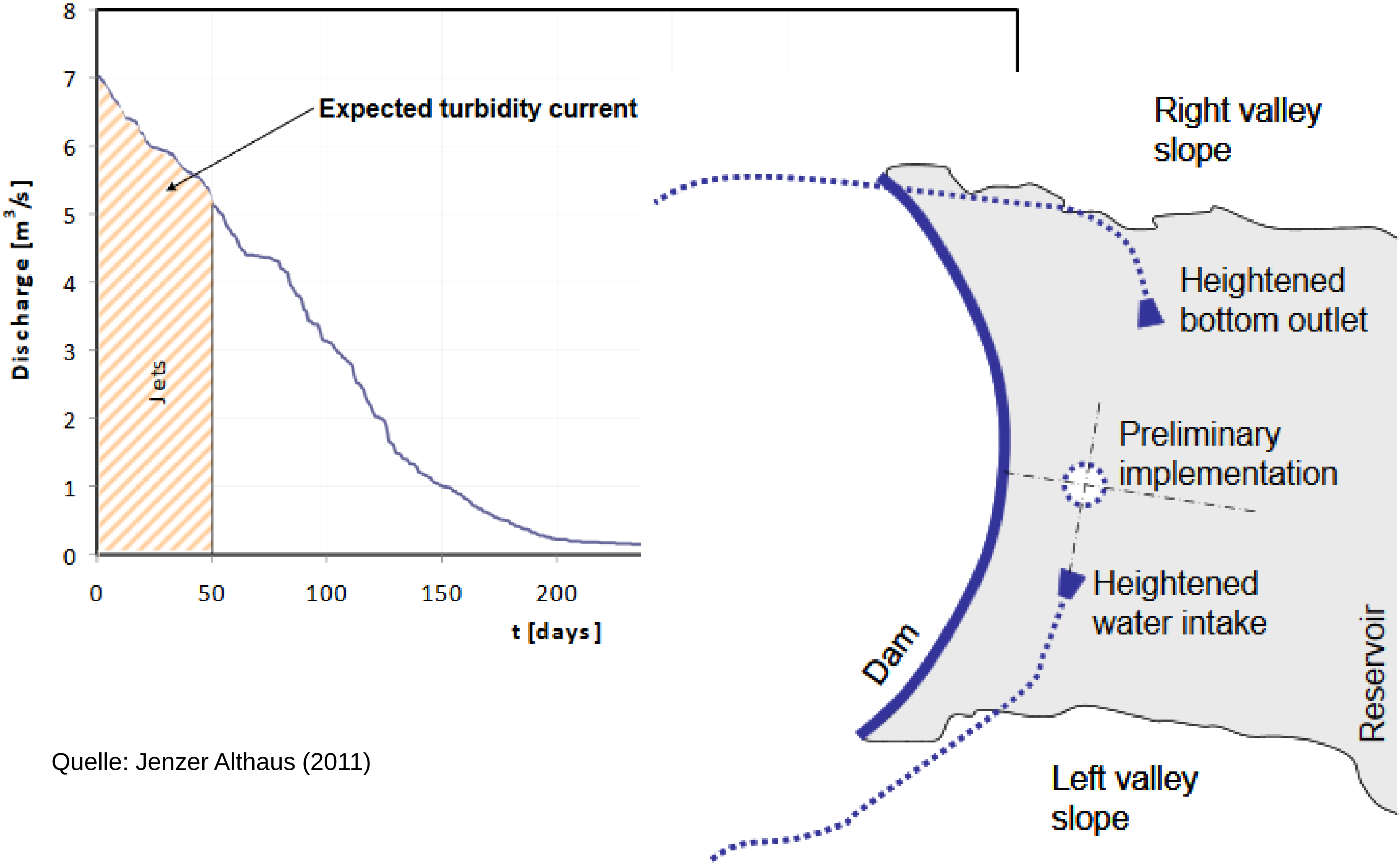
Erzeugung von Turbulenz mittels Wasserstrahlen



Quelle: Jenzer Althaus *et al.* (2008)

Erzeugung von Turbulenz mittels Wasserstrahlen

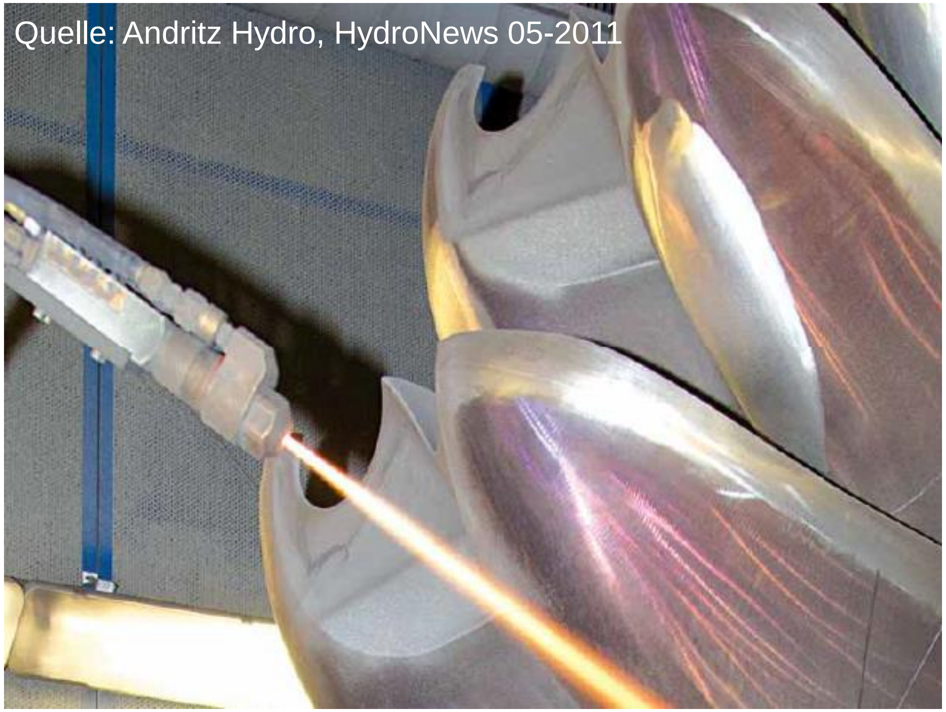
Mögliche Anordnung und Betriebsdauer (Fallbeispiel Mauvoisin)



Quelle: Jenzer Althaus (2011)

Begrenzung der Turbinenabrasion

- **Hartbeschichtung (Wolframkarbid-partikel in Kobalt-Chrom-Matrix)** mittels Hochgeschwindigkeits-flammspritzen (HVOF) aufgetragen



Quelle: Andritz Hydro, HydroNews 05-2011

- **Weichbeschichtungen (Polymere)**

- **Legierungen** (z.B. «Stellite») und Kombinationen mit Hartbeschichtungen

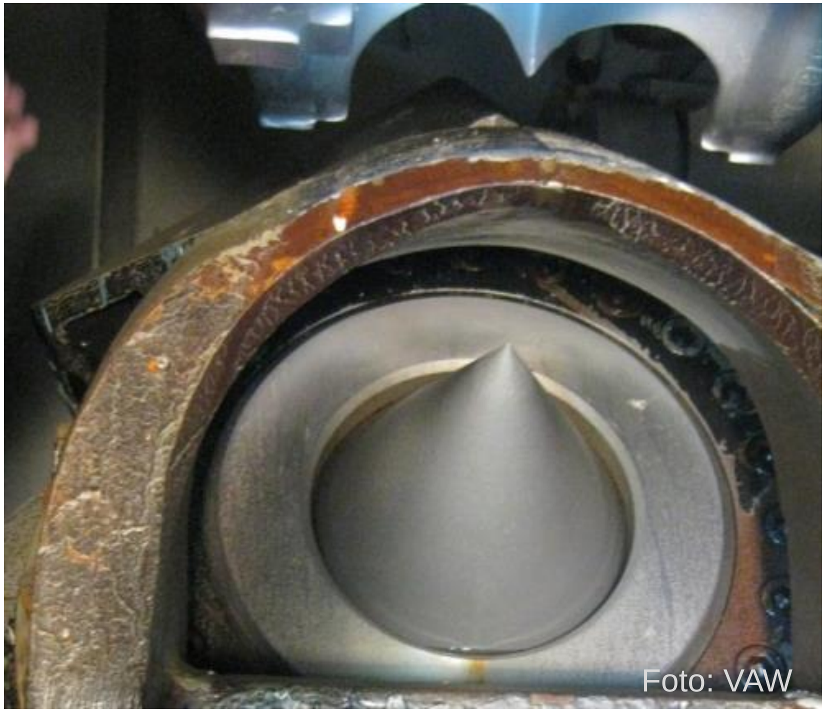


Foto: VAW

- **Hartschichten schweissen**
- **Andere Stahlgüten**

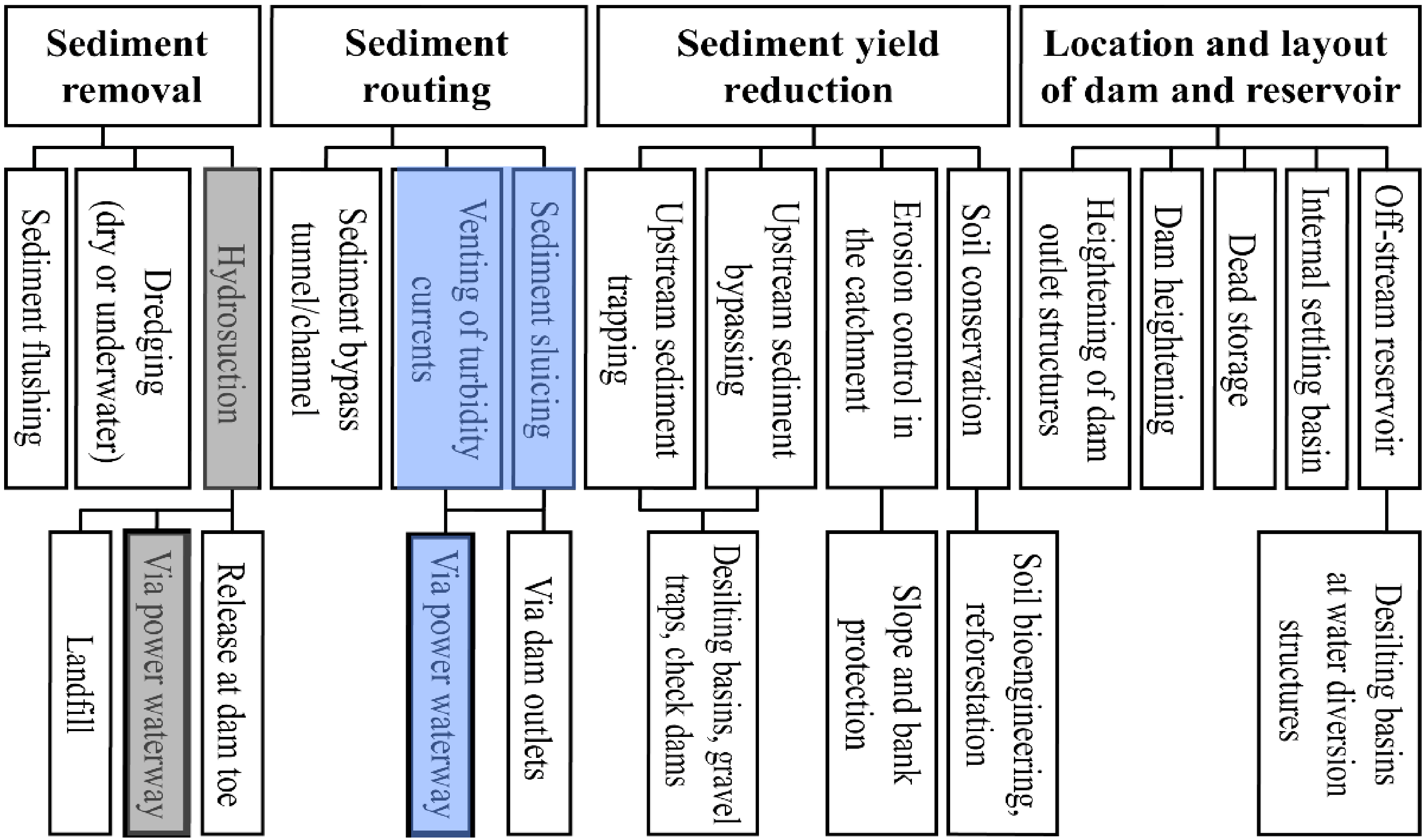
Schlussfolgerungen

Feinsedimentableitung über den Triebwasserweg als interessante Massnahmen gegen Stauraumverlandung, besonders unter folgenden **Voraussetzungen:**

- **Verlandung im Wesentlichen durch Feinsedimente** (ist in vielen Speichern der Fall)
- **Niedrige bis mittlere Fallhöhen** und somit nicht zu hohe Fliessgeschwindigkeiten in den Turbinen;
- **Relativ kleine Sedimentpartikel**, DWA (2006) erwähnt Ton- bis Mittelsilt mit $d \leq 20$ µm als geeignet;
- **Geringe bis mittlere Härte der Sedimentpartikel** (z.B. Sedimentgesteine);
- **Geeignete Turbinenauslegung (**siehe z.B. IEC 62364)

→ **betriebswirtschaftliche Optimierung je nach Anlage**

Massnahmen gegen Stauraumverlandung



(II) (I)

modified from Boes & Hagmann (2015)

Measures against reservoir sedimentation

Measures against reservoir sedimentation

Reduce sediment input

- Reduction of erosion on soils, embankments and river beds
- Sediment retention upstream of main dam
- Off-stream reservoirs with suitable in- and outlets
- Sediment bypass tunnels or channels along the whole reservoir length
- Equip water adductions with sediment traps and stop operation during floods

Increase sediment output

Sediment passage (without settling)

Pass sediment-rich waters through reservoirs

- Via outlets, bypass tunnels (partial reservoir length) or **power waterways** without reservoir drawdown
- Via low level outlets during reservoir drawdown

Removal of sediment deposits

- Flushing via outlets, bypass tunnels (partial reservoir length) or **power waterways** with reservoir draw-down
- Hydraulic transport to dam toe, in **power waterways,** other reservoirs or landfill
- Dry excavation with road transport

Further possibilities

- Design large dead storage
- Sediment reloca-tion in reservoir
- Dam heightening and modification of outlets

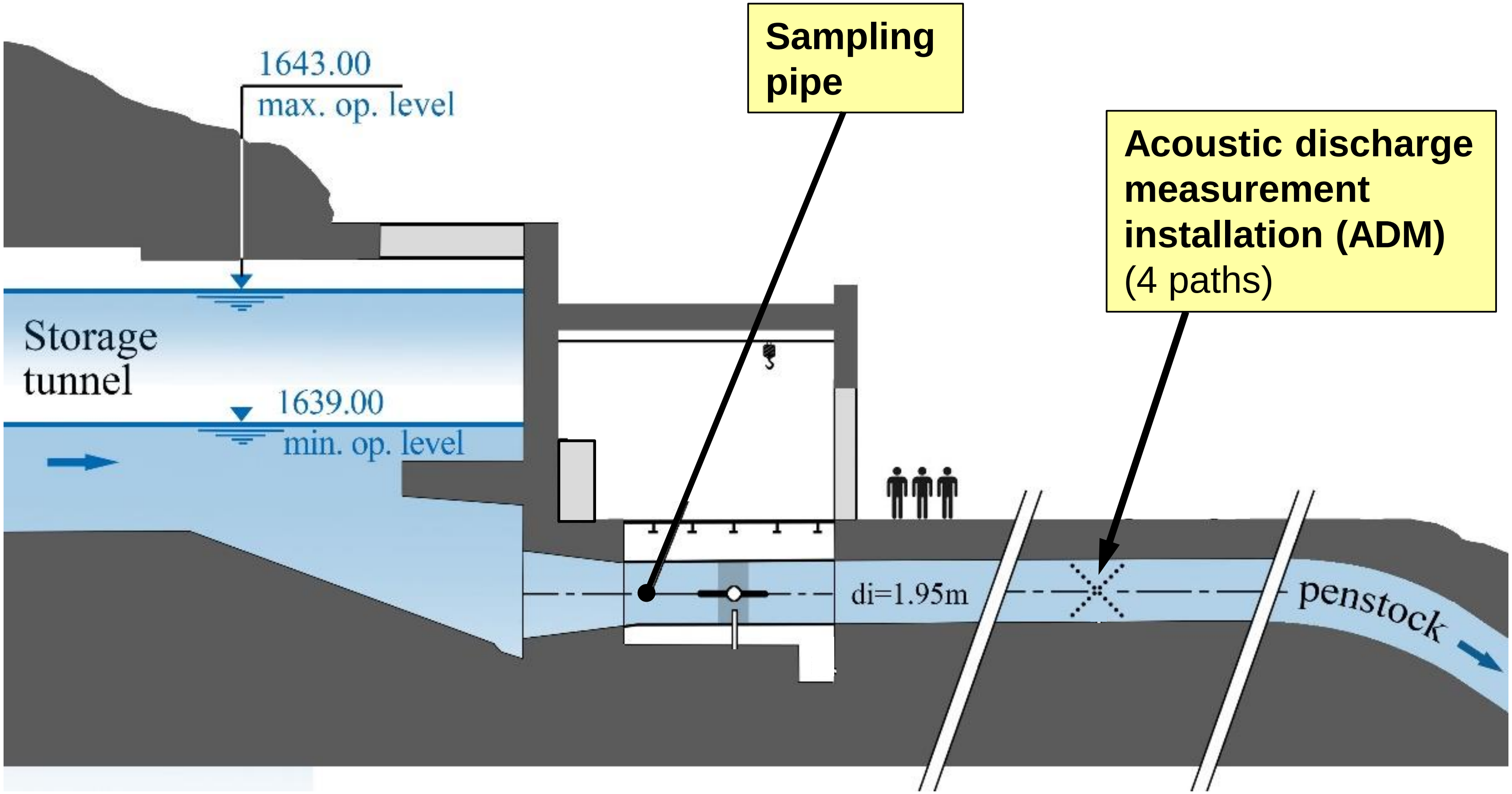
Conversion from storage to run-of-river HPP

Dismantling of dam with erosion of sediment deposits

(modified from ICOLD 1989,
Boes and Hagmann 2005, Schleiss et al. 2016)

Setup for suspended sediment monitoring

In the valve chamber

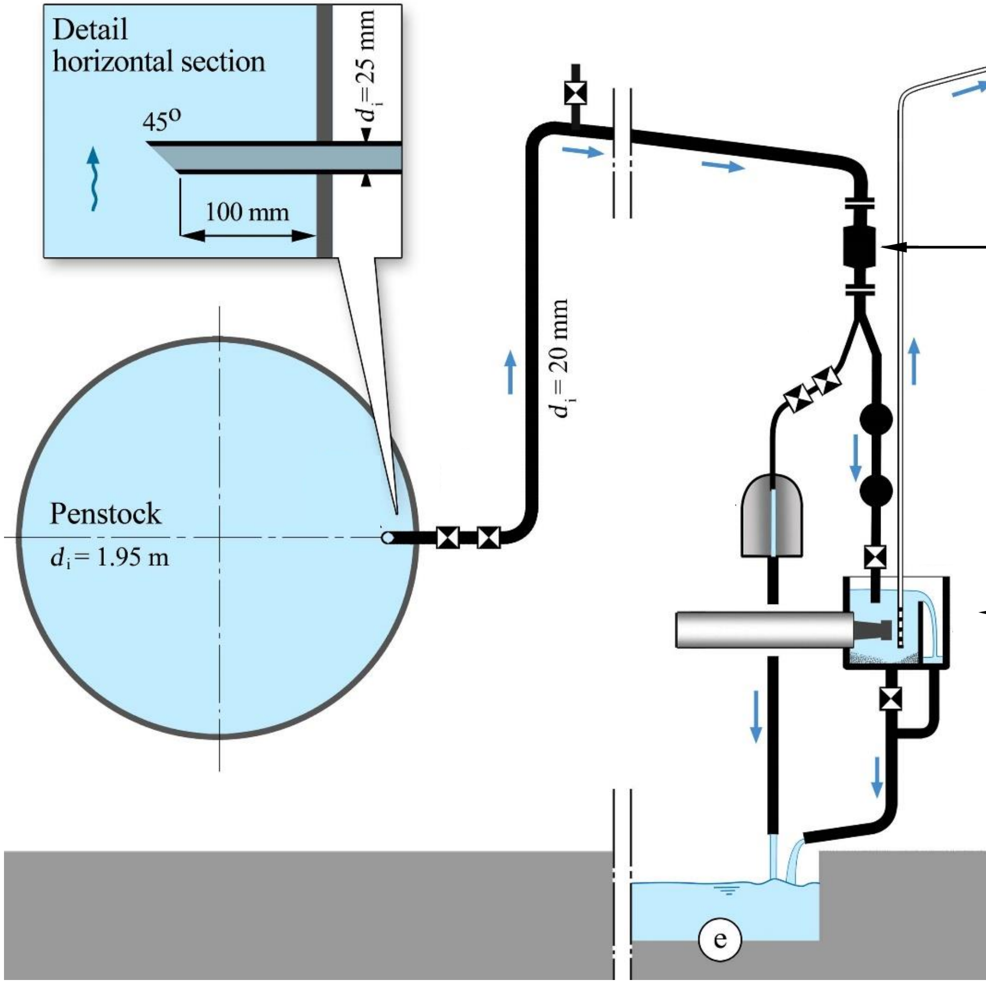


Felix *et al.* (2017)

Setup for suspended sediment monitoring

In the valve chamber

Water sampler



Coriolis Flow- and Density Meter (CFDM)

Turbidi-meters

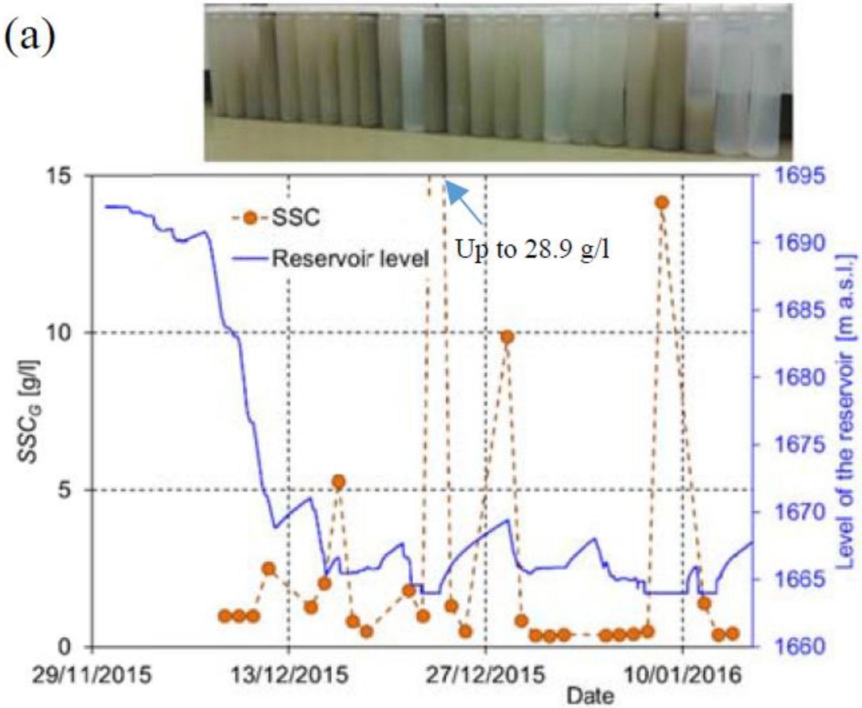
Felix *et al.* (2016)

Studien zu Schwebstoffen und Turbinenabrasion

Erhöhte SSC im Triebwasser infolge ausserordentlichen Seespiegelabsenkungen

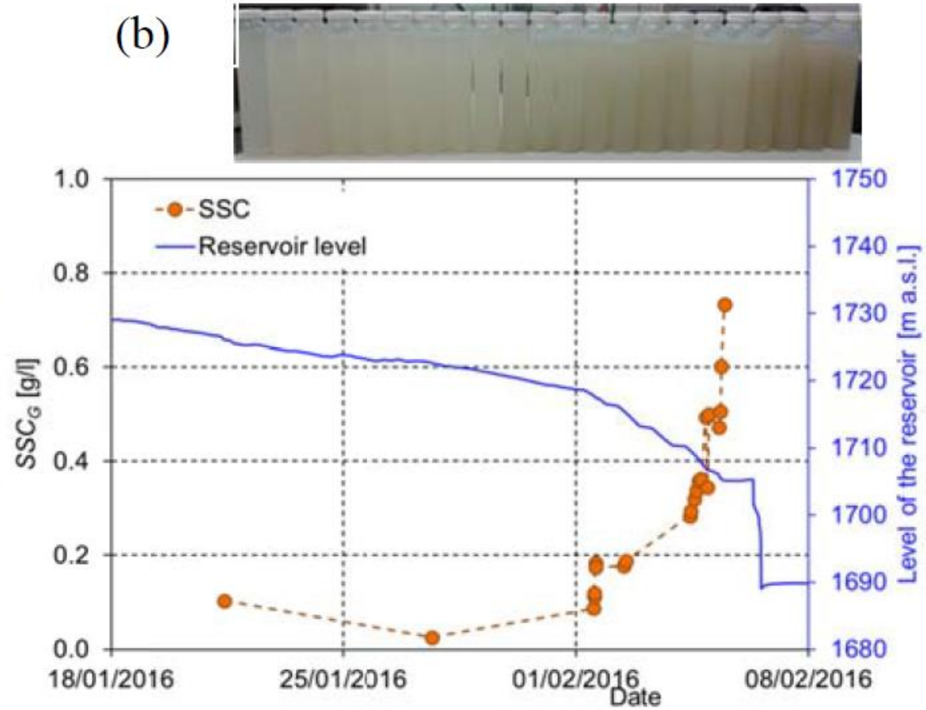
WKA Kaunertal (500 MW), Österreich

TIWAG



WKA Handeck 2 (136 MW)

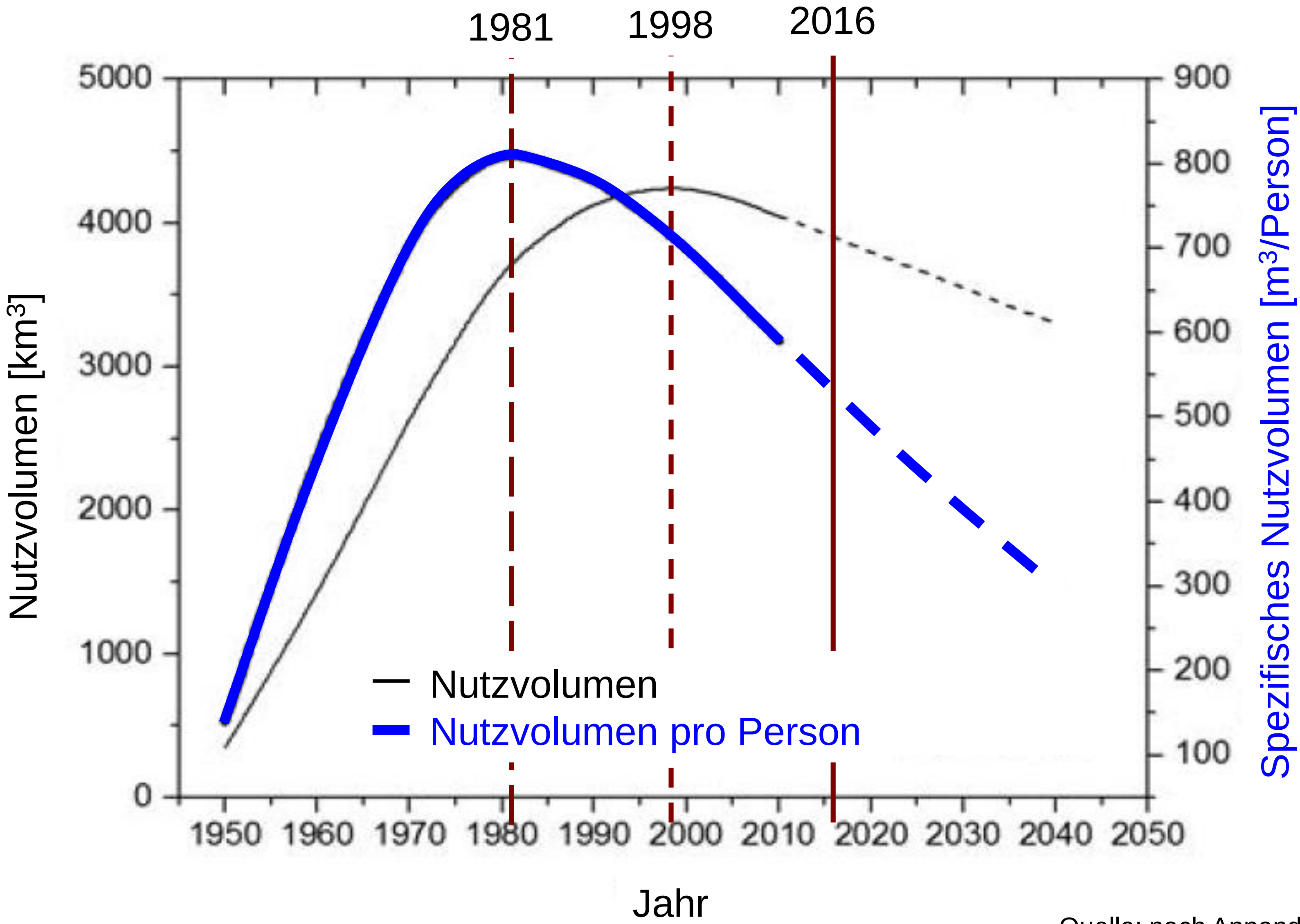
KWO



Quelle: Fernandes *et al.* (2016)

Stauraumverlandung

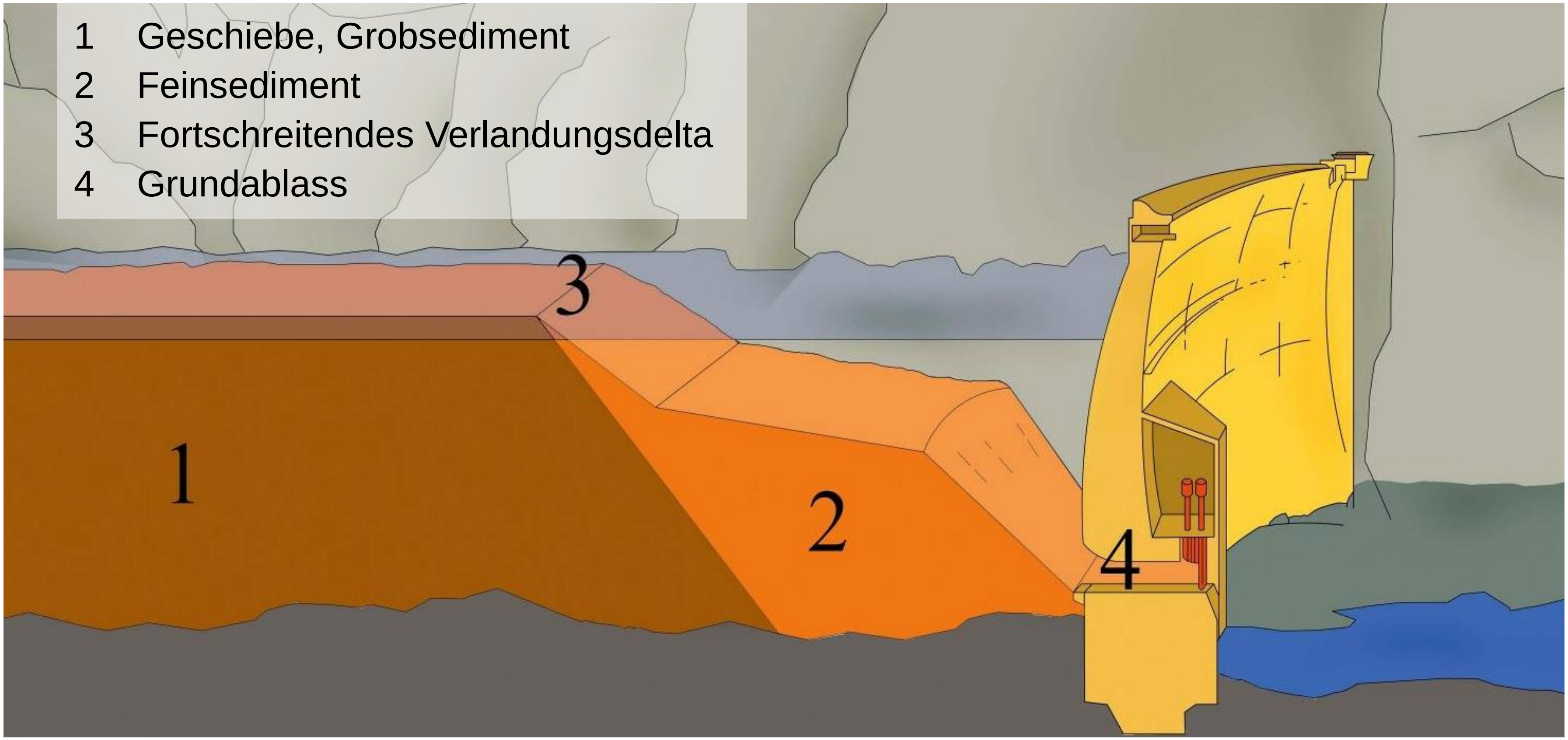
Entwicklung des Speichervolumens weltweit



Quelle: nach Annandale (2013)

Auswirkungen von Stauraumverlandung

Beeinträchtigungen von Betrieb und ggf. Talsperrensicherheit



Quelle: ewz

Stauraumverlandung

(Quelle: Stamm et al. 2016)

Sedimentablagerungen im Räterichsbodensee (BE) während der Entleerung aufgrund von Bauarbeiten

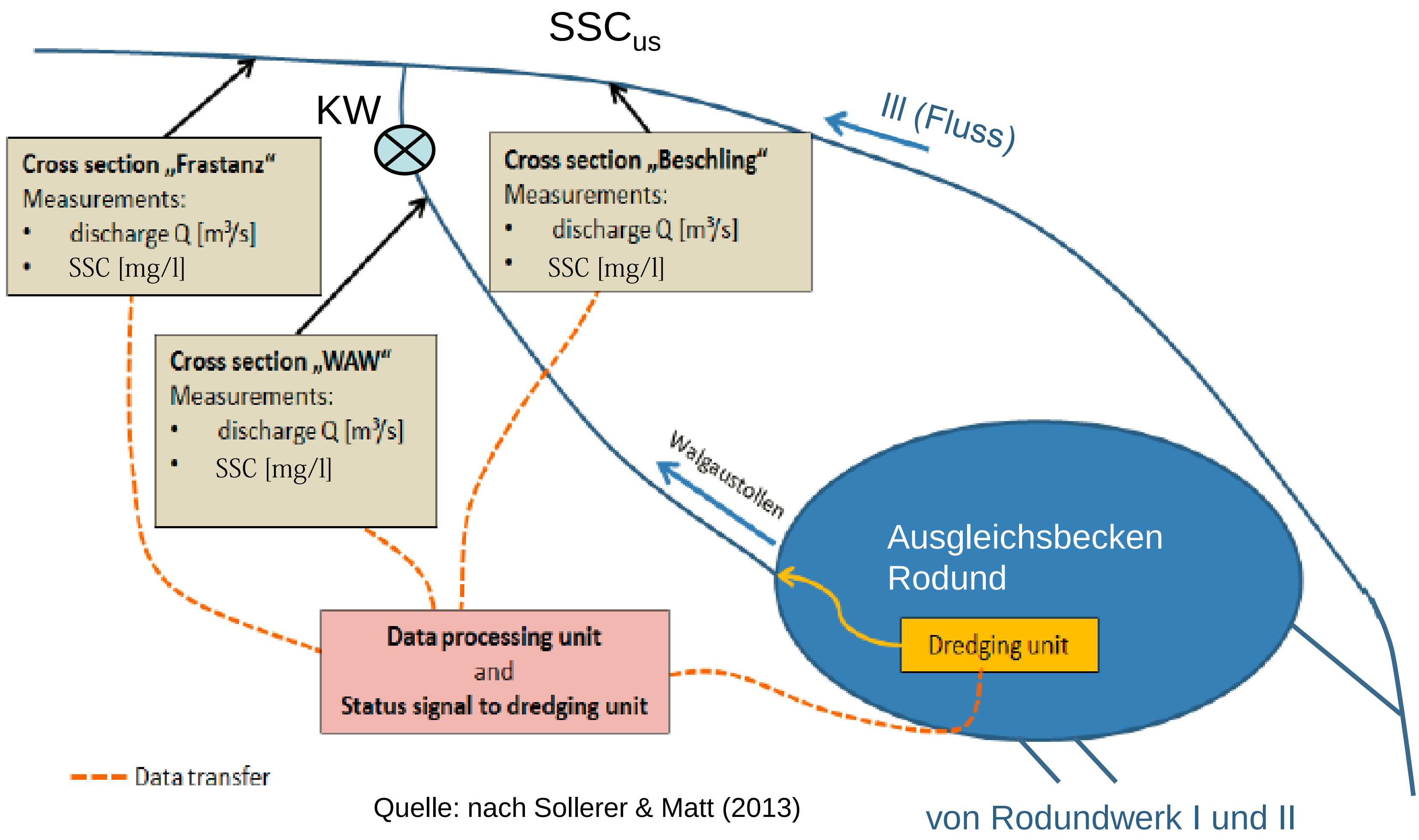
Auswirkungen von Stauraumverlandung

Verlust der Speicherfunktion → Laufwasserkraftwerk

Beispiel Maigrauge (FR)

(II) Feinsedimente lösen, fördern und durchleiten
Fallbeispiel Walgauwerk, Österreich

Systemübersicht mit Lage der Messstellen



Quelle: nach Sollerer & Matt (2013)

(II) Feinsedimente lösen, fördern und durchleiten

Fallbeispiel Walgauwerk, Österreich

Wasser von mehreren Speichern mit vergletscherten Einzugsgebieten

+ Flusswasserfassung

Ausgleichsbecken im Nebenschluss mit V_{Nutz} = 1.8 hm^3 (ehemals 2.1 hm^3)

2 Francis, total 86 MW,
H = 162 m, Q_d = 68 m^3/s

Saugbagger mit Sediment-Förderkapazität von 200 m^3/h, d.h. ≤ 4800 m^3 /Tag

im Triebwasser ≤ 1.4 g/l bei Ausbauwassermenge

Quelle: nach Sollerer & Matt (2013)

Sediment conveyance through power waterway

Compensation basins Rodund of HPP Walgauwerk, Austria

Several upstream storage HPPs from glaciated catchments

+ intake from the river

Off-stream reservoirs with active storage 1.8 Mio m^3 (originally 2.1 Mio m^3)

2 Francis, 86 MW, 162 m head, design discharge 68 m^3/s

Floating hydrosuction unit (capacity 200 m^3 sediment / h)

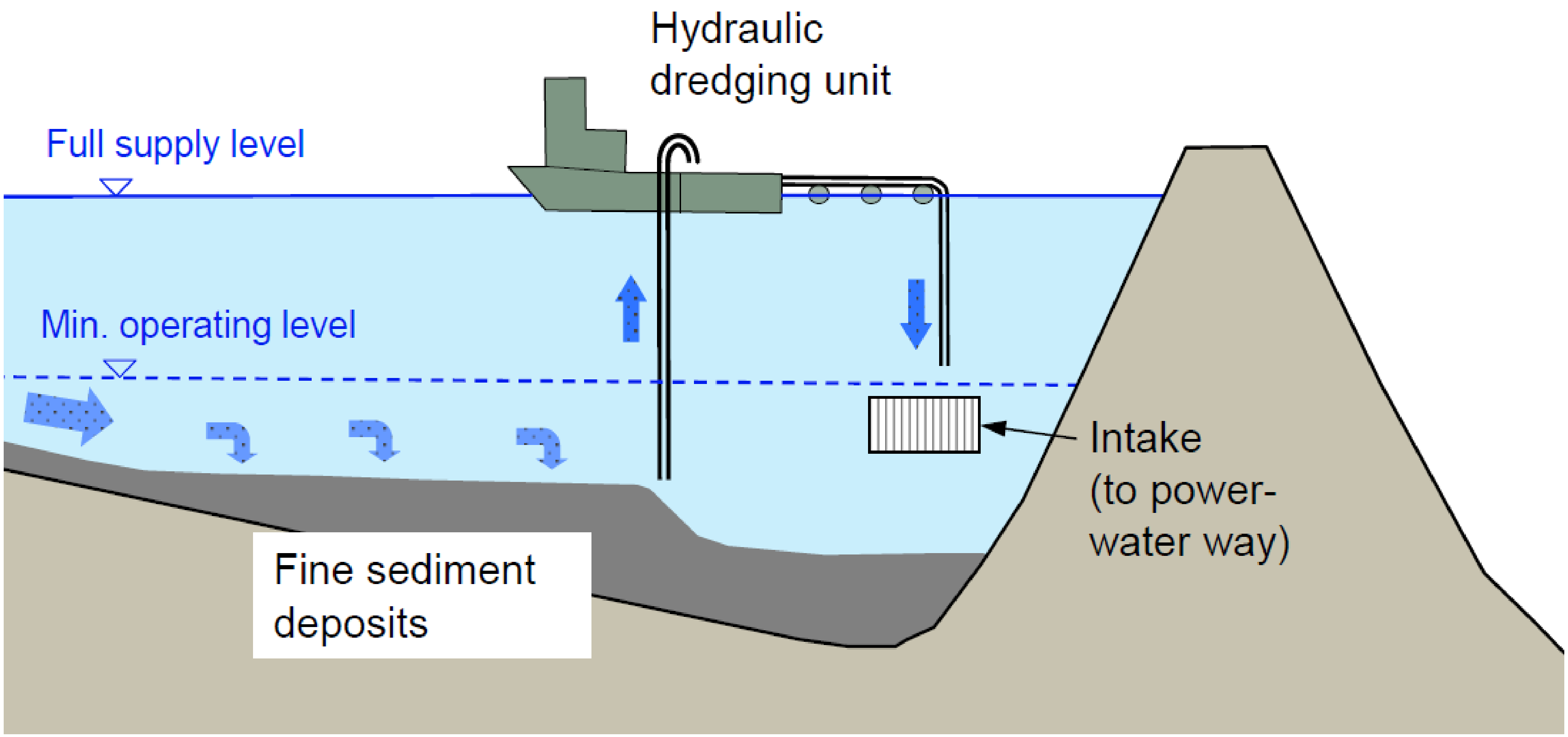
$\leq$ 4800 m^3 /day

Additional SSC in power water:

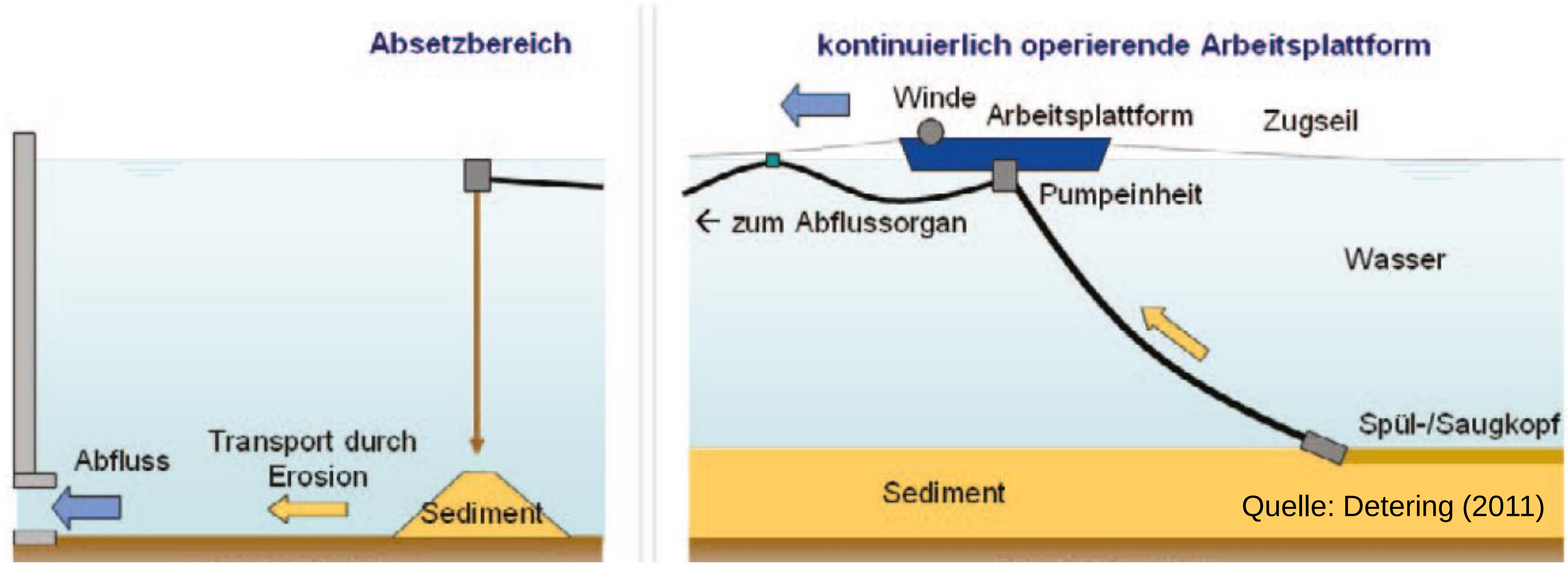
0 if $SSC_{us} \leq 0.05$ g/l

0.2 g/l if 0.05 g/l $< SSC_{us} <$ 0.2 g/l

1.5 * SSC_{us} if $SSC_{us} \geq 0.2$ g/l

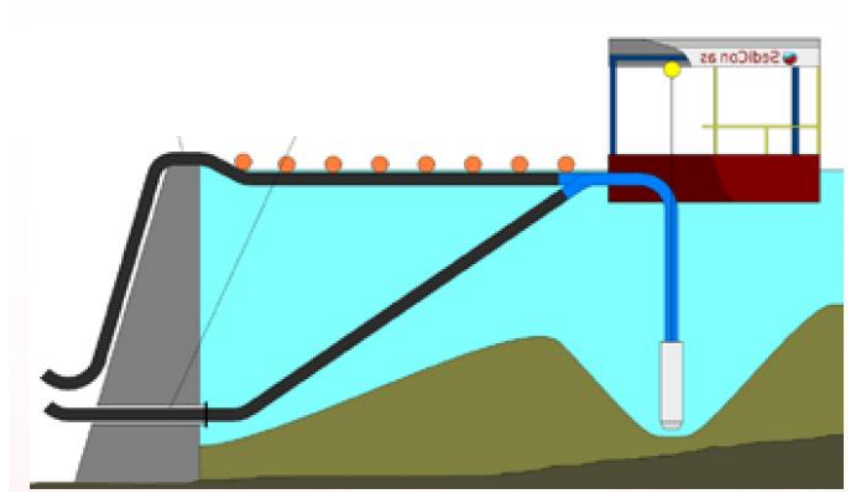

Hydraulic
dredging unit
Full supply level
Min. operating level
Intake
(to power-
water way)
Fine sediment
deposits

Saugbaggerung (Hydro-suction)



Quelle: Detering (2011)


Quelle: www.sedicon.no



Quelle: www.sedicon.no

Sediment conveyance through power waterway

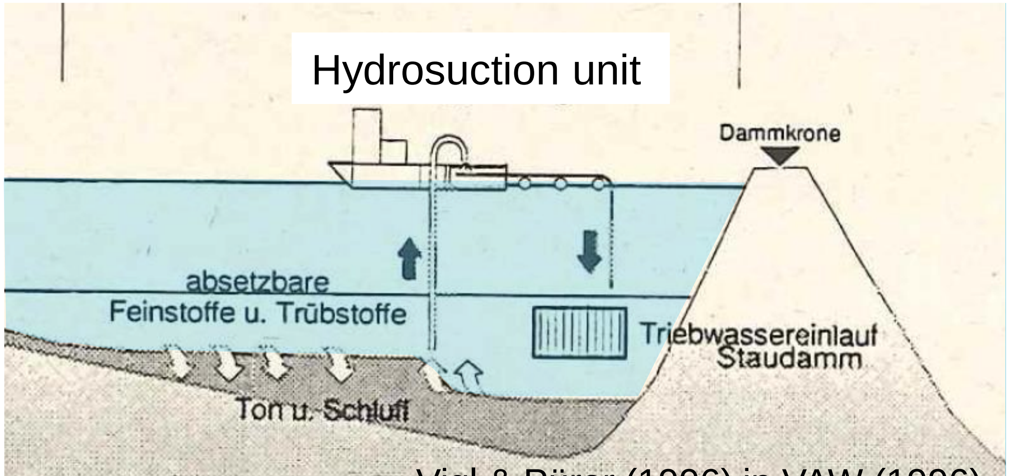
Reservoir Bolgenach of HPP Langenegg, Austria

Reservoir Bolgenach
6.5 Mio m³ (originally 8.4 Mio m³)

2 Francis, 74 MW, 280 m head,
design discharge 32 m³/s

Additional SSC in power water
0.02 to 0.2 g/l (below admissible values)

≤ 500 t/day (80 000 t/year)

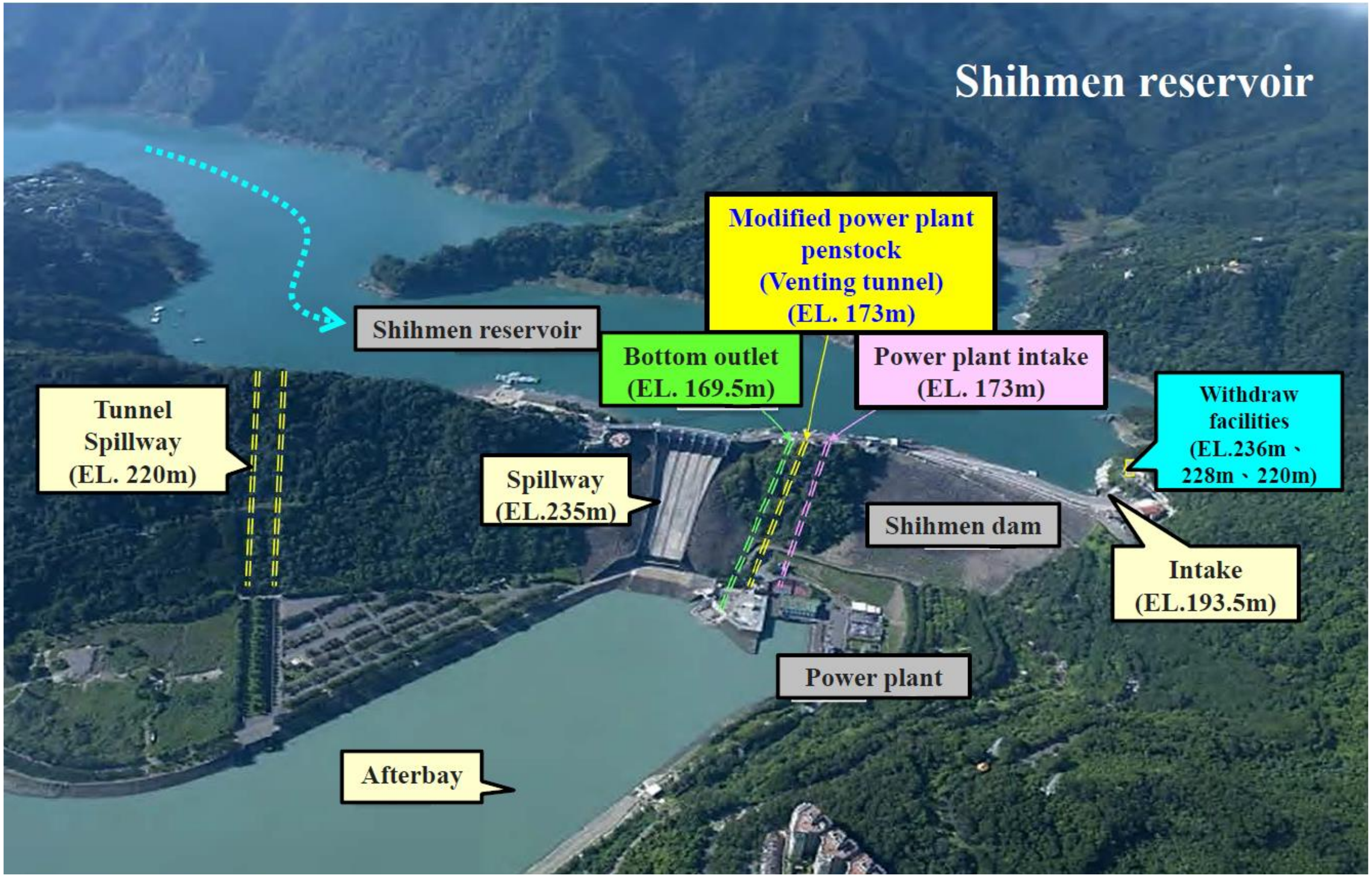


Vigl & Pürer (1996) in VAW (1996)

(I) Feinsedimente über Triebwasserweg durchleiten

Fallbeispiel Shihmen Reservoir, Taiwan

V_{1964} = 309 hm^3, V_{2011} = 215 hm^3 → −30% bzw. − 0.64%/Jahr



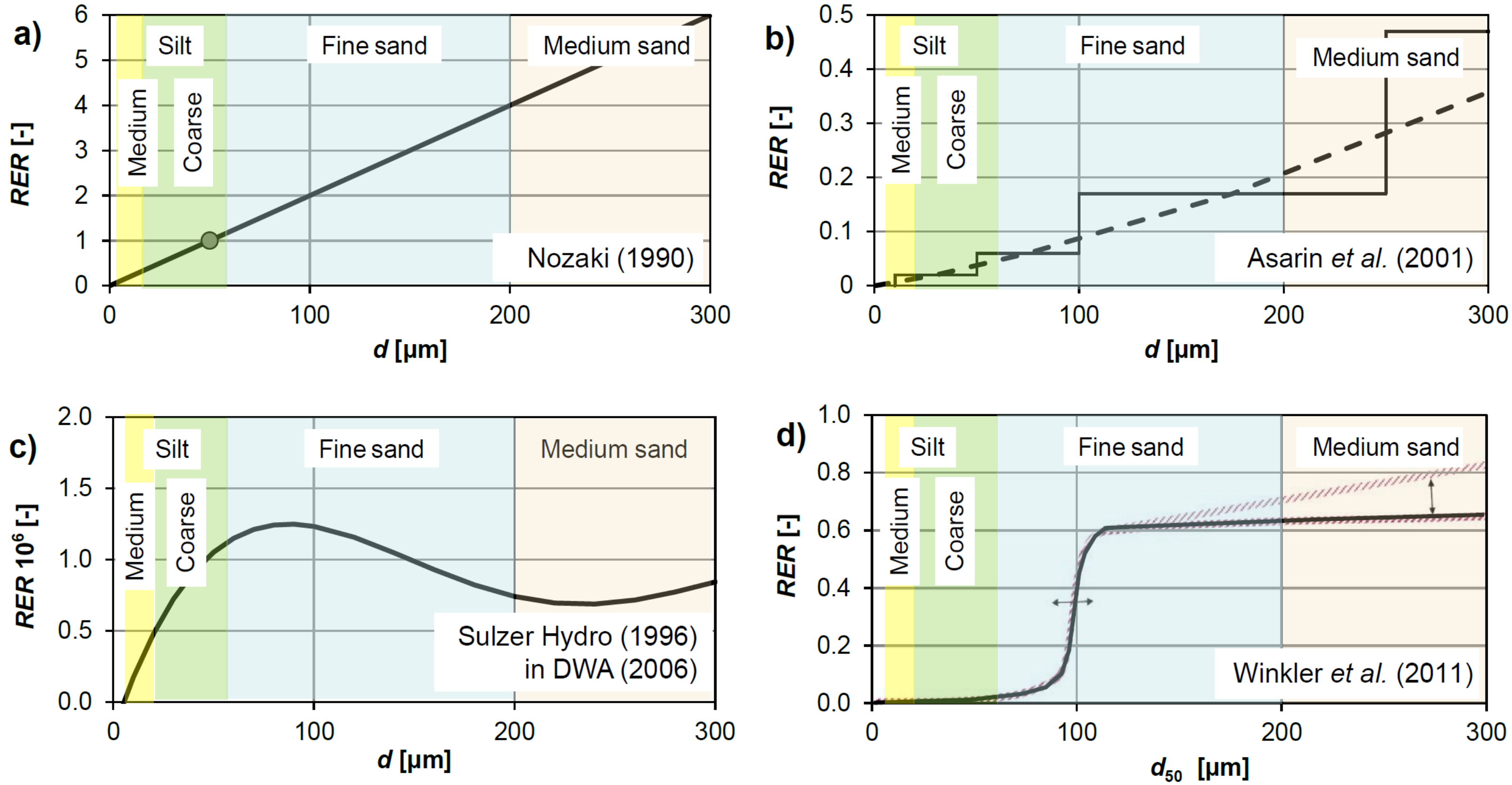
Quelle: Lai et al. (2015)

(I) Feinsedimente über Triebwasserweg durchleiten

Fallbeispiel Shihmen Reservoir, Taiwan

Quelle: Wikipedia

Effect of particle size on turbine erosion



Economic potential of temporary turbine switch-offs

Scenario of flood event in July 2012 at HPP Fieschertal (2 turbines)

− 50’000 €	**Generation loss** during 16 h **downtime** (during abundant inflow) (2 * 32 MW * 16 h ≈ 1 GWh with an assumed price of 50 €/MWh) corresponds to 0.6 % of the annual electricity generation
+ 200’000 €	**Avoided repair costs** (rough estimate)
+ 30’000 €	**Avoided generation loss** because of **less reduced efficiency** (estimate)
+ 30’000 €	**Avoided generation loss** because of **no runner change required** (one turbine at full load, 17 h)
− ….	Potential **penalty** for **deviation** from the **production schedule** (or no penalty considering force majeure)
~ 200’000 €	**Net benefit**

➡ In this constellation, a turbine switch-off during the flood would have been clearly **profitable**