# Reservoir Sedimentation

## Processes, problems and management strategies

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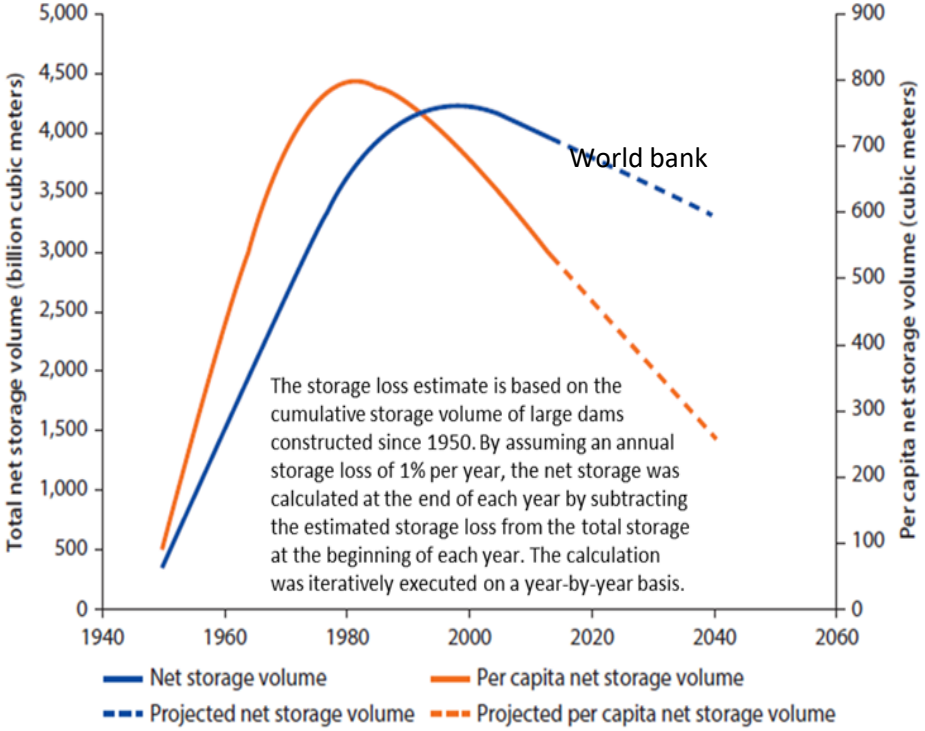
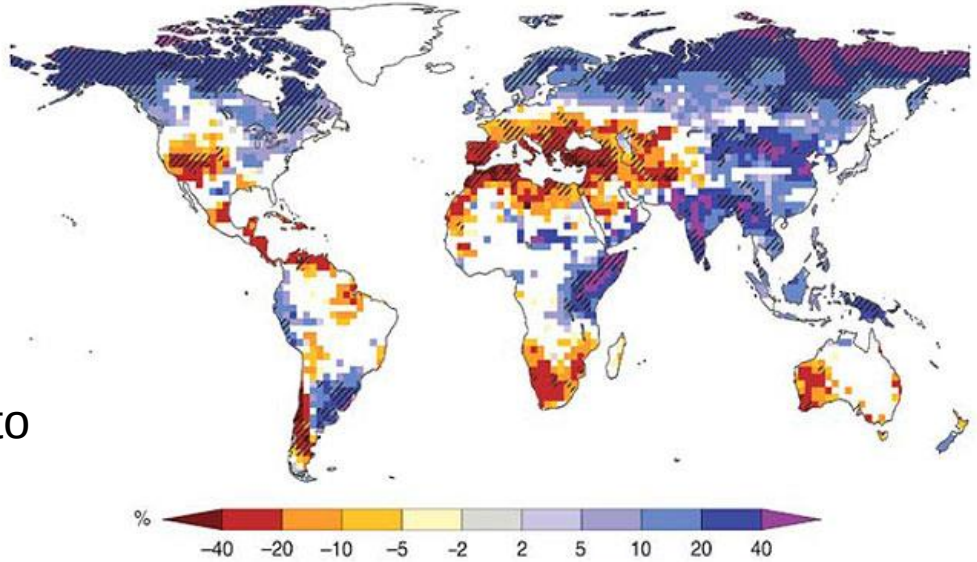
# INTRODUCTION

- Rate of reservoir sedimentation: average annual storage loss of 2.3 % in China to 0.68% in North America.
- Global rate of storage loss due to sedimentation **has outpaced** the rate of new storage construction.
- Without further actions, one quarter of all reservoirs will lose their storage to sedimentation in the next 25 to 50 years.
- Combating the storage loss corresponds to adding about 50 billion cubic meters of storage per year worldwide, with a replacement cost of nearly US$18 billion



# INTRODUCTION

- Global water use and hydropower increase with population and development.
- Climate Change: Mean flow, Hydrologic variability, Deforestration, Sediment Loads.
- Accumulation of reservoir sediment is steadily degrading our ability to ensure reliability of:
  - Water Supply and irrigation (Food Production).
  - Flood Management and Hydropower.
- Sustainable sediment management is needed:
  - To preserve the reservoir benefits for future generations **(Intergenerational Equity).**
  - To reduce environmental impacts.

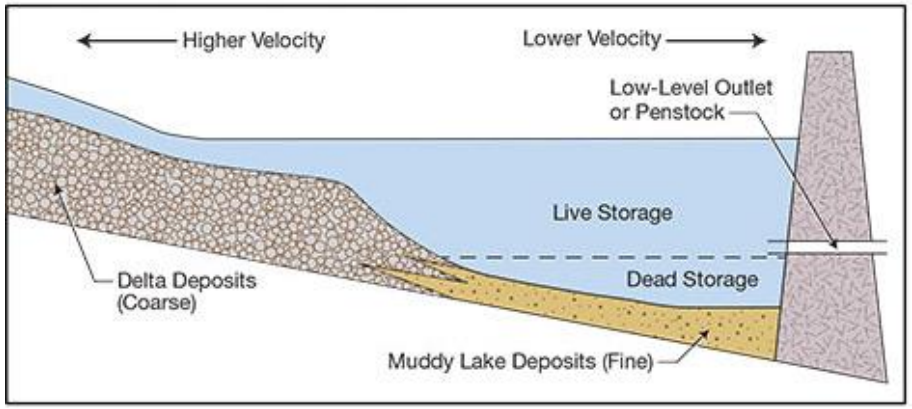


Climate change: Mean annual flow increase/decrease (Annandale 2019)

# RESERVOIR DESIGN LIFE

- **GIVEN:** selected site for a dam → **FIND:** elevation of lowest outlet
- Design life: typically 50 or 100 years.
- Accepted practice was to design reservoirs to be filled with sediment.
  - Estimate the reservoir sedimentation volume and spatial distribution.
- Design the dam's outlet to be above the reservoir sedimentation level over the design life.
- Future generations will take care and handle the consequences of sedimentation.

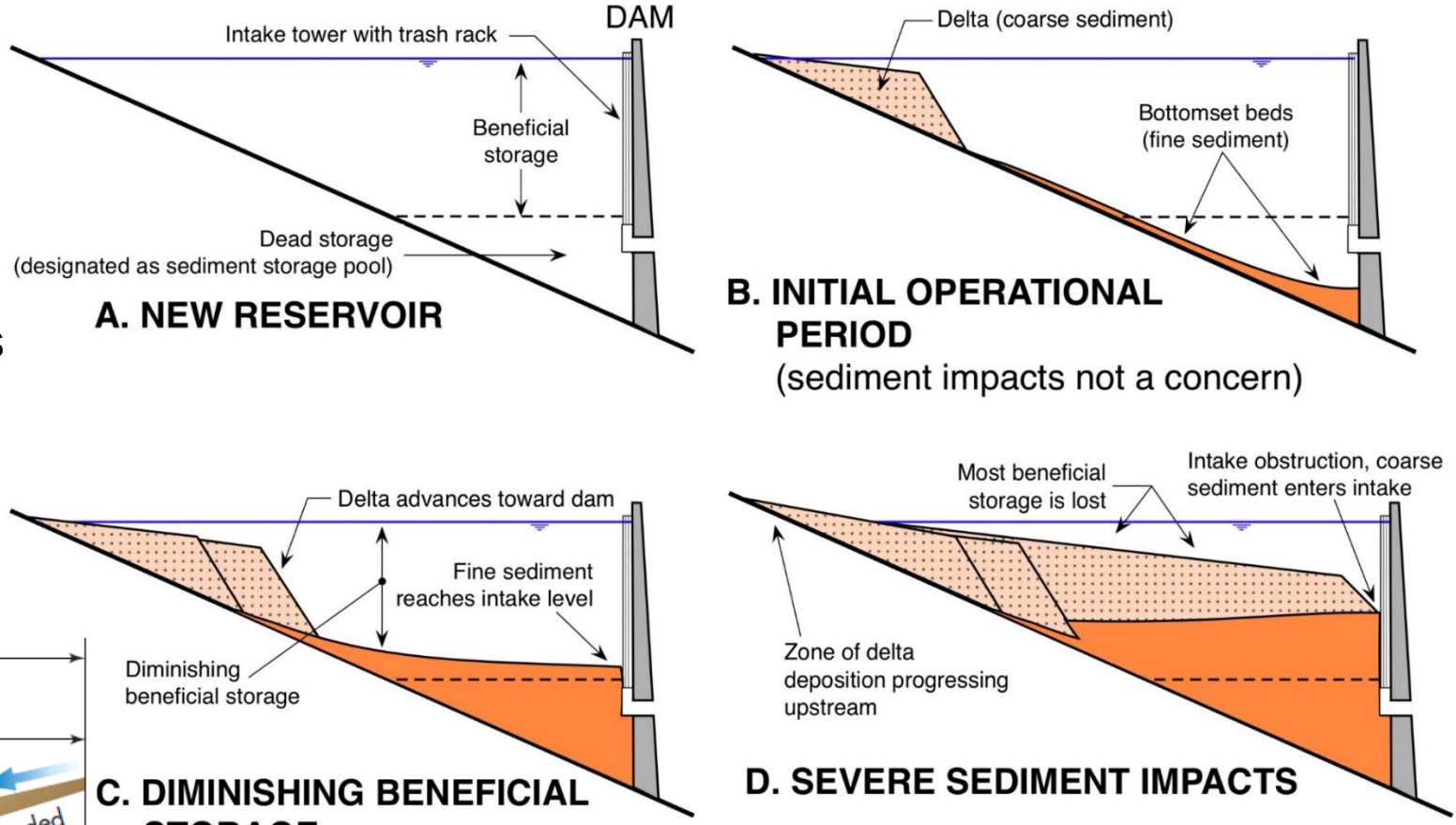
Reservoir Sedimentation Manual



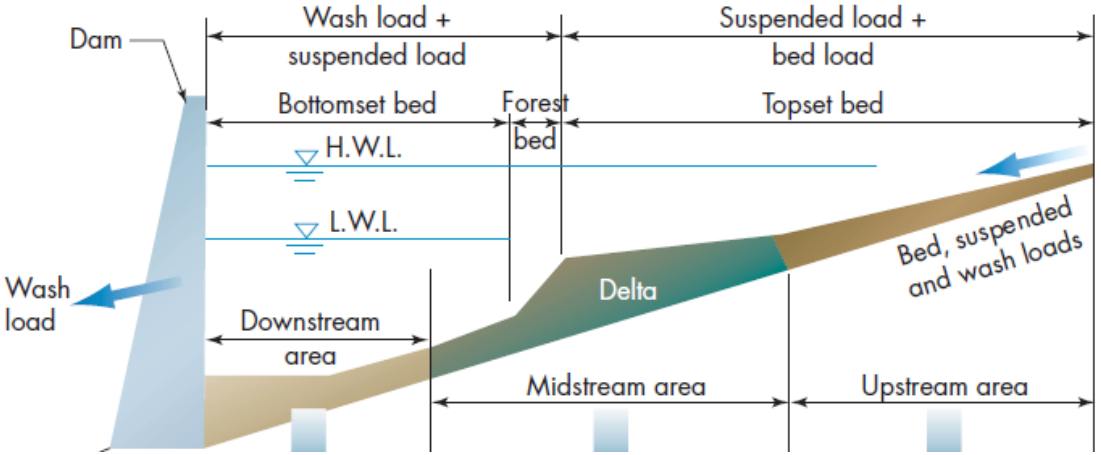

World Bank: "*The last century was used to build reservoirs. This one will be used to solve sediment problems*."

# RESERVOIR SEDIMENTATION

- Some eroded sediments may temporarily reside on hillsides and in floodplains.
- Reservoir blocks downstream transport of sediment.
- Only very fine sediments (washload) pass the dam.
- Coarse material trapped and advances toward dam.



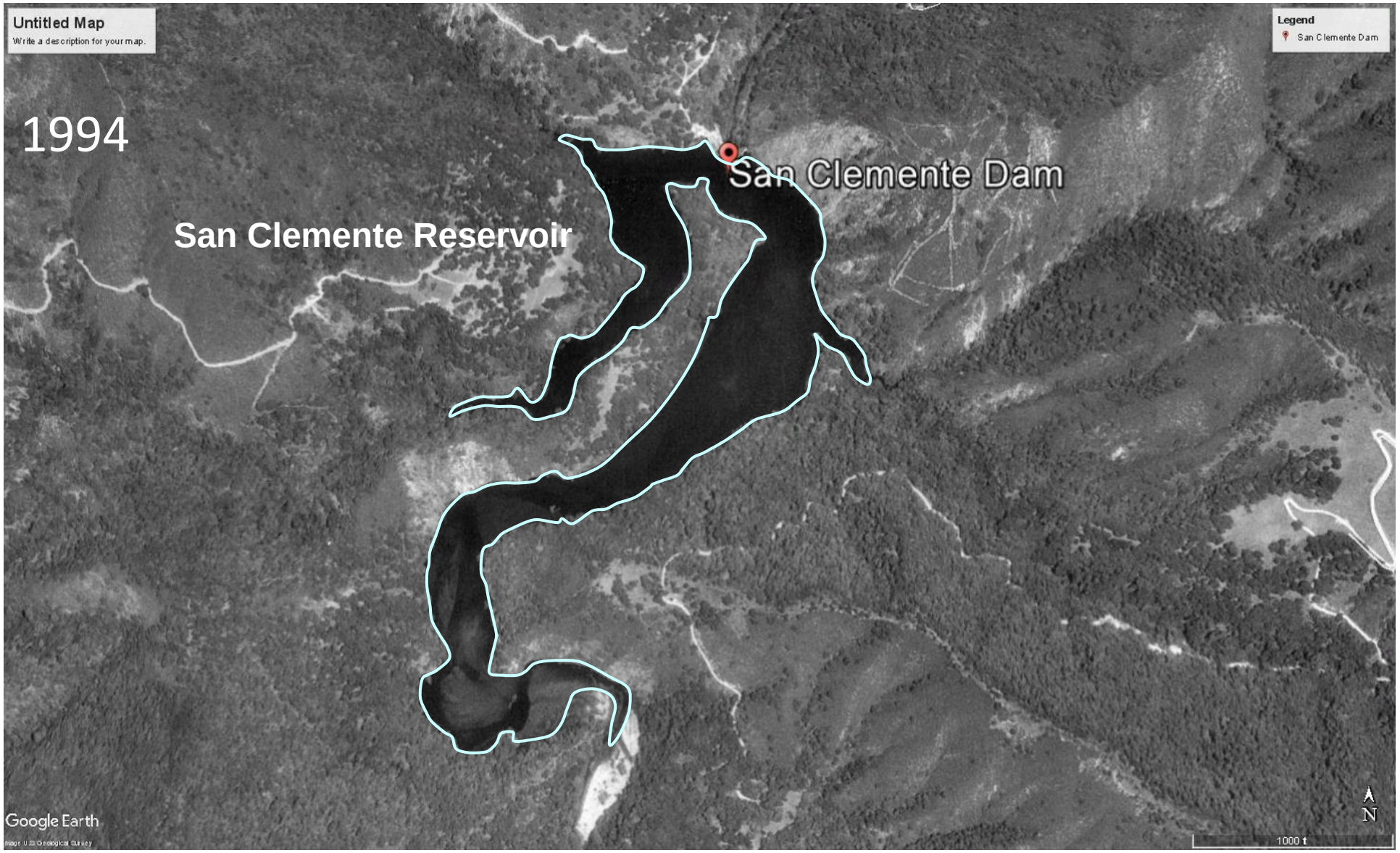

G. Morris



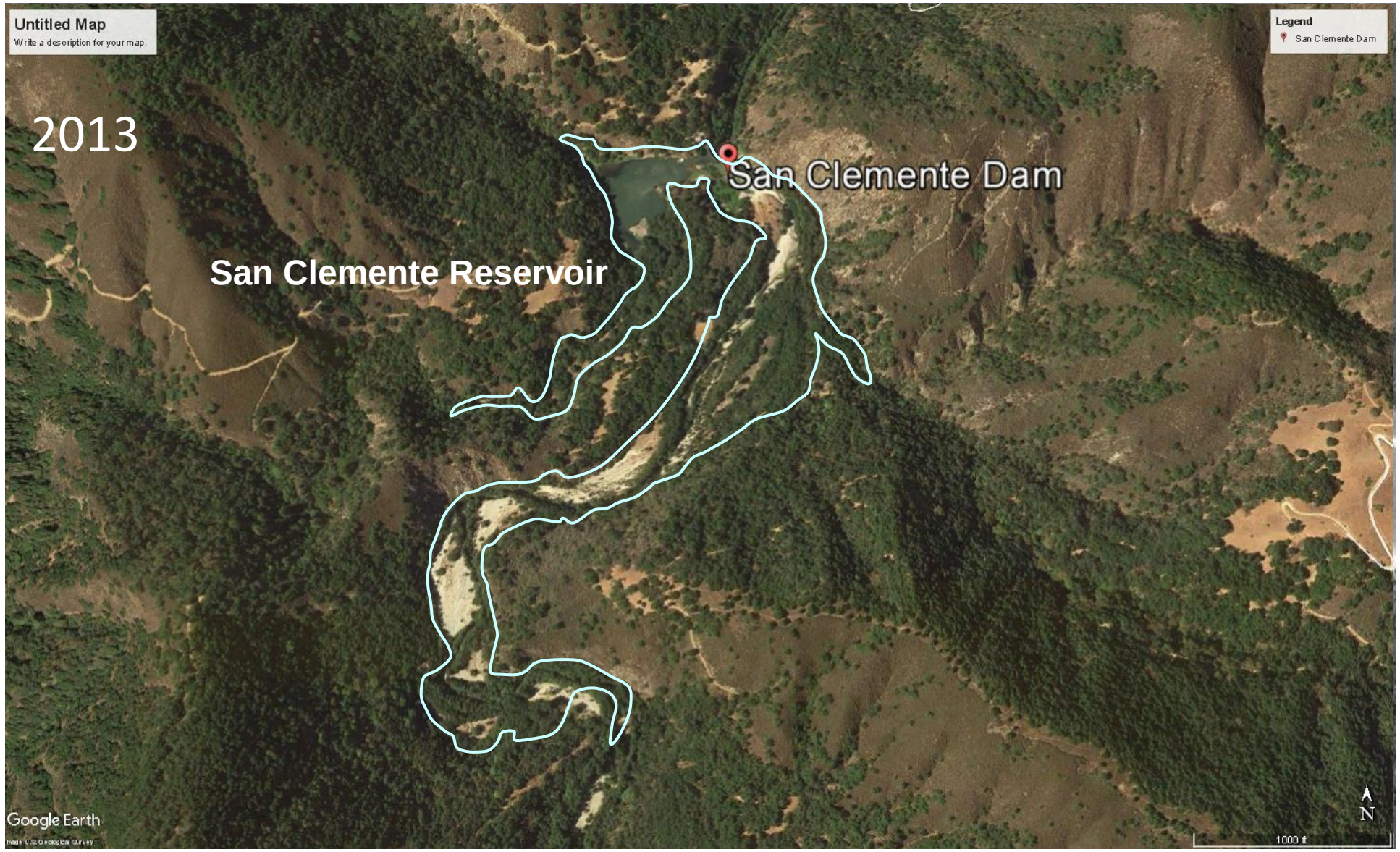

Kantoush et al.

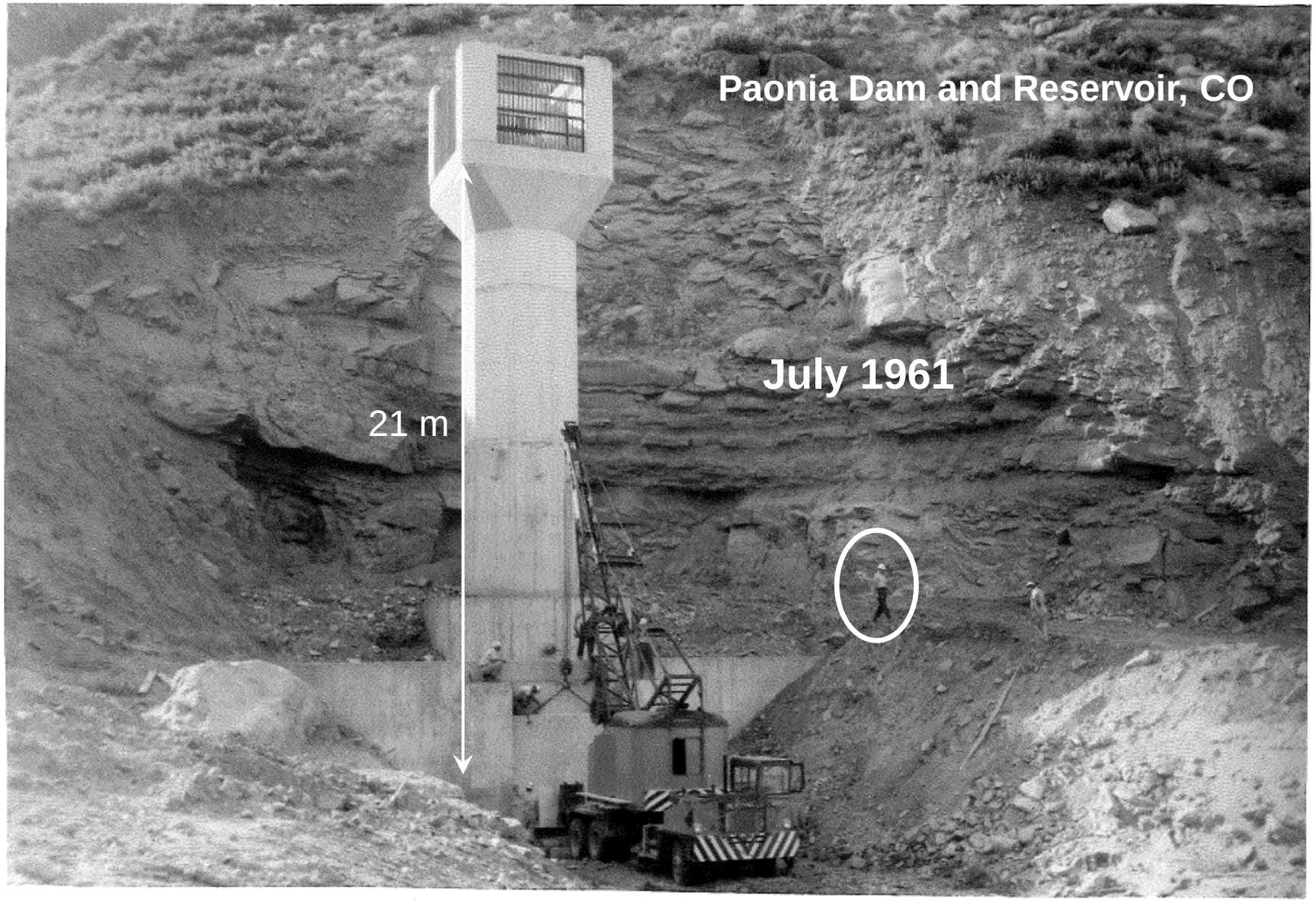
- Sediment accumulates in the reservoir **= reservoir sedimentation**
  - Reservoir → "sediment tomb"
  - A long-term process

# WITHOUT RESERVOIR SEDIMENT MANAGEMENT



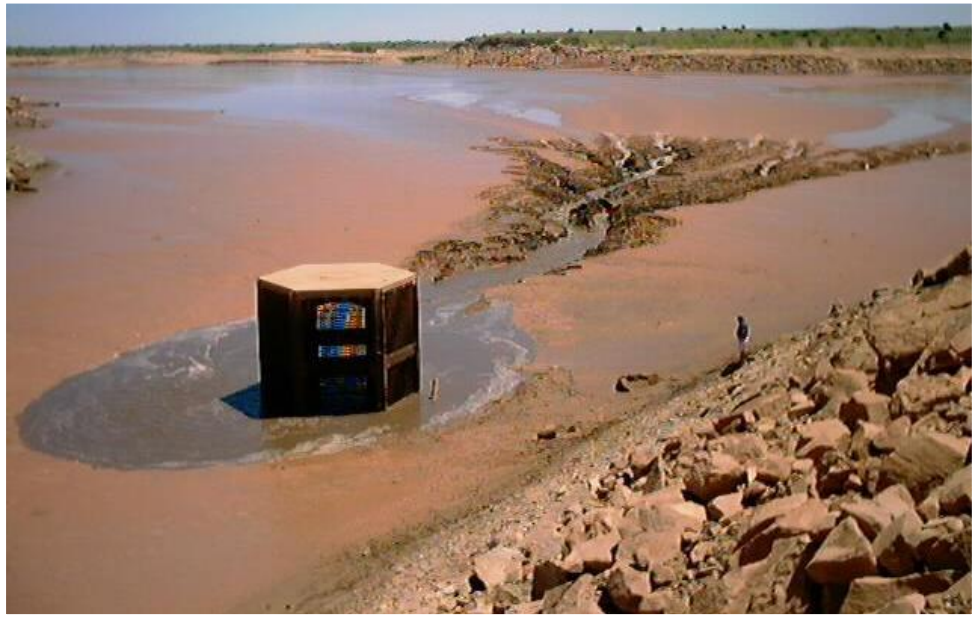
# WITHOUT RESERVOIR SEDIMENT MANAGEMENT




Paonia Dam and Reservoir, CO
July 1961
21 m

# WITHOUT RESERVOIR SEDIMENT MANAGEMENT

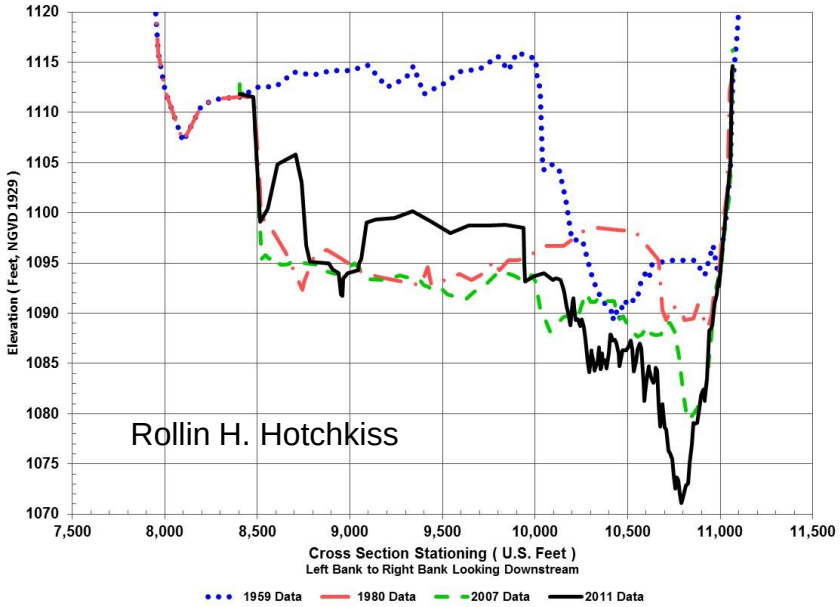
- Sediment discontinuity from upstream to downstream.
- Physical impacts downstream of the dam.
- Physical impacts within reservoir and upstream.
- Ecosystem impacts.
- Eventual economical costs can be expensive:
  - Lost storage capacity over time (with increased water demand).
  - hydropower peaking/seasonal storage.
  - Buried or impaired dam outlets, water intakes, boat ramps & marinas.
  - Development of new water storage at other more expensive locations.



# WITHOUT RESERVOIR SEDIMENT MANAGEMENT

- Downstream of the dam:
  - Channel degradation, infrastructure erosion, and habitat loss.
  - Coastal erosion caused by sediment deficit.
  - Re-infiltration of saltwater into groundwater at river delta/coastline.
- Water is “hungry”:
  - Mobilizes sediment from streambed and banks.
- Degradation proceeds up tributaries.
- New dam construction needed to create replacement water storage.

Replacement of missing sediment is costly (e.g. Colorado, Rhine)




Typical Degradation Cross Section
Missouri River Sediment Range 783.6 – 1960 River Mile 753.2

# WITHOUT RESERVOIR SEDIMENT MANAGEMENT

- Upstream sedimentation Impacts
  - Loss of reservoir storage.
  - Reduced channel conveyance capacity and increased flood risk.
  - Groundwater levels rise.
  - Reduced bridge clearance.
  - Unstable roadway beds.
  - Burial of ancillary reservoir features: navigation channels, boat ramps, marinas.

https://nm.water.usgs.gov/nawqa/riog/images/15_big.jpg

# WITHOUT RESERVOIR SEDIMENT MANAGEMENT

- Sediment flowing through the turbines contains high levels of hard minerals:
  - Sand or gravel is very abrasive to dam outlets, turbines and spillways.
  - Sediments clog the cooling water intakes of the electromechanical equipment.
  - Sediments increase operation and maintenance costs and diminish the amount of power that can be generated.

# ECOSYSTEM IMPACTS

- Reduced biodiversity inside the reservoir.
- Upstream streambed is smothered.
- Vegetation development on deposited sediment
- Less turbid water.
- Temperature modification, less oxygen within the reservoir
- Complete change in stream channel ecosystem downstream.
- Decreases in nutrients affect the aquatic ecosystem.
- Riverbed armoring interferes with salmon redds.
- Methane emissions from impounded rivers.

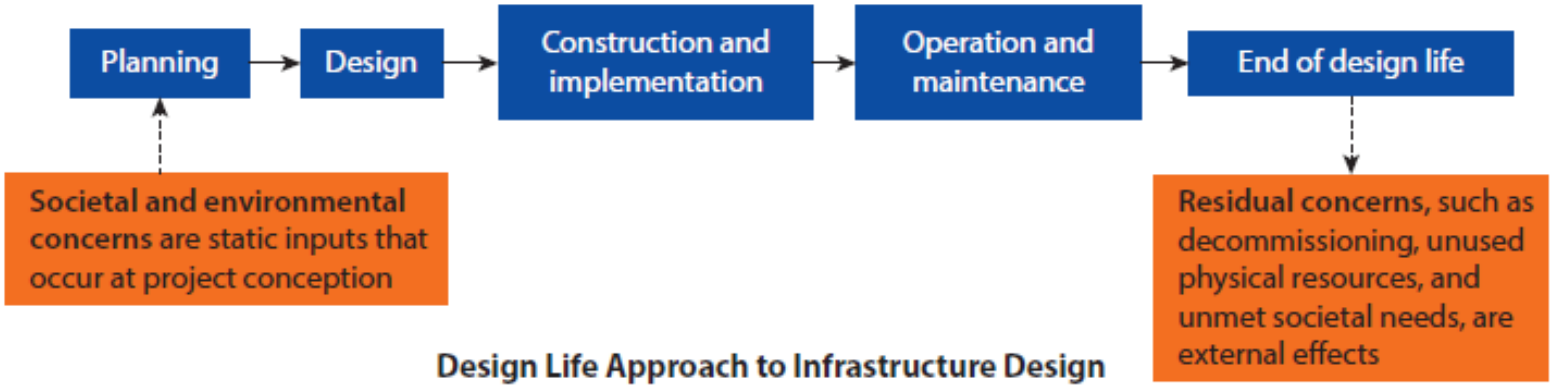
Phragmites Established on Deposited Sediment in Lewis and Clark Lake

Annandale (2015)

https://photos.smugmug.com/Salmonid-Topic/Redd-Superimposition/i-k8xGzT2/1/517ba216/L/_DS37451-L.jpg

# OLD BEST MANAGEMENT PRACTICE

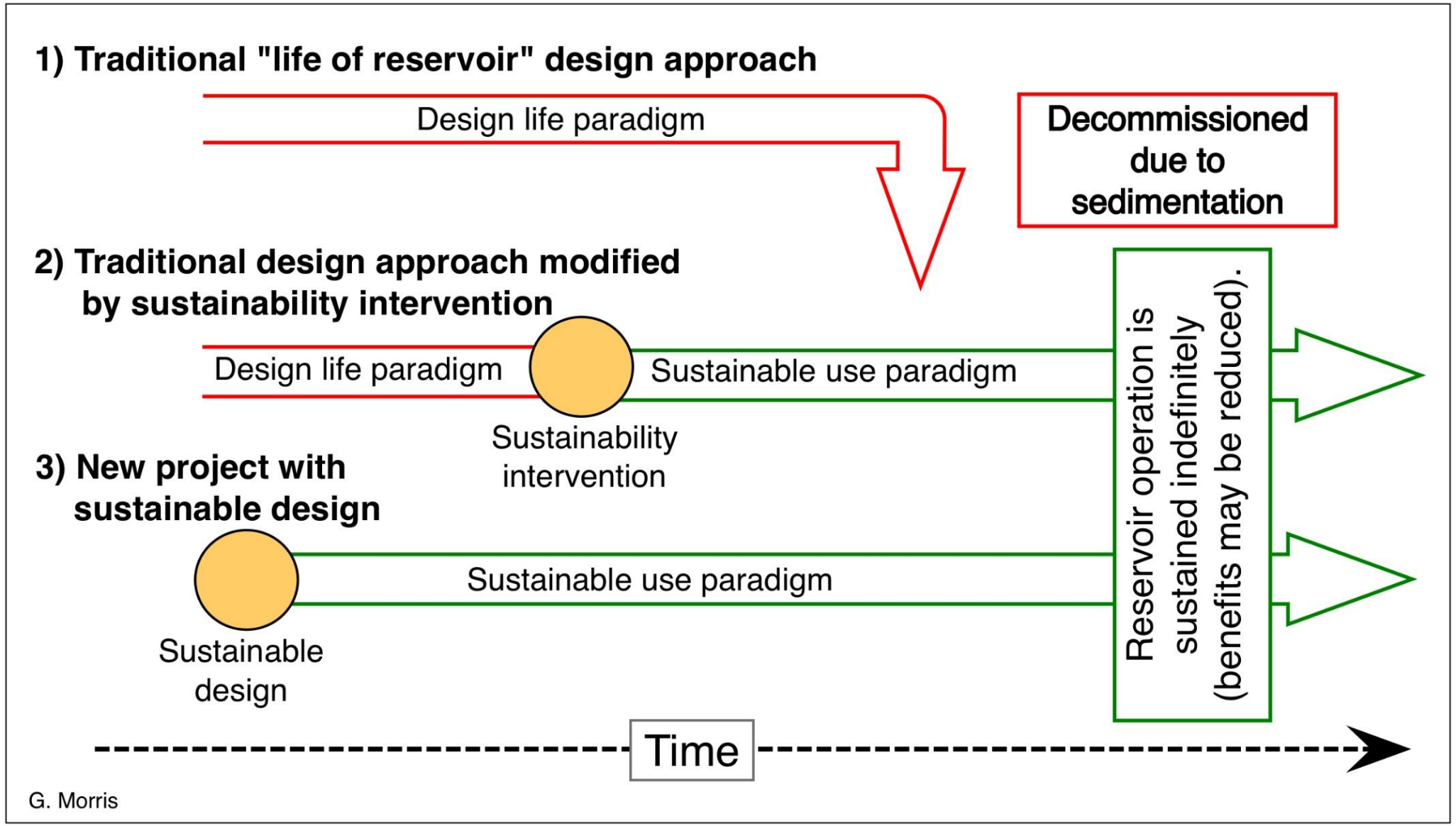
- NO ACTION, let the reservoir eventually fill with sediment (hopefully after you retire).
- INTERGENERATIONAL INEQUITY
  - 1st generation conceives, plans, designs, and constructs a dam and reservoir.
  - 2nd generation starts receiving benefits, repays capital costs, and pays Operation and Maintenance (O&M) costs.
  - 3rd generation continues receiving benefits, repaying capital costs, and paying O&M costs.
  - 4th generation pays O&M costs, but not for sediment management.
  - Last generation is stuck with retirement bill and has to develop new water storage at a higher cost.




**Design Life Approach to Infrastructure Design**

*Source:* Adapted from Palmieri et al. 2003.

# NEW PARADIGM: SUSTAINABLE MANAGEMENT

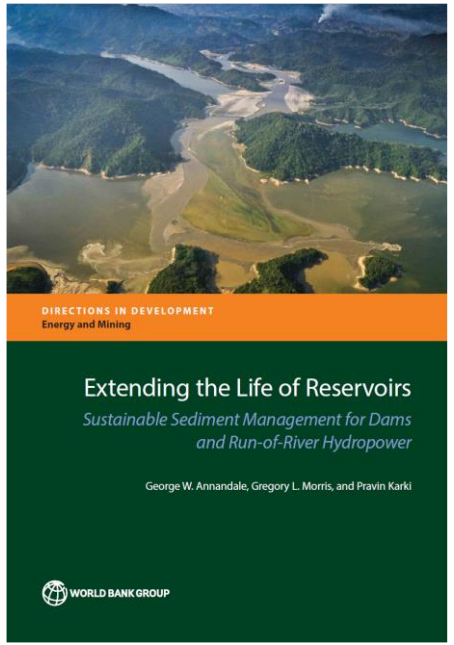


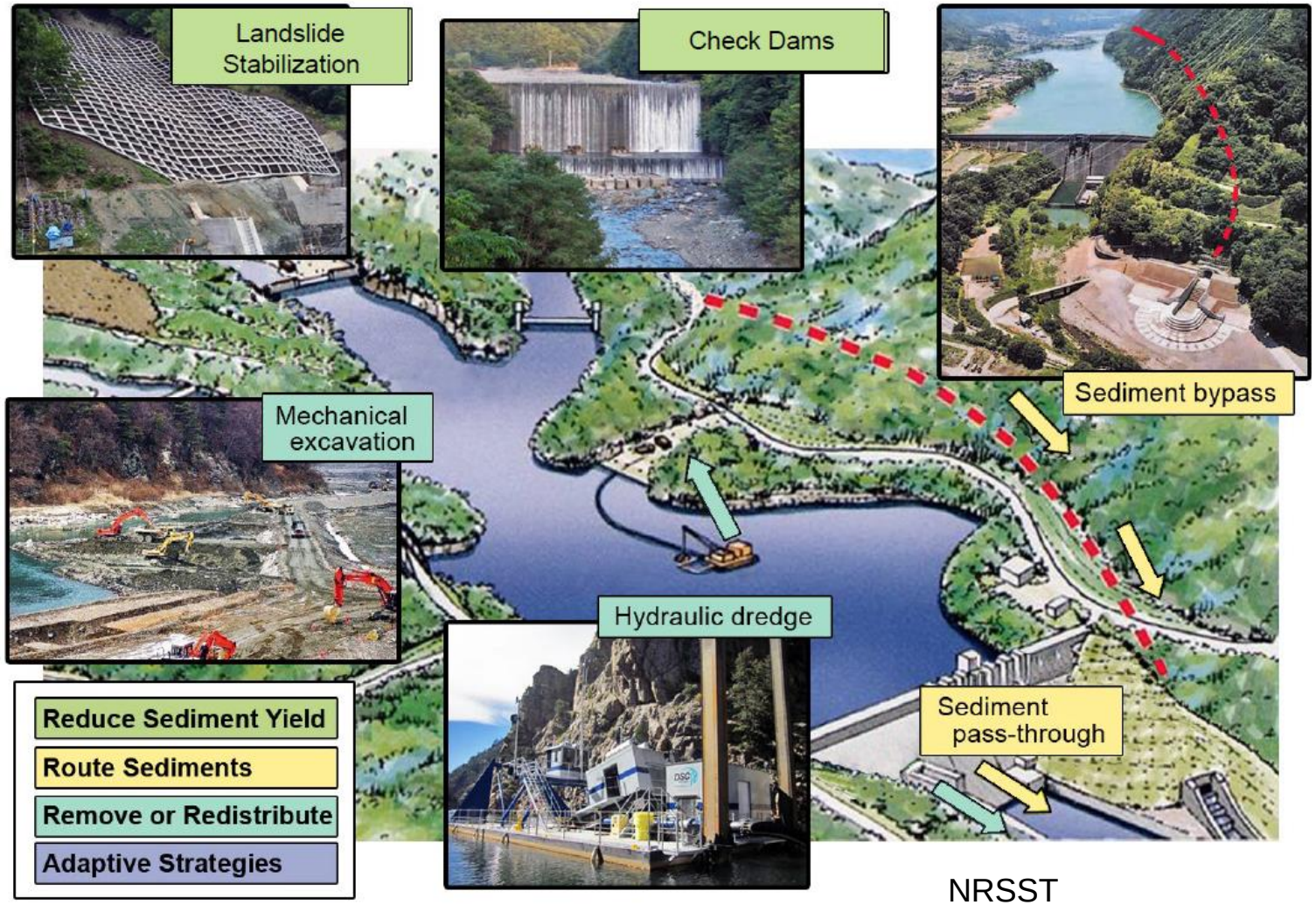
# SUSTAINABLE RESERVOIR SEDIMENT MANAGEMENT STRATEGIES

**Sustainable sediment management seeks to:**

1. Retard the rate of storage loss,
2. Maintain long-term reservoir capacity,
3. and bring sediment inflow and outflow into balance to maximize benefits from the reservoir,

While minimizing environmental harm

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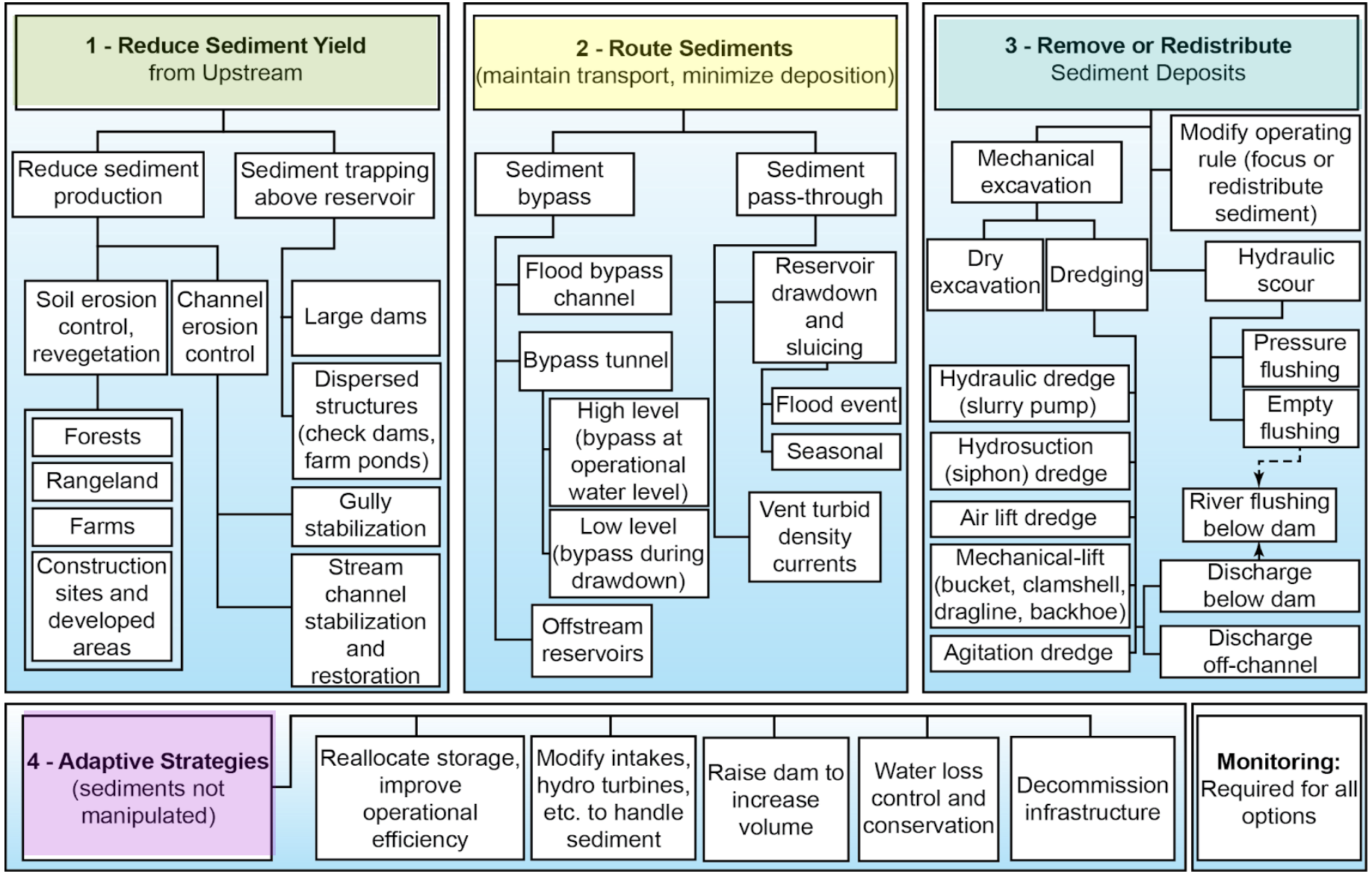
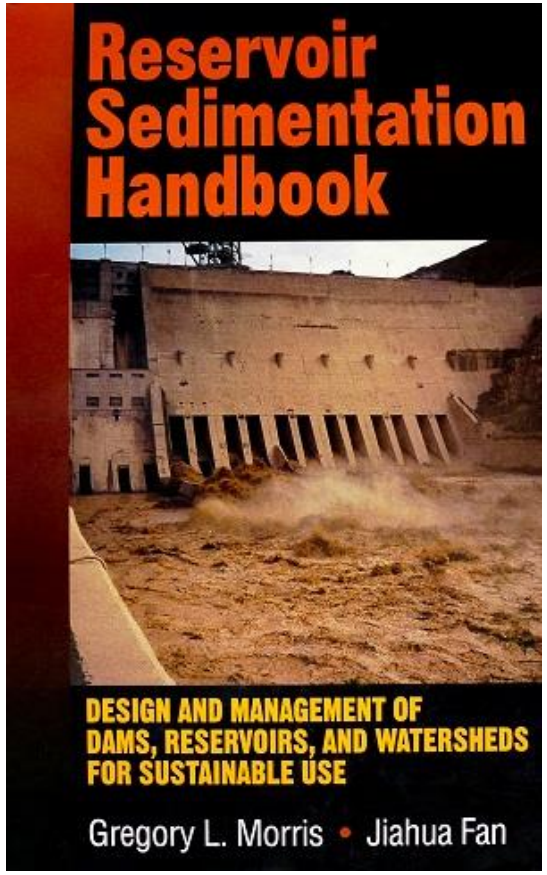
# SUSTAINABLE RESERVOIR SEDIMENT MANAGEMENT STRATEGIES




Technical resource –

Freely available on Internet

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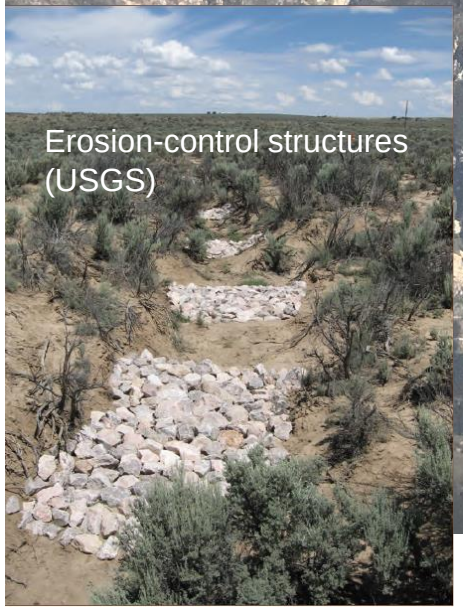
# REDUCE SEDIMENT YIELD

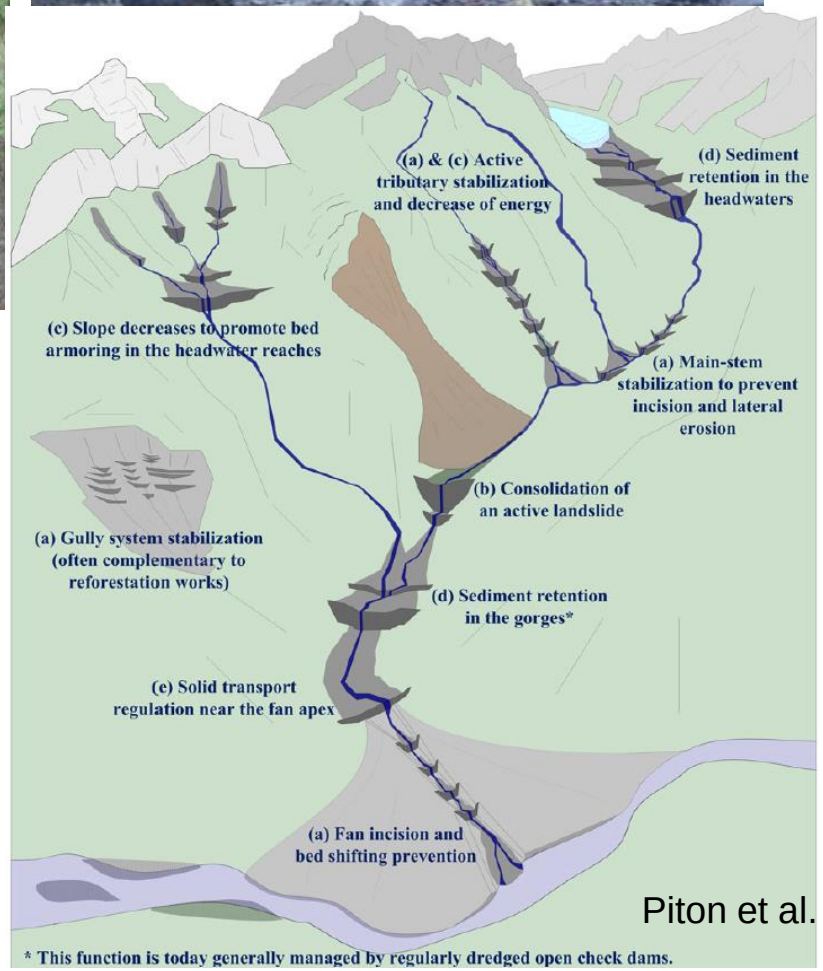
- Reduce sediment production:
  - Soil erosion control and revegetation.
  - Landslide erosion control.
  - Channel erosion control.
- Sediment trapping above reservoir:
  - Large dams.
  - Small check dams and farm ponds.
  - Gully stabilization.
  - Stream channel stabilization and restoration.

Check dams in French Alpine mountains

Sabo/check dam in steel (Sumi and Kantoush, Japan)

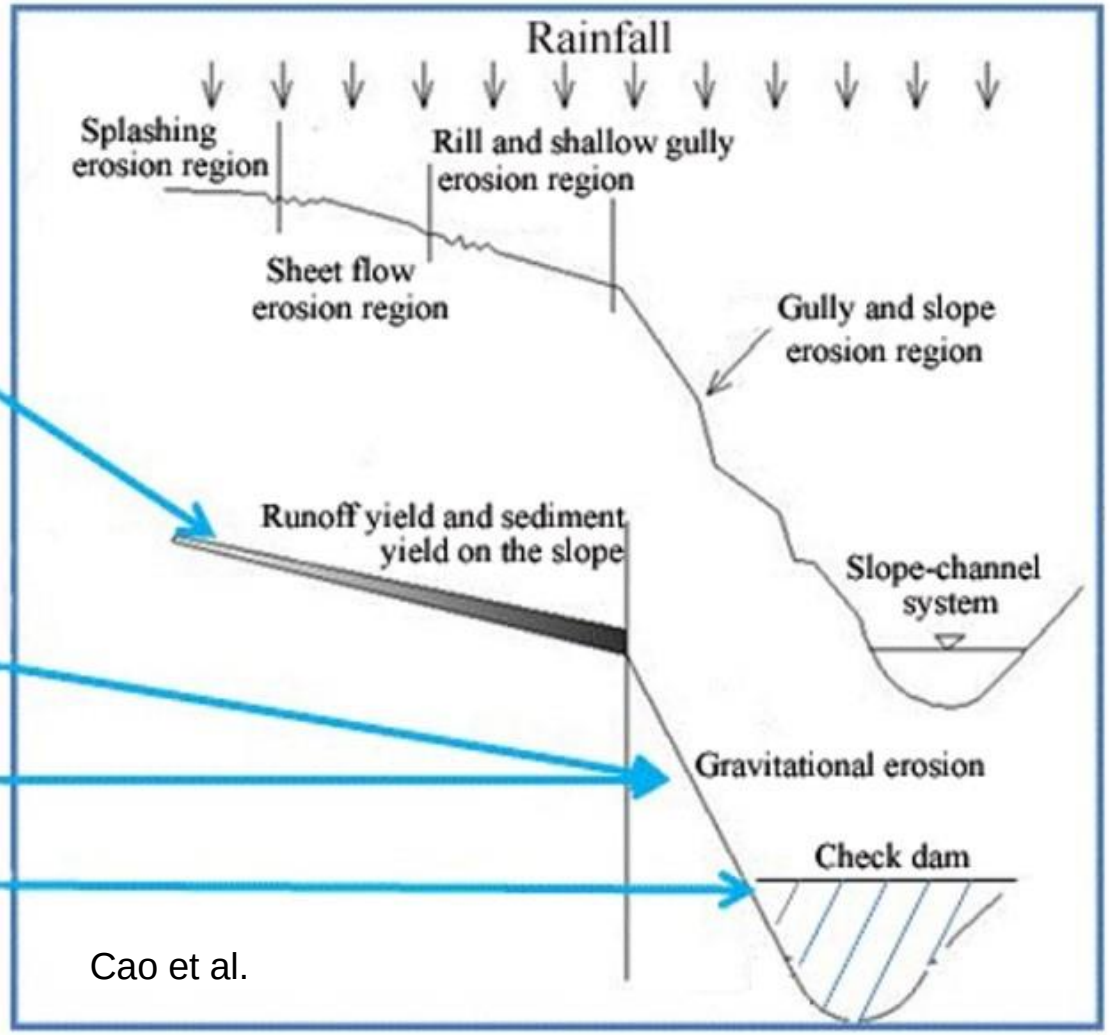


Erosion-control structures (USGS)




Piton et al.

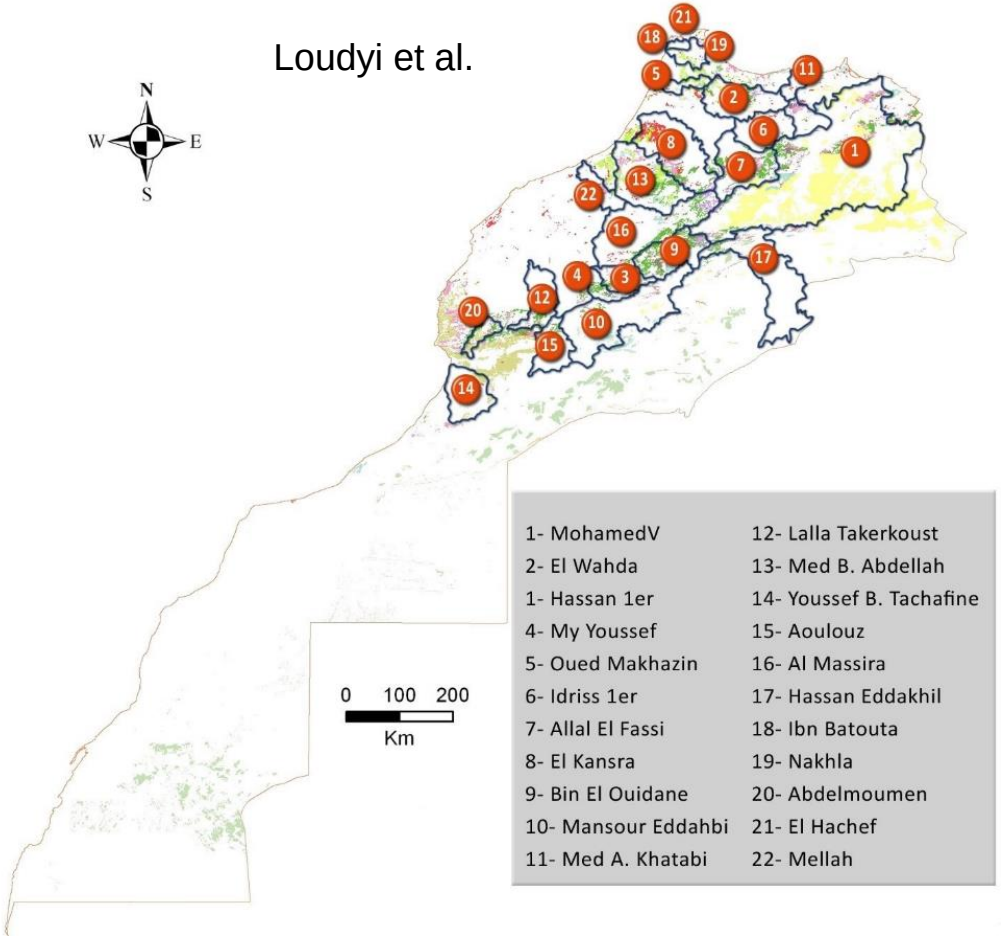
# Example from China



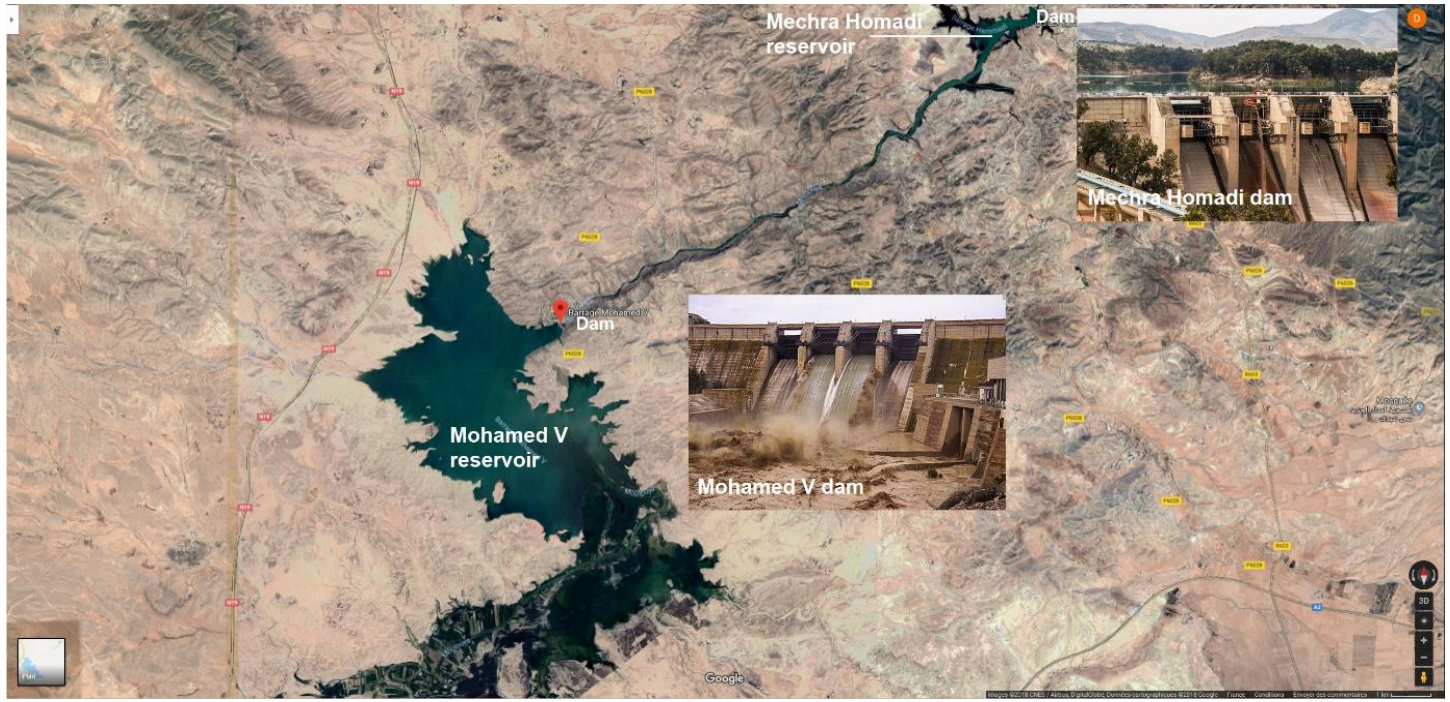

Cao et al.

- Loess Plateau (640,000 km$^2$): check dams, forest, grass vegetation, terracing.
- More than 100,000 check dams have been built since 1950s.
- Interception of 21 billion m$^3$ of sediments.
- Formation of fertile farmland terracing in the areas between dams.

# Example from Morocco

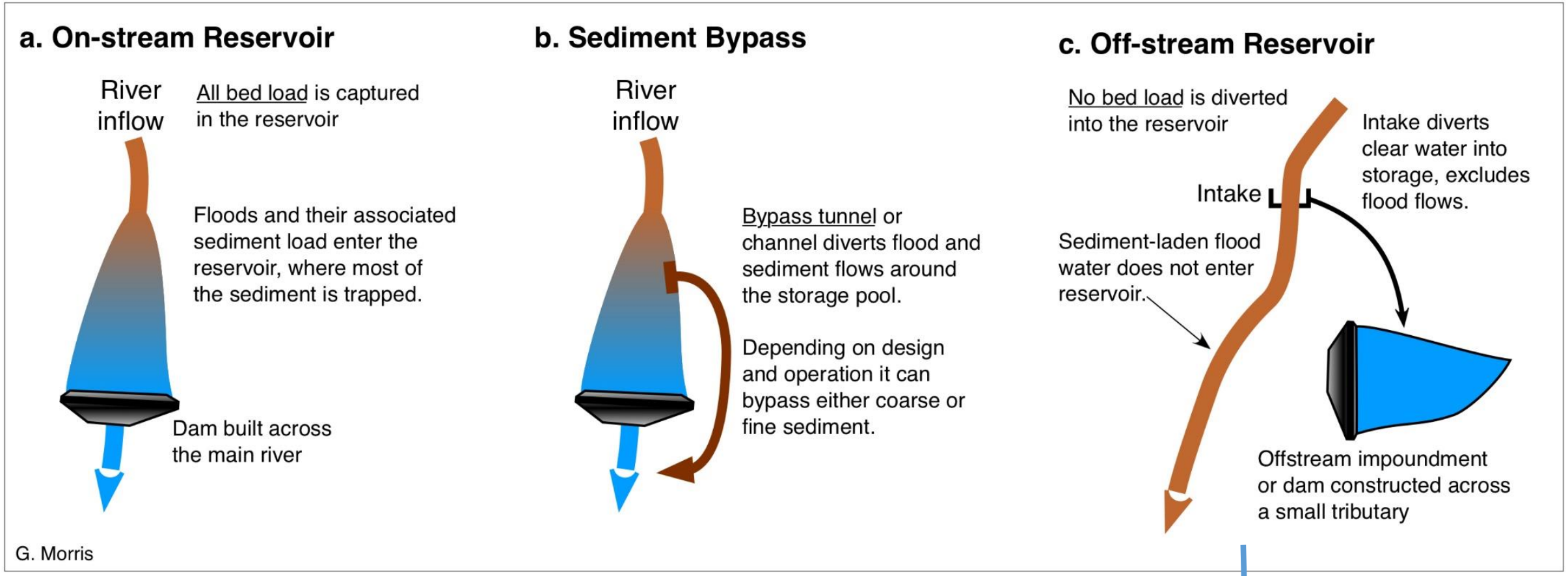



- Reservoir sedimentation: capacity loss: nearly 75 Mm³ per year
- Strong erosion rate: 2,000 t/km²/year.
- Few dams equipped with bottom outlets.
- Dredging operations too expensive, rarely conducted.
- Constructions of 59 new dams by 2030, mainly for water supply.
- Raising some highly silted reservoirs.




- A **National Watershed Management Plan** for implementing erosion control for 22 high-priority watersheds.
- Reforestation of catchments covering 1,500,000 ha at a rate of 75,000 ha/year.
- Since 1996, 650,000 ha have been reforested in 18 watersheds.

# RESERVOIR SEDIMENT ROUTING




Under favorable conditions, the rate of sediment delivery into a reservoir may be reduced by over 90%.

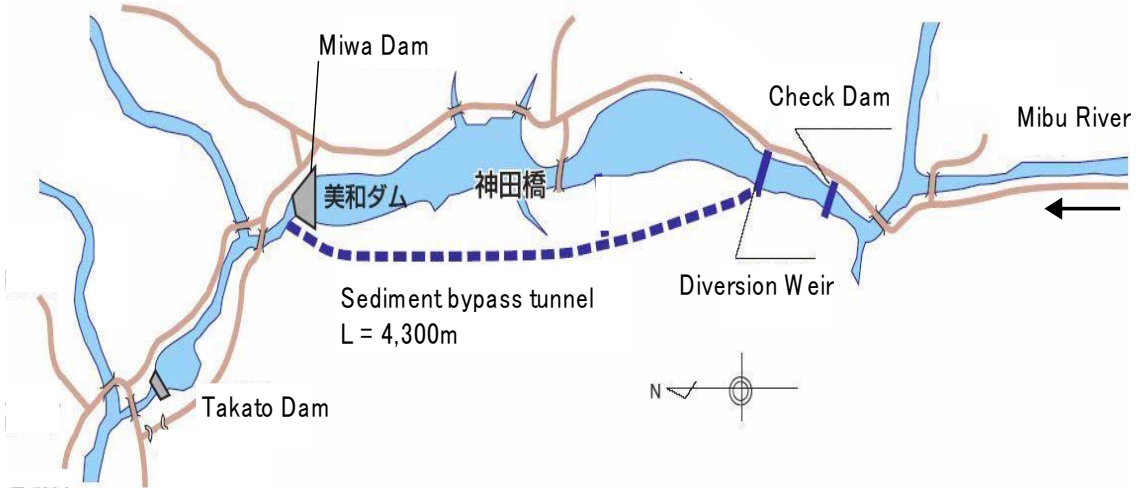
# RESERVOIR SEDIMENT ROUTING

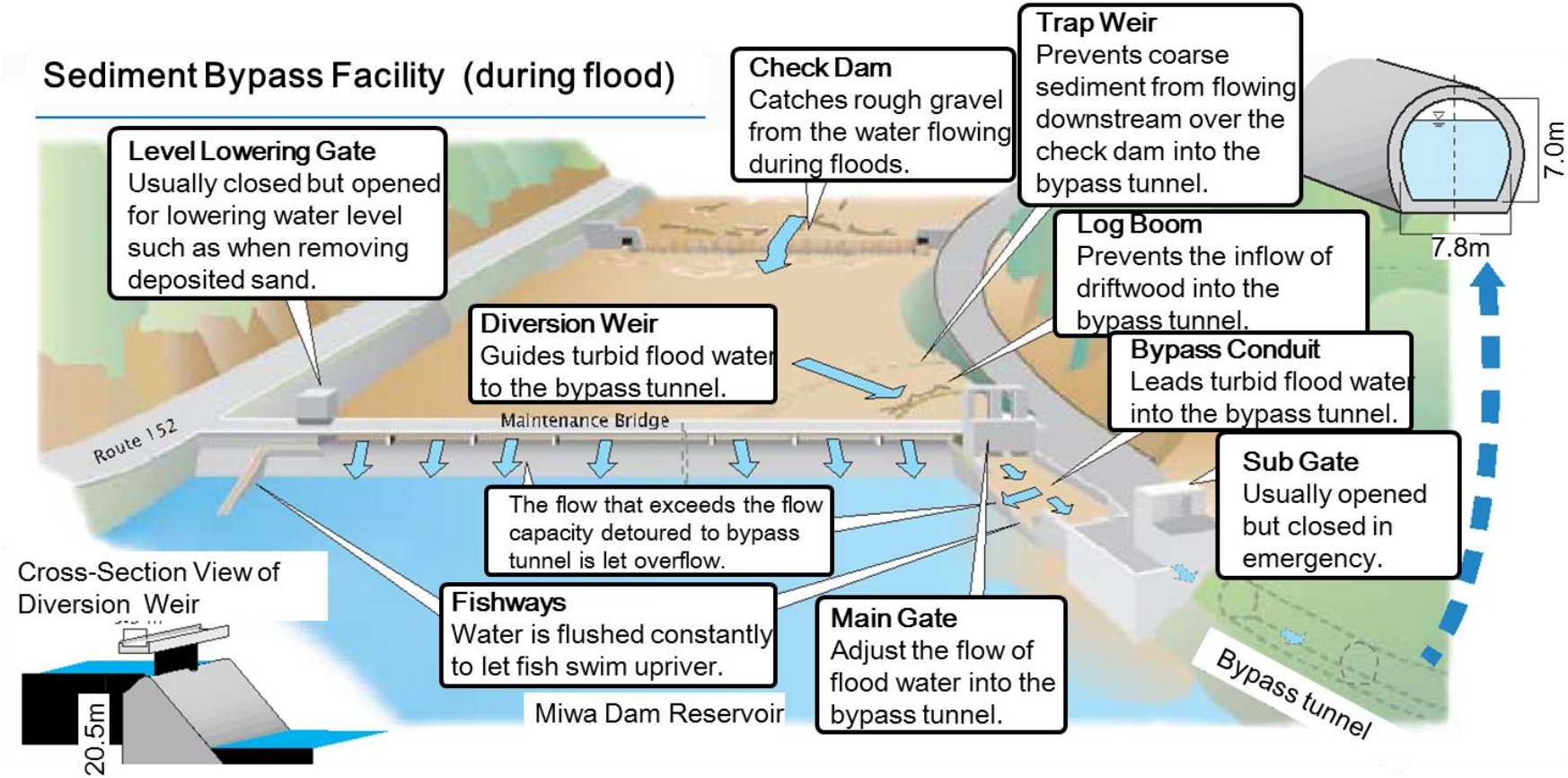
## Bypass tunnels

Abraded concrete invert . Runcahez SBT, Switzerland (Photograph: M. Müller-Hagmann, VAW, ETH Zurich)

# Example from Japan

- Sediment Bypass Tunnel at Miwa Dam:
  - Check dam (height: 10.2 m, sedimentation capacity: 200,000 m3)
  - Diversion weir (height: 20.5 m, sedimentation capacity: 520,000 $m^3$)
  - Inflow & outflow facilities
  - Tunnel (length: 4,300 m, maximum flow rate: 300 $m^3/s$)



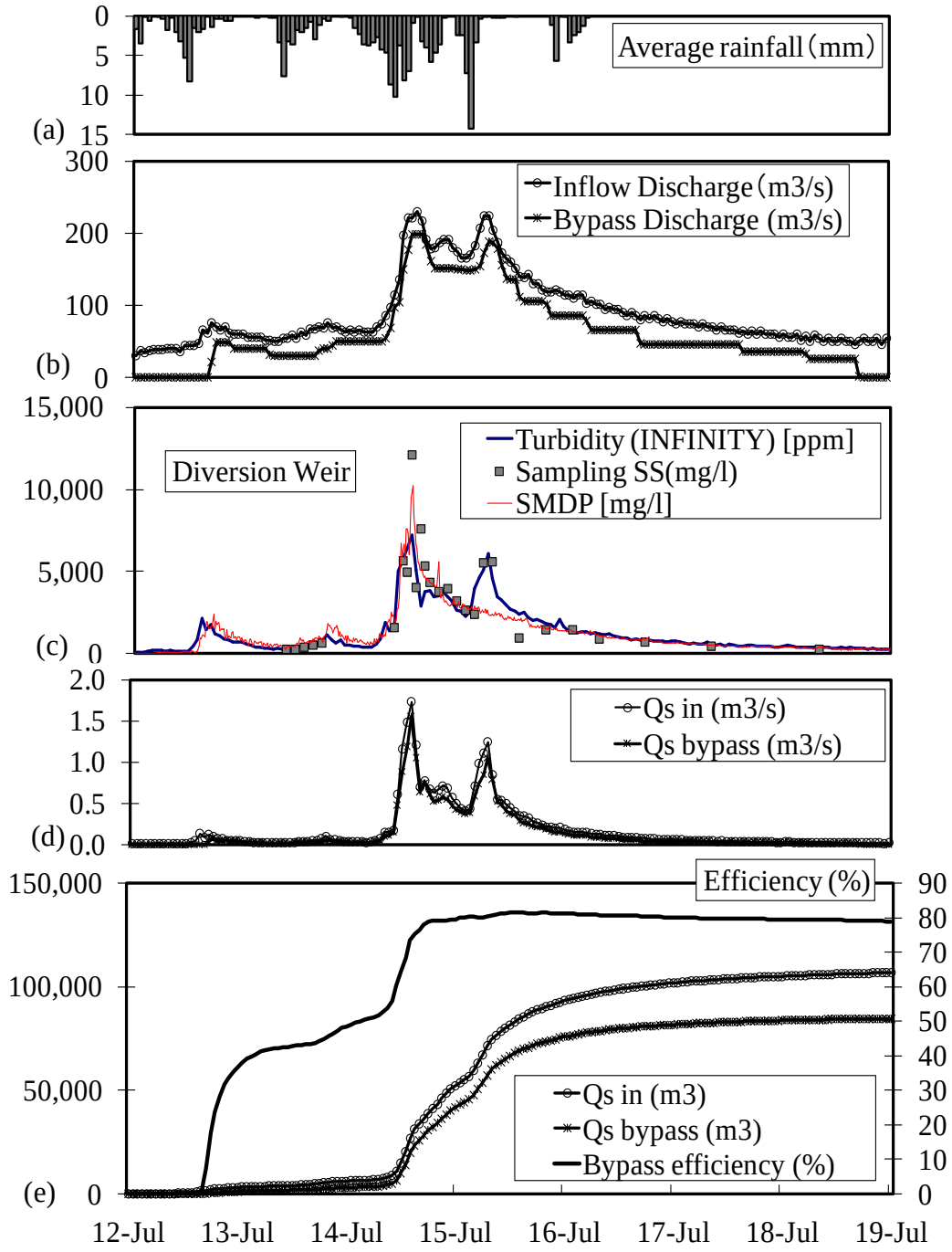
(a) Rainfall

(b) Inflow and bypass discharges

(c) SSC measurements

(d) inflow and bypassed sediment discharge

(e) Efficiency of bypass scheme on 13 and 14 July




## Performance of bypass tunnel at Miwa dam reservoir

- Water discharge is 230m³/s and 80% of water inflow bypassed from the tunnel.
- Several preliminary small flood events filled up the storage volume of Miwa reservoir.
- Then the peaks of SSC could effectively passed through tunnel on time without delay.
- Efficiency: 80%
- Sediment discharge volumes:

  84,000 m³／107,000 m³

- Comparison with the previous years bypass operations:

  July 2006, $Q_p$= 366 m³/s

  150,000 m³／326,000 m³

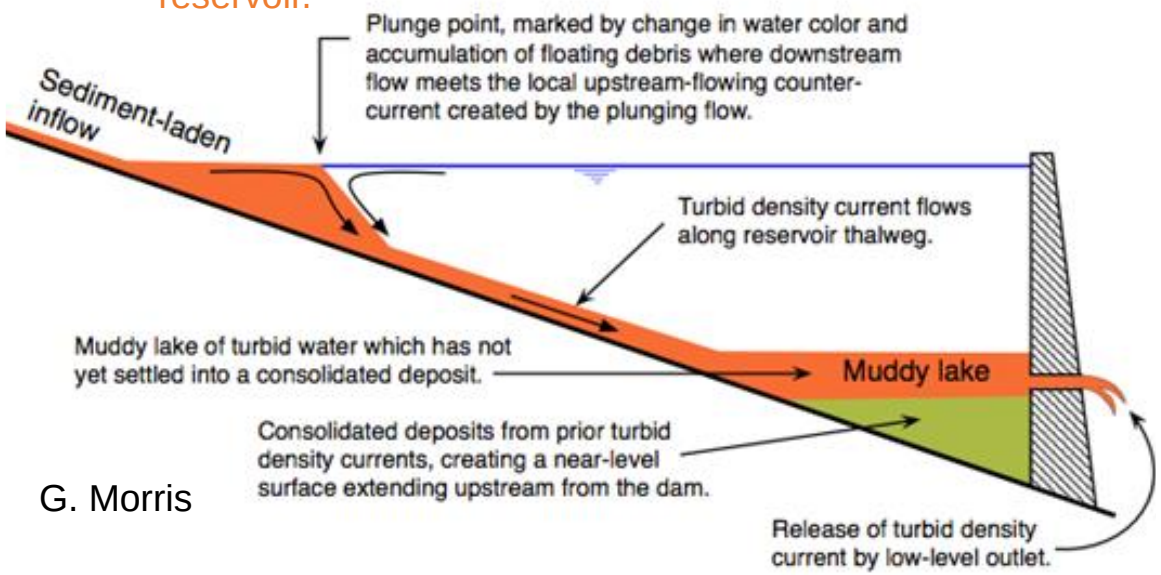
  Sep. 2007, $Q_p$=568 m³/s

  155,000 m³／461,000 m³

# RESERVOIR SEDIMENT ROUTING

## Turbid Density Currents in Reservoirs

- Turbid density currents containing fine sediment may be released:
  - If a low-level outlet or Turbidity siphons operate continuously during flood events,
  - or if the low-level outlet is operated based on the predicted or monitored arrival time of the turbid density current at the dam.
  - Hydropower turbines.
- Efficiency of density currents depends on:
  - Predicting the arrival time at the dam,
  - and operating outlets to minimize the settling period in the reservoir.

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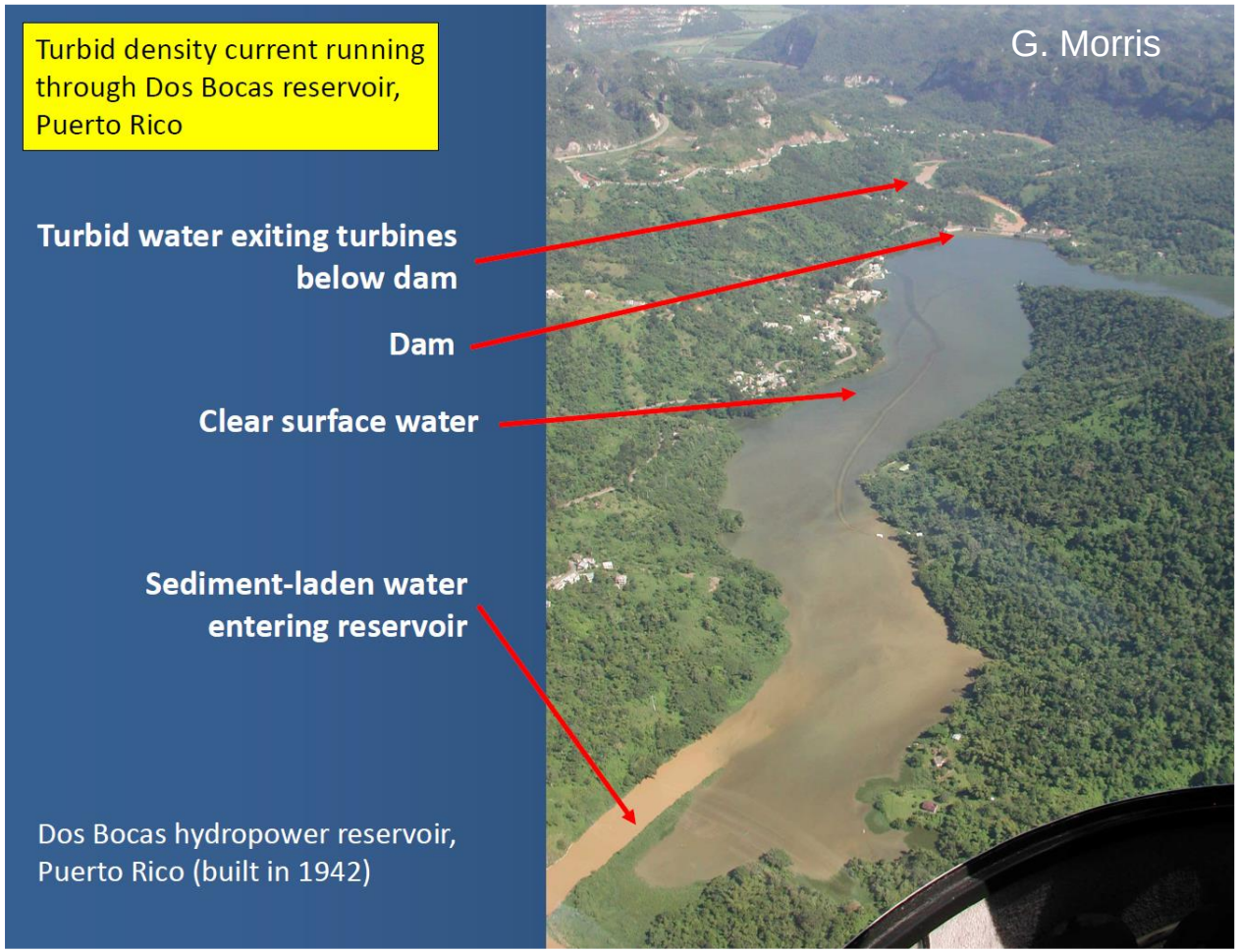
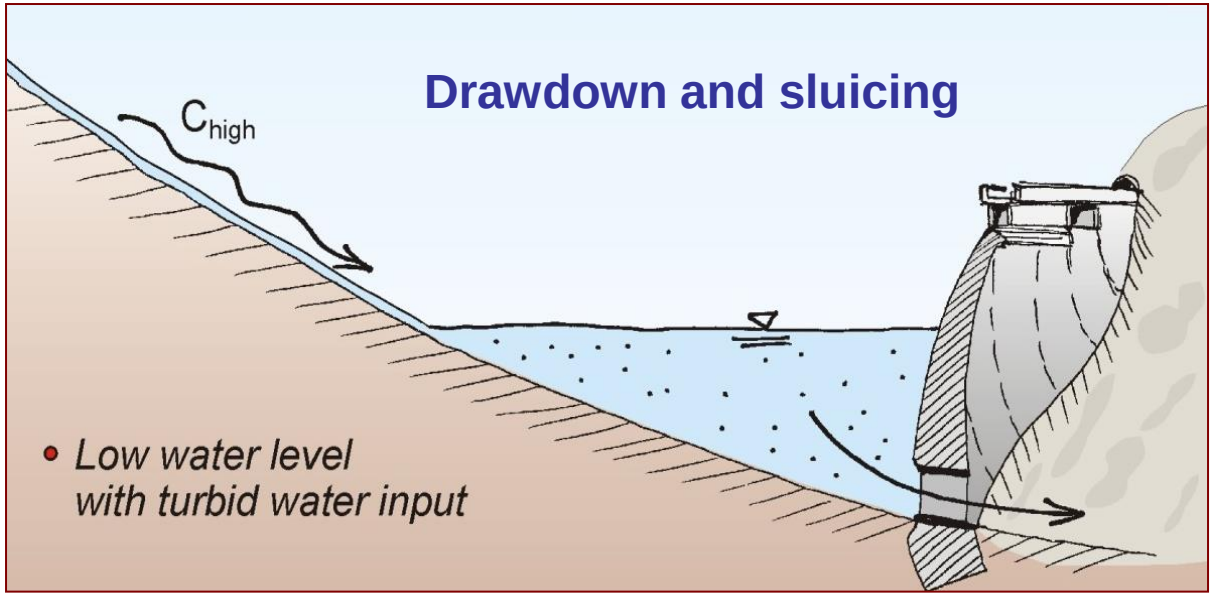
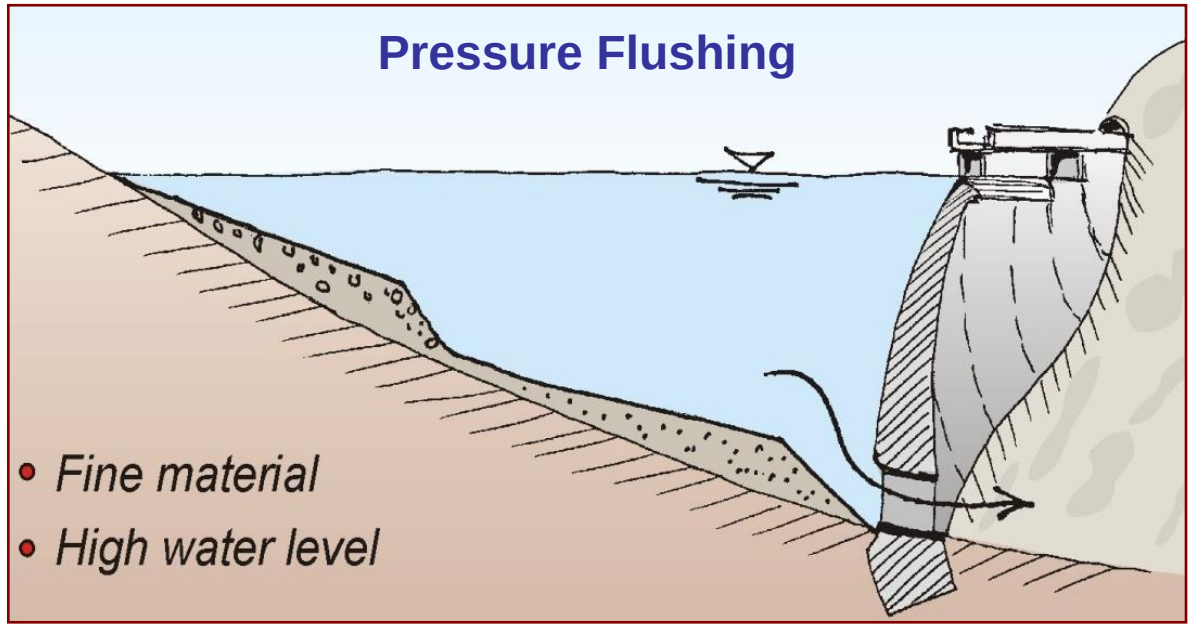
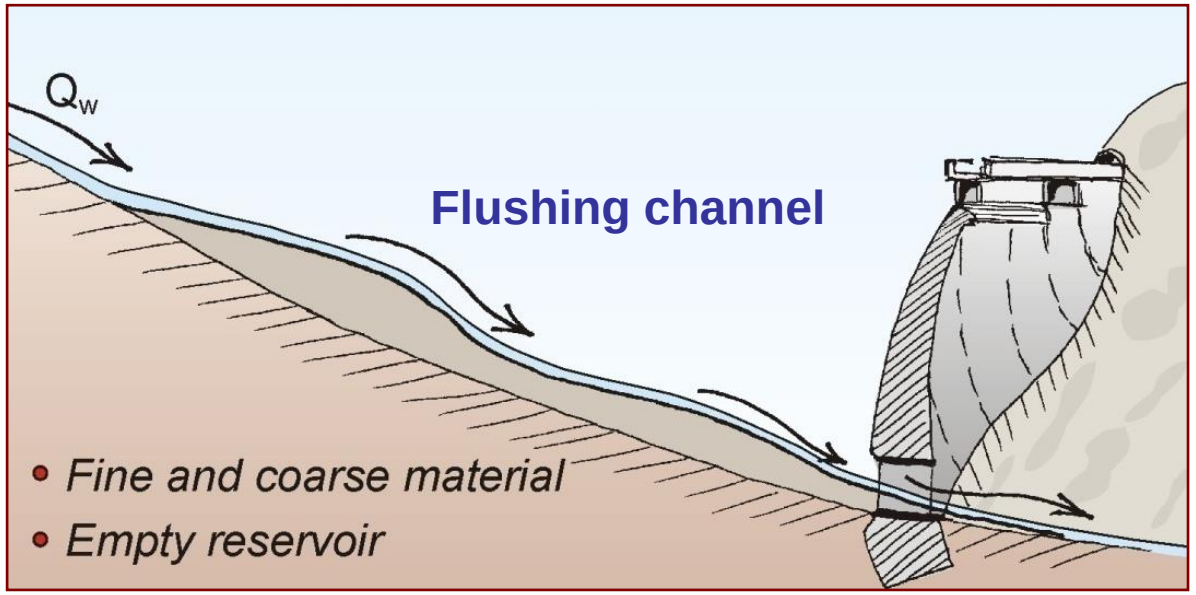


# REMOVE OR REDISTRIBUTE SEDIMENT

**Flushing through the bottom outlets**

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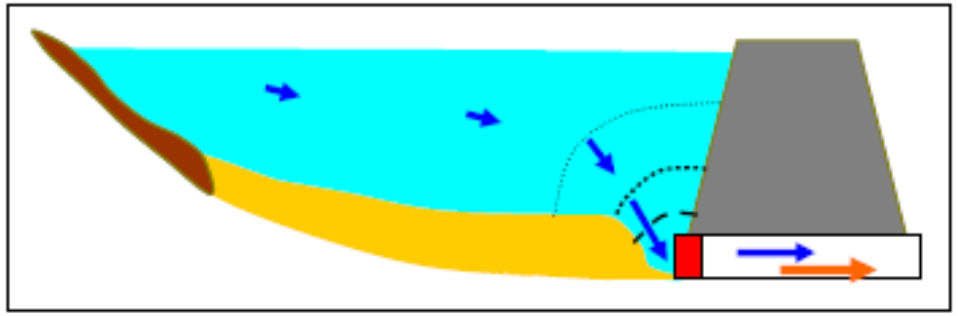
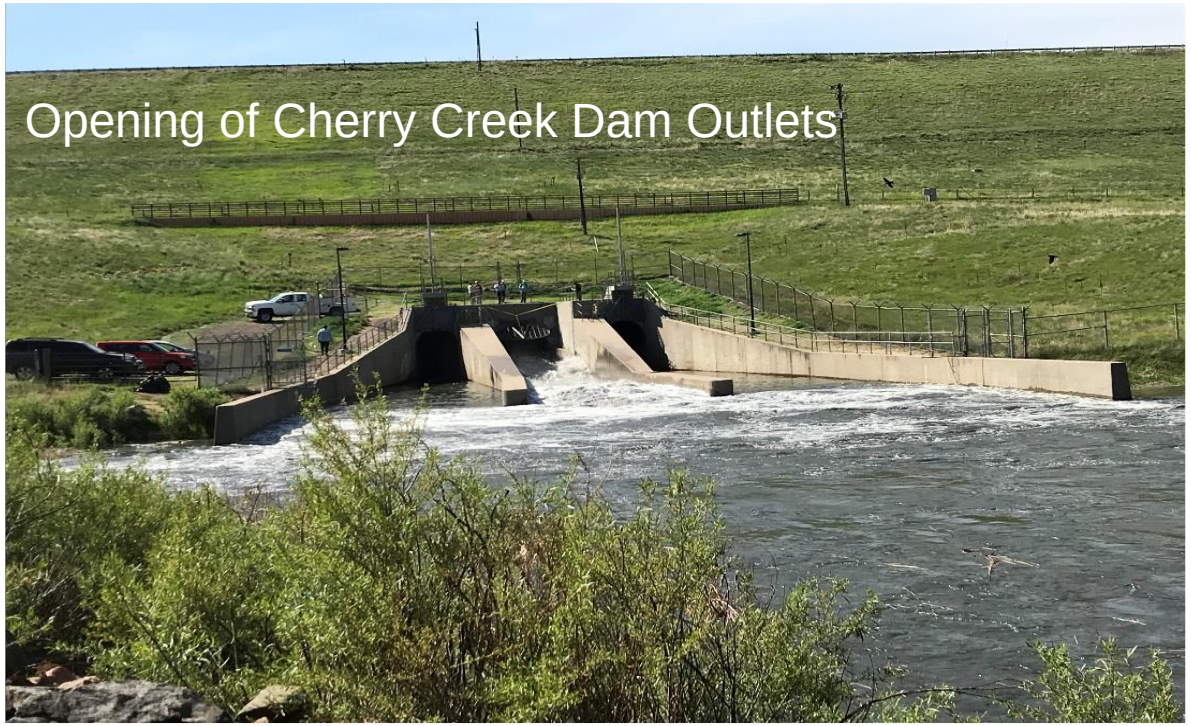
# REMOVE OR REDISTRIBUTE SEDIMENTS

**Pressure flushing of sediments near the dam outlet**

- A submerged low-level outlet is opened to release sediment while the reservoir water level is high.
- Pressure flushing can be used to keep the immediate vicinity of an intake free of sediment.

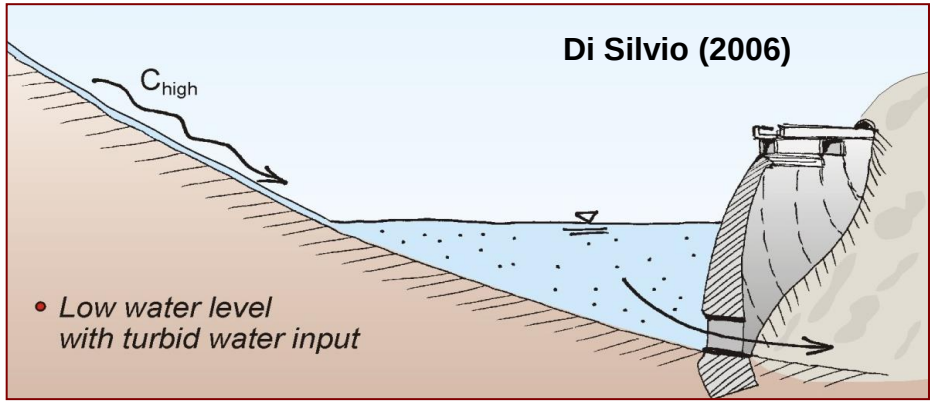




# REMOVE OR REDISTRIBUTE SEDIMENTS

## Drawdown and sluicing of sediment

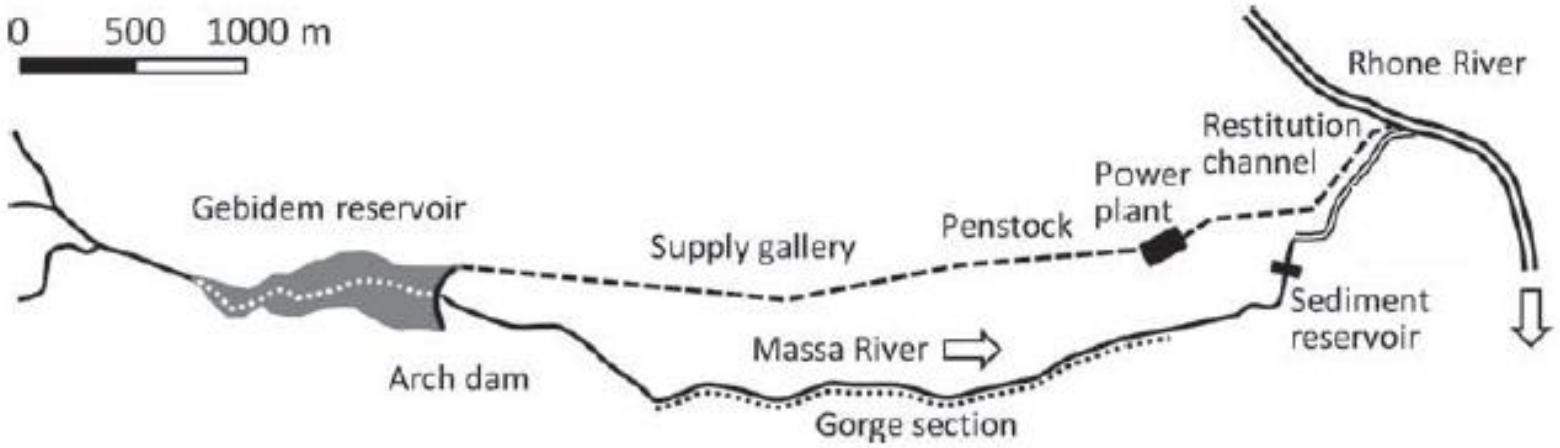
- Drawing down the water level during periods of high flood discharge and sediment load.
- Drawdown may be timed to match individual floods, guided by real-time reporting gauges and hydrologic modeling.
- Limited to hydrologically small, narrow reservoirs.



# REMOVE OR REDISTRIBUTE SEDIMENTS

## Example of flushing channel: Gebidem Reservoir, Switzerland

- Opening low-level outlets to completely empty the reservoir.
- A flushing channel is actively being eroded within the reservoir.
- Long-term volume of sediment that can be sustained by flushing is limited by the width and depth of the channel.
- High suspended concentration downstream of the dam: construction of a dilution supply gallery in 2006.

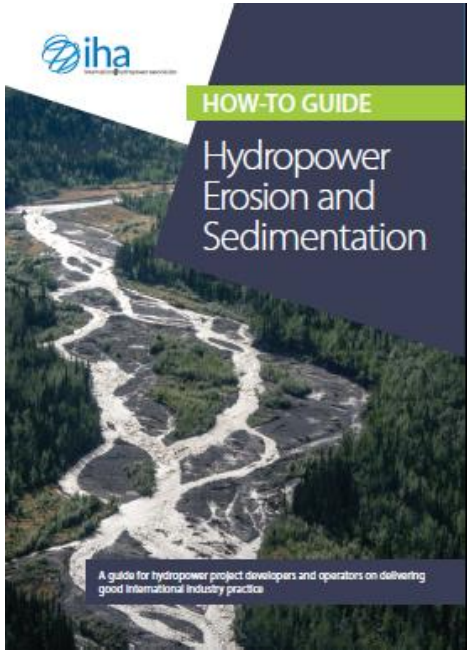



Meile et al.

# ENVIRONMENTAL IMPACTS OF FLUSHING OPERATIONS

- Flushing operations release water with high suspended sediment load of adverse chemical properties due to their long retention in the reservoir.

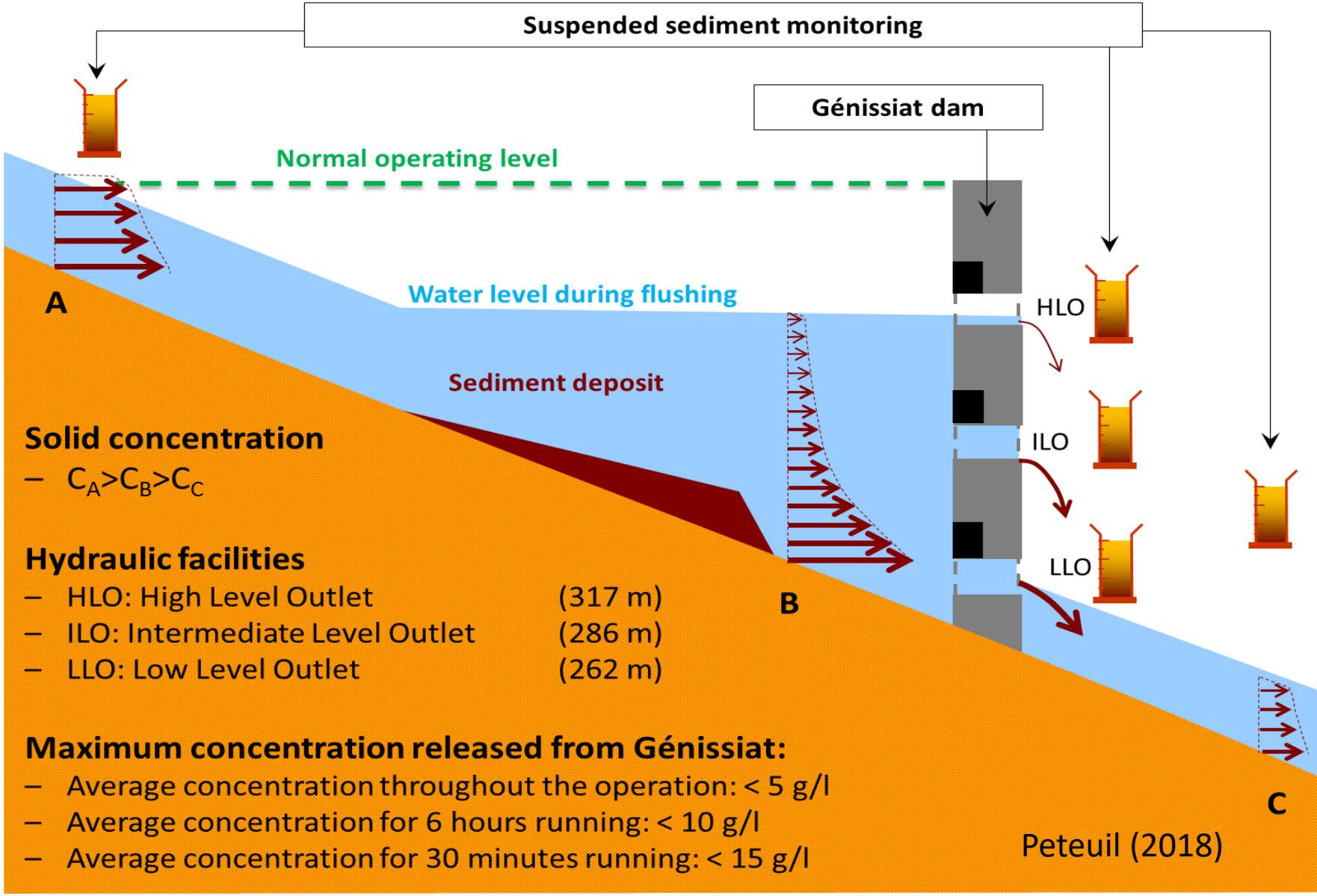
| Physical and chemical impacts: | Biological impacts: | Social impacts: |
|---|---|---|
| • Release of waters with low dissolved oxygen, lower temperatures, and higher heavy metal concentrations;<br>• Release of waters with strong odour, and $H^2S$ degassing in relatively new reservoirs;<br>• Reduction in visibility and light penetration;<br>• River morphological impacts such as infilling of pools and clogging of river gravels with fine sediment;<br>• Large releases of accumulated solid wastes;<br>• Release of trapped methane, a greenhouse gas. | • Stress on aquatic biota and fish kills;<br>• Direct smothering of benthic flora and fauna;<br>• Destruction of spawning sites and nursery habitats. | • Sedimentation of water treatment plants;<br>• Sedimentation of irrigation canals, as well as flood control and navigational channels;<br>• Impacts on recreational amenity;<br>• Reduction in fisheries productivity;<br>• Safety of river users during flushing. |



Fish mortality following a drawdown operation in an Italian reservoir. (Courtesy: S. Bastasi)

# “Environmentally friendly flushing” concept from the Génissiat Dam (Rhone), France

- The Low Level Outlet (LLO) discharges highly concentrated water.
- The Intermediate Level Outlet (ILO) releases less concentrated flows.
- The High Level Outlet (HLO) discharges clear water.
- The efficiency of the flushing program is controlled with the benefit of real-time sediment concentration monitoring implemented at the dam site and in downstream stations.



# REMOVE OR REDISTRIBUTE SEDIMENTS

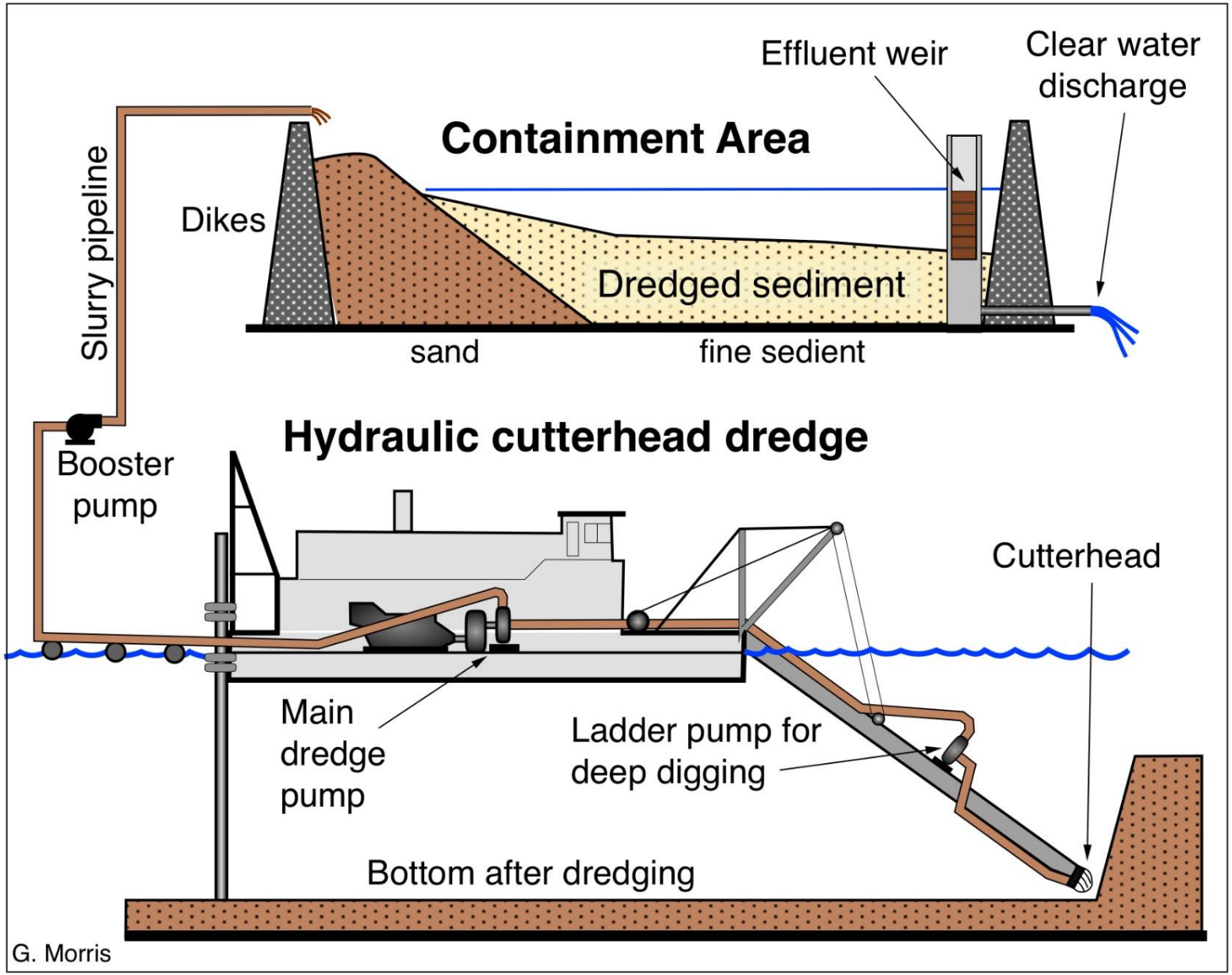
**Mechanical or hydraulic dredging or dry excavation**

- Hydrosuction dredging uses gravity and suction. No external power needed.
- Dredging uses cutterheads and pumps.
- Dry excavation removes exposed (not submerged) sediment using conventional earth-moving equipment when the reservoir pool is low or empty.
- Transport by slurry pipeline, truck, or conveyor belt for discharge to the downstream river channel, disposal site, or beneficial use.

Dry exavation at Longefan Reservoir, France (EDF)

# Example of hydraulic dredging system

Dredging removes sediment from underwater, most commonly using a cutterhead type hydraulic dredge that pumps material out of the reservoir as a flowable slurry

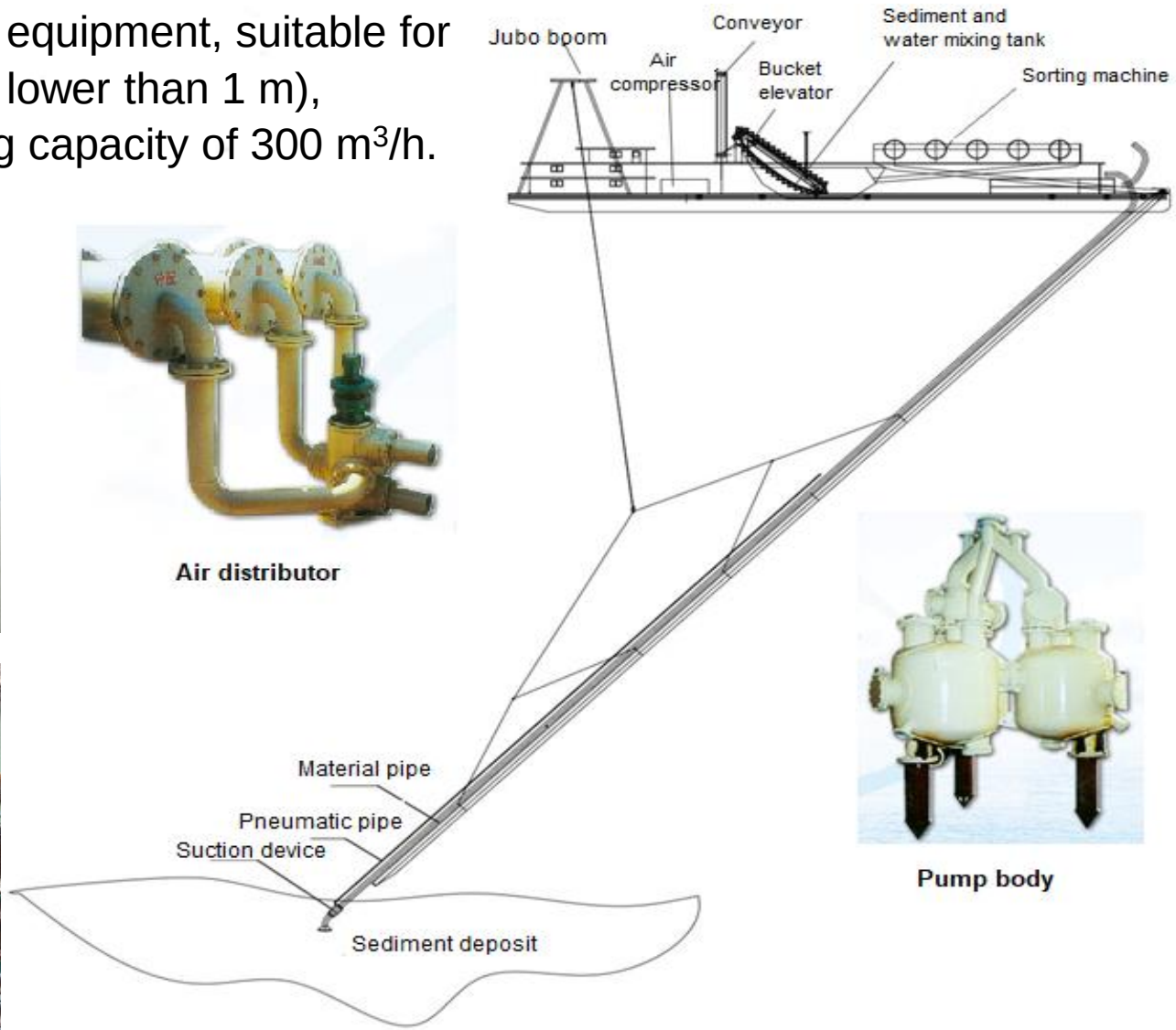


# Pneumatic pump desilting technology

Cao et al

The Jiang Yin Water Conservancy Mechanization Engineering Company Ltd has developed a deep-water pneumatic pump desilting equipment, suitable for various types of coarse deposits (diameter of sediment lower than 1 m), operating at a maximum depth of 120 m with a dredging capacity of 300 $m^3$/h.

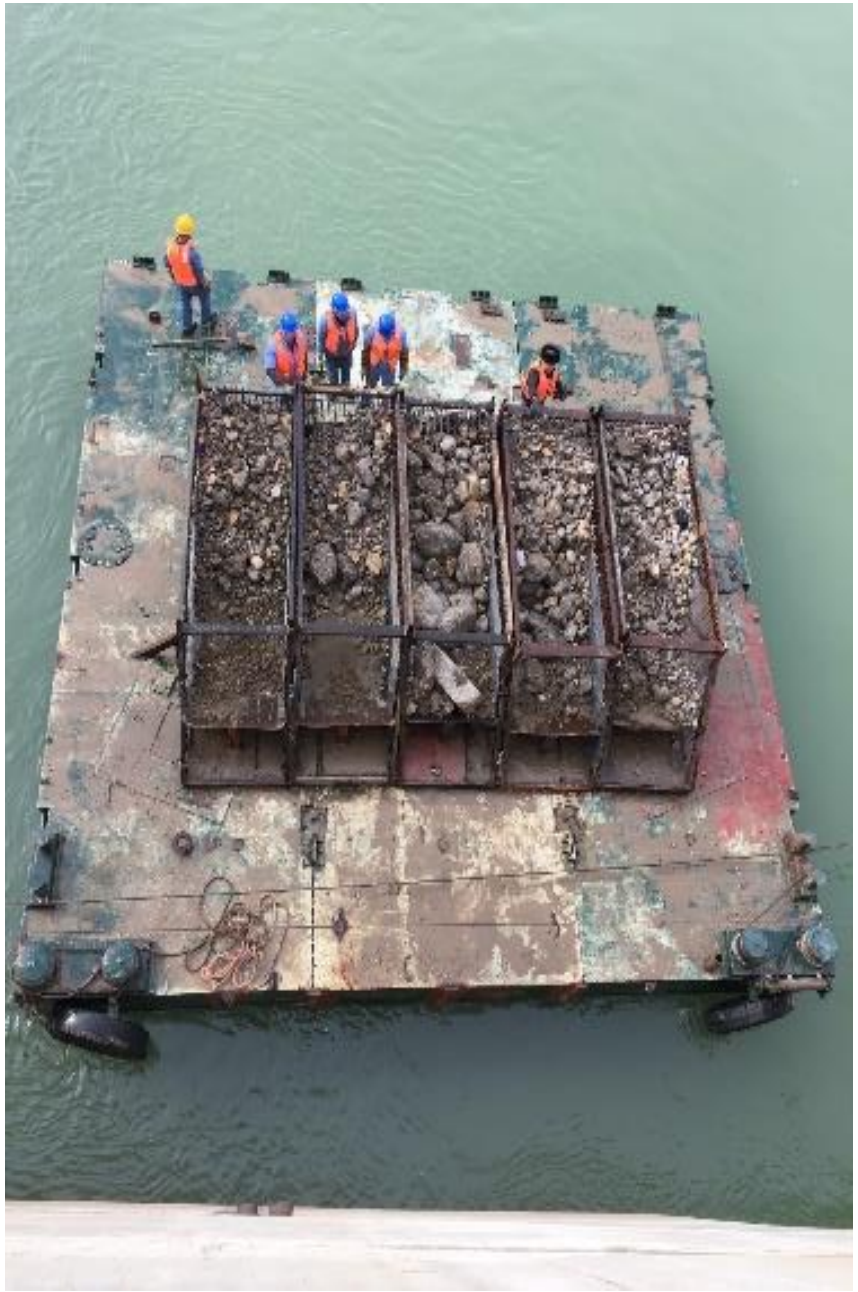
Air distributor






Pump body

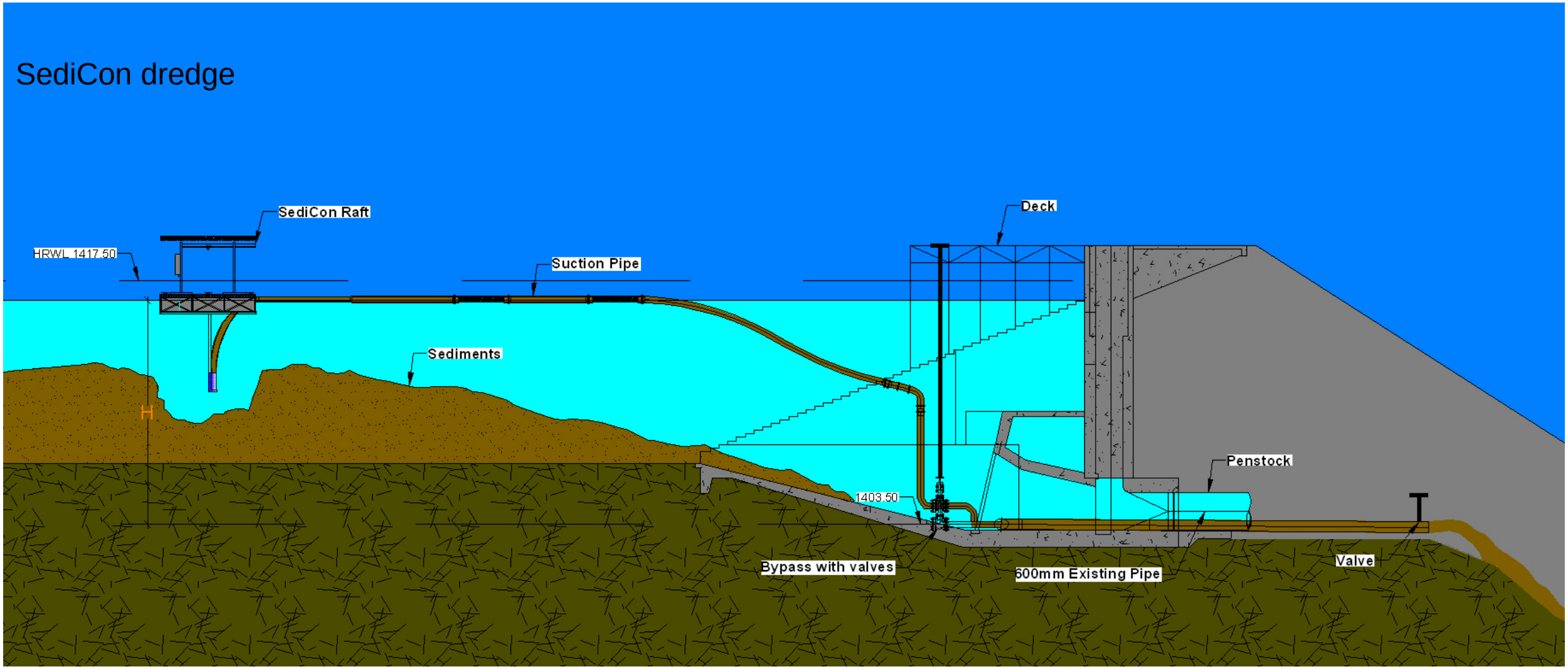
# Pneumatic pump desilting technology



Cao et al.

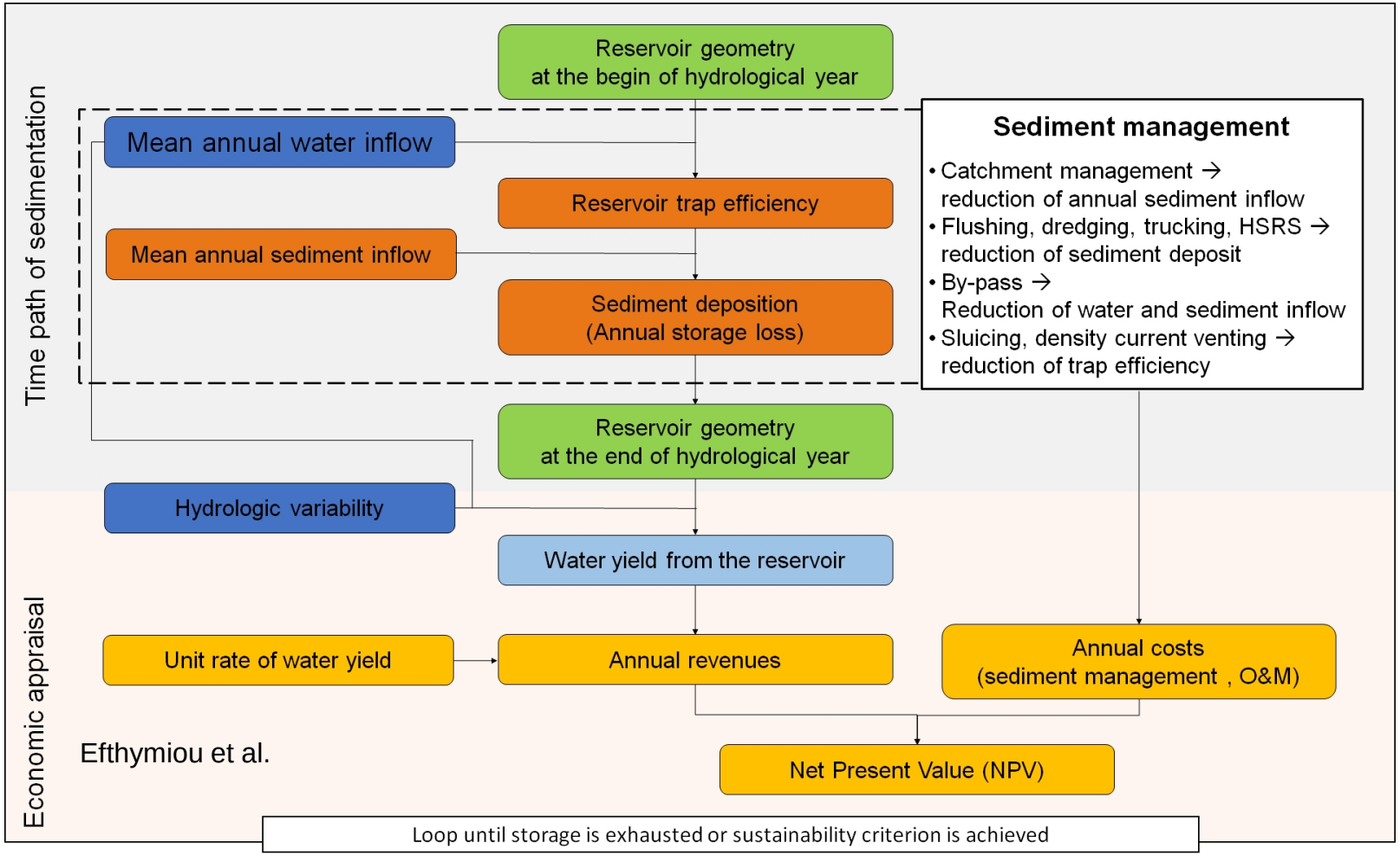
# Example of Hydrosuction dredging system

- Technical feasibility of hydrosuction depends on the available head and length of the discharge pipeline.
  - Aattractive option for small reservoirs of limited length.
  - Can also be used to keep the vicinity of intakes free of deposits.



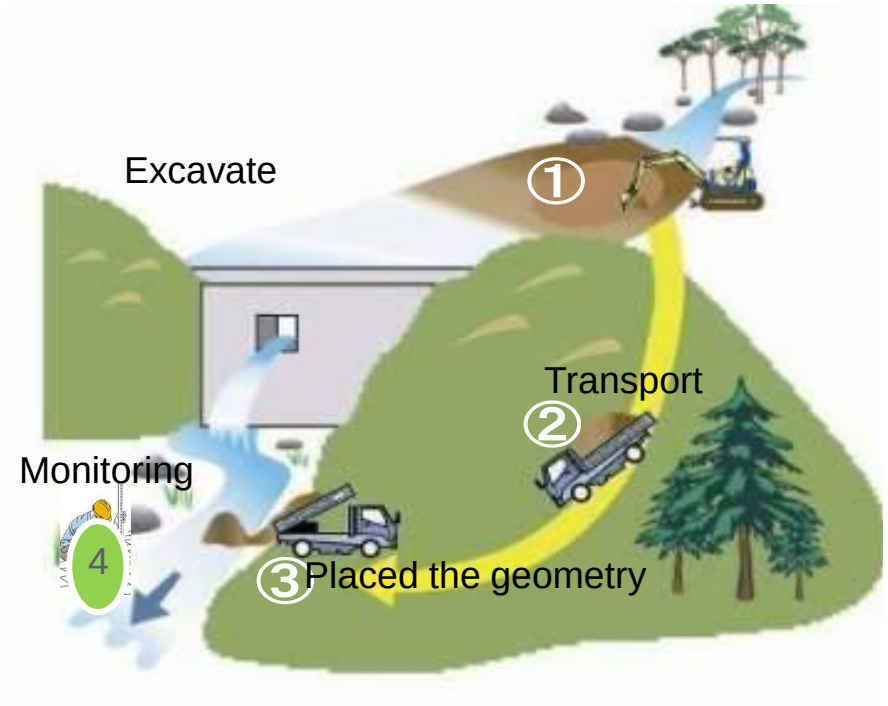
# ASSESS FEASIBILITY OF ALTERNATIVES

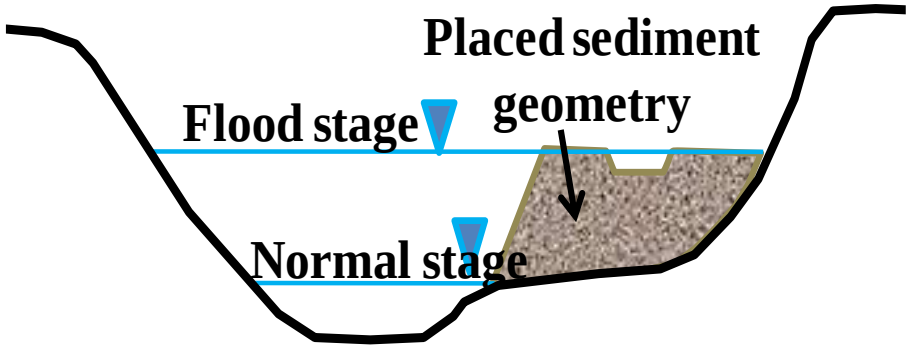
- Technical, environmental, legal, social, and economic feasibility;
- **Reservoir Conservation Model RESCON 2**
  - https://www.hydropower.org/sediment-management/resources/tool-reservoir-conservation-model-rescon-2-beta
- Compare consequences of alternatives to the consequences from the eventual retirement of the reservoir and the need to construct a new reservoir elsewhere;

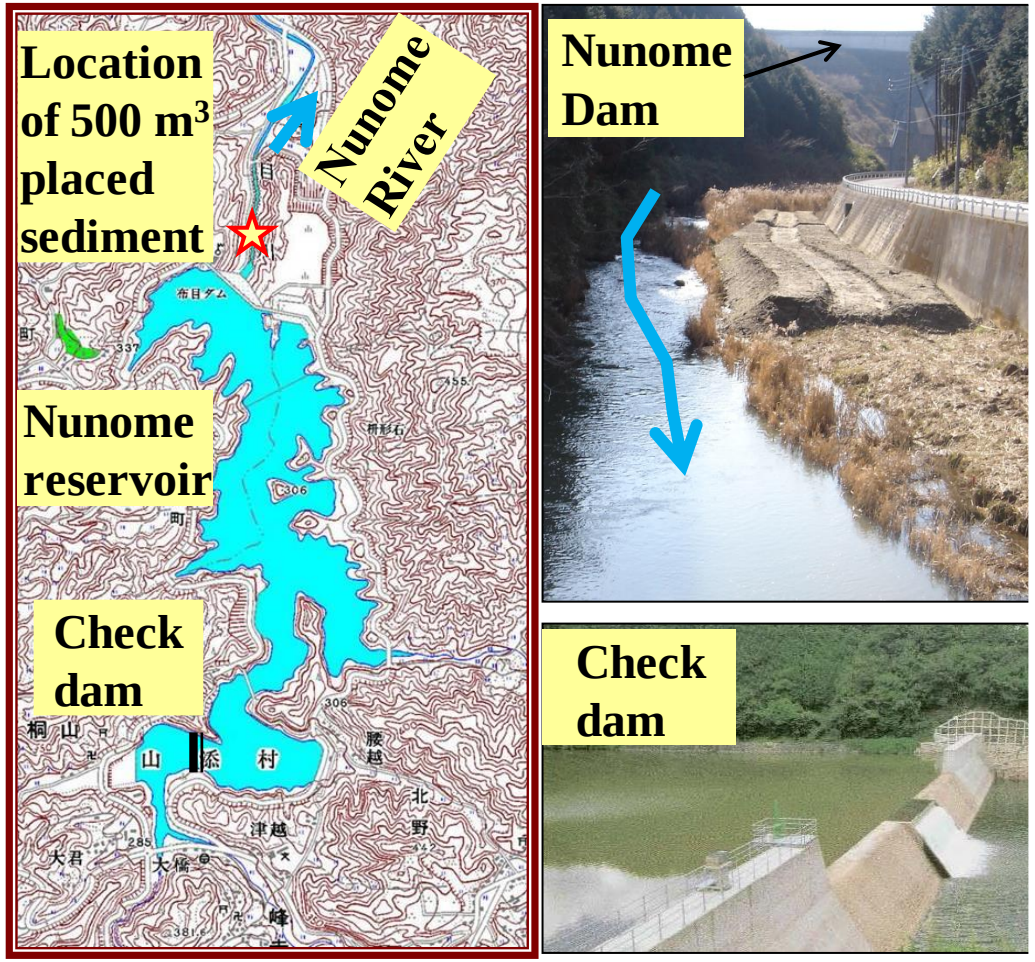



Flow chart of RESCON 2 analysis for the assessment of reservoir performance. O&M: Operation & Maintenance

# CONCEPT OF SEDIMENT REPLENISHMENT DOWNSTREAM OF DAMS




Sediment Replenishment in Nunome Dam

Cross section of the placed sediment geometry on the bank of Nunome River, Japan

# SEDIMENT REPLENISHMENT OPERATIONS

Widely applied in Japan
Dense monitoring

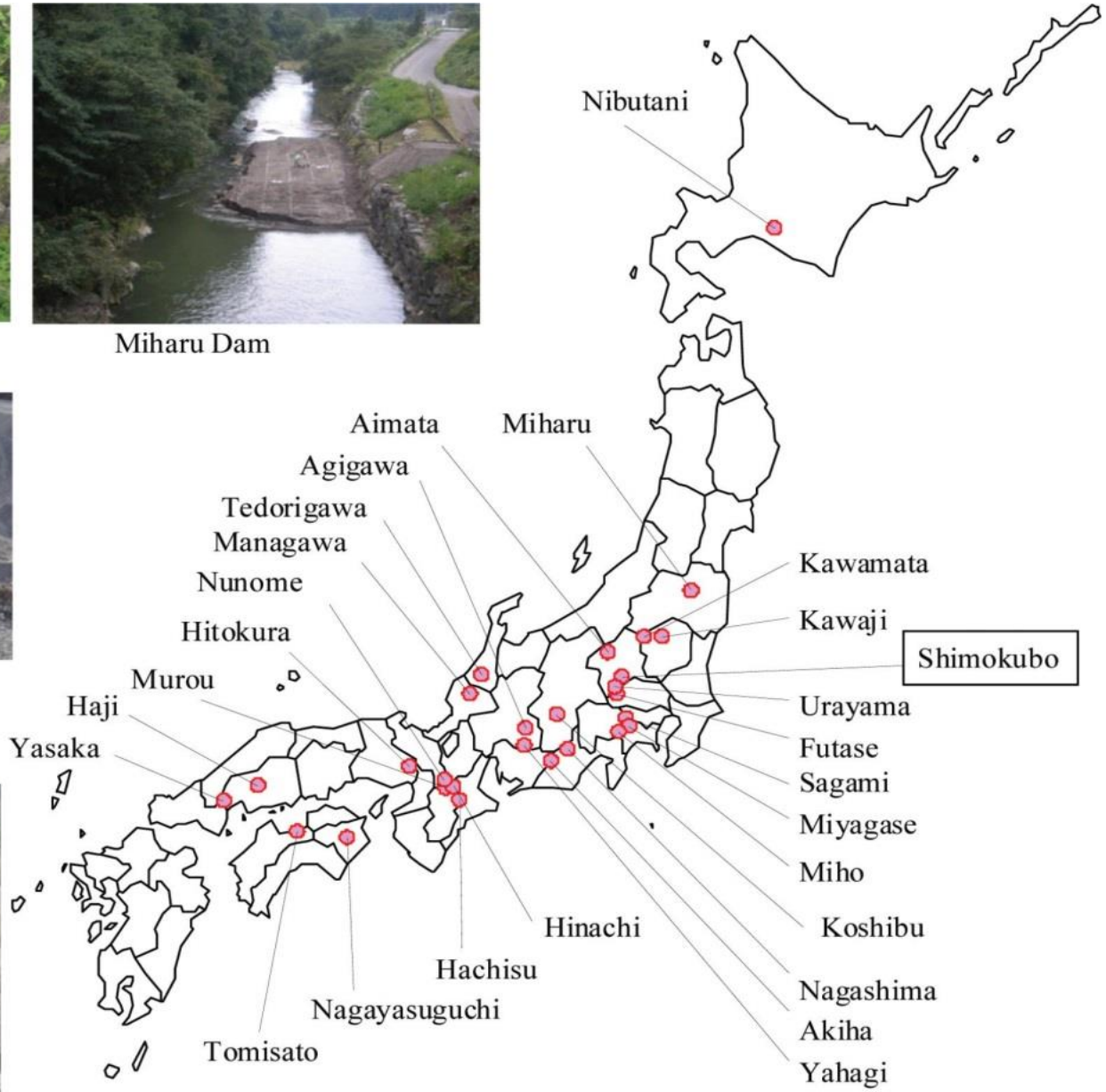
Futase Dam



Miharu Dam

Koshibu Dam

Nagayasuguchi Dam



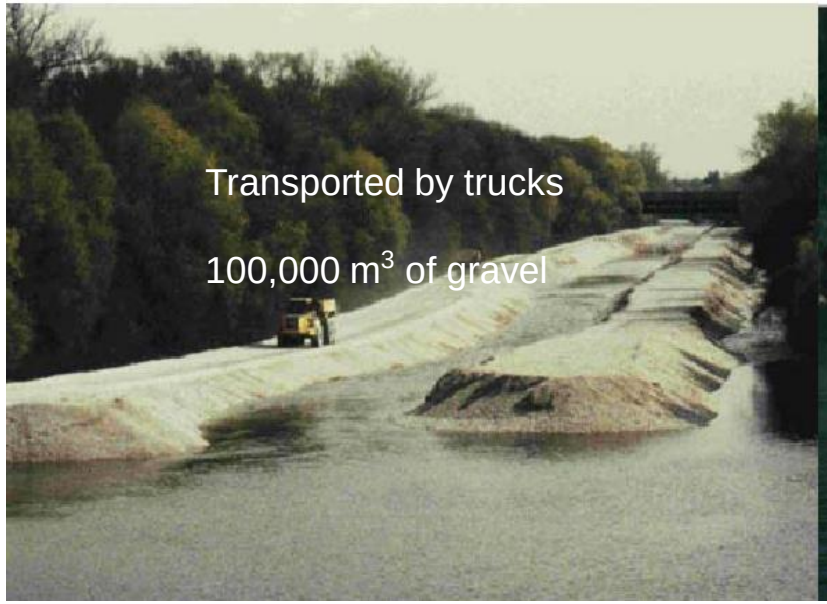

Sakurai et al.

# Sediment Replenishment in Buech River, France

Transported by trucks: 40,000 $m^3$ of gravel deposited downstream of St Sauveur dam

# Sediment Replenishment in Isar River, Germany

**Seven Hartman, ALPRESERV project.**



# NEED FOR SEDIMENT MONITORING

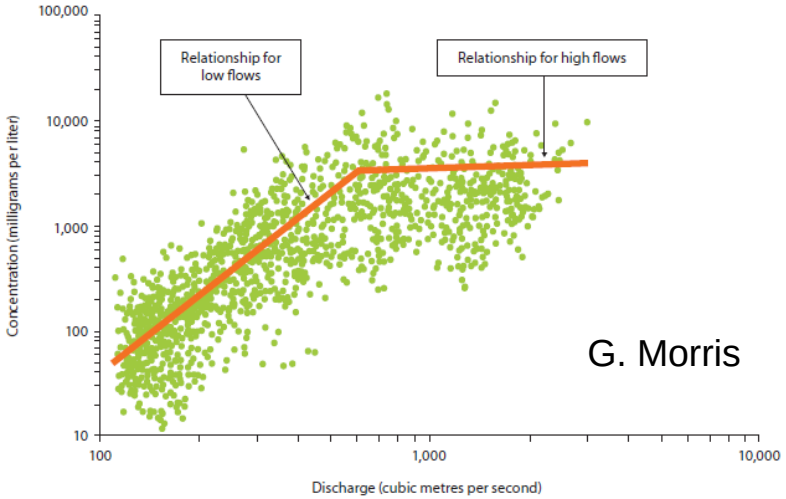
- The first obvious signs of a sediment problem may be the plugging of a dam outlet or reservoir water intake with wood and sediment.
- Reservoir surveys are periodically needed to monitor & forecast problems and avoid crisis management.

$$\textit{Frequency} = \frac{\textit{Projected Reservoir Age}}{10\ \textit{Surveys}}$$

*Frequency* = survey frequency in years per survey,
*Projected Reservoir Age* = Age of reservoir, in years, when sedimentation has reached the dam's lowest outlet or other important dam or reservoir facility

- Monitoring is now more important because most reservoirs are in the 2nd half of their sediment-design life.
- A decade or more may be needed to plan and implement sustainable sediment management plans.
- No action will lead to the eventual retirement of the dam and reservoir.

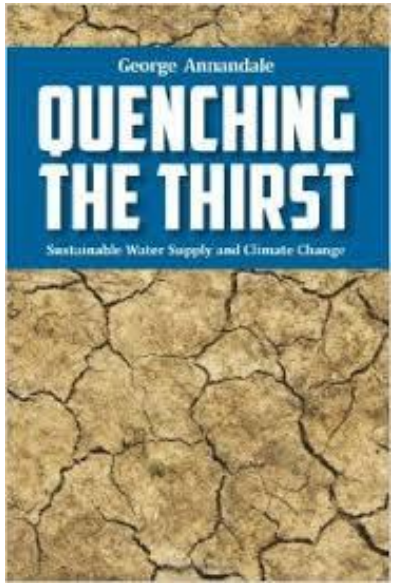
Vibracore Sampling of Sediment Cores to 60 m depth, La Esmeralda, Colombia (G. Morris)




G. Morris

# CONCLUSIONS

- Suitable sediment management options should be selected:
  - Flushing, Bypassing, Dredging, Replenishment etc.
  - Types of feasible strategies will vary from site to site, and also vary over time.
  - Compare cost and impacts of strategies with the costs of eventually retiring the reservoir and constructing additional water storage elsewhere.
  - Future generations should be considered when choosing a reservoir sediment management plan.
- Focus on managing recent or future sedimentation rather than past sedimentation.
- Both quantity and quality of the supplied sediment should be studied:
  - How much sediment should be supplied to downstream ?
  - What kind of grain size is Environmentally accepted ?
  - Both quantity and quality of the supplied sediment should be studied
  - **What about contaminated sediments?**
- Sediments passing through a reservoir or released downstream may have adverse impacts on channel morphology and ecosystem.
- Monitoring is now more important because most reservoirs are in the 2nd half of their sediment-design life.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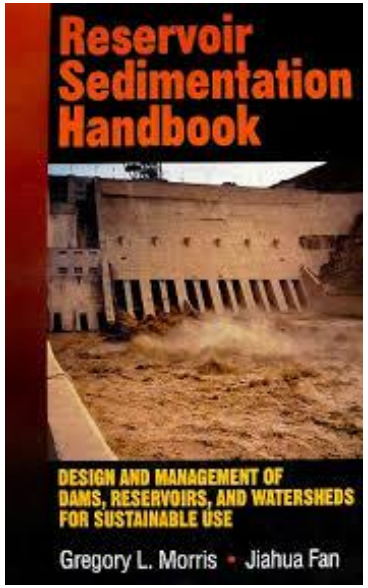
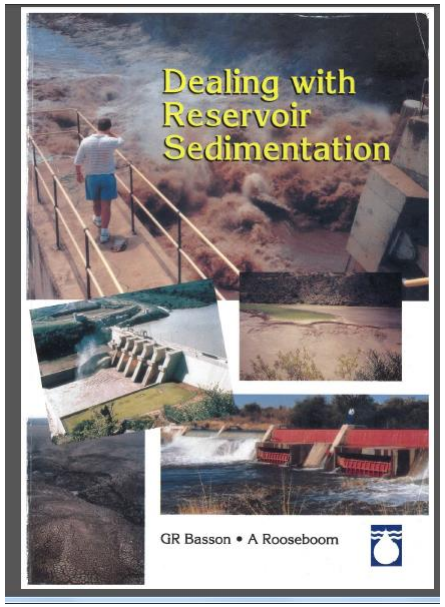
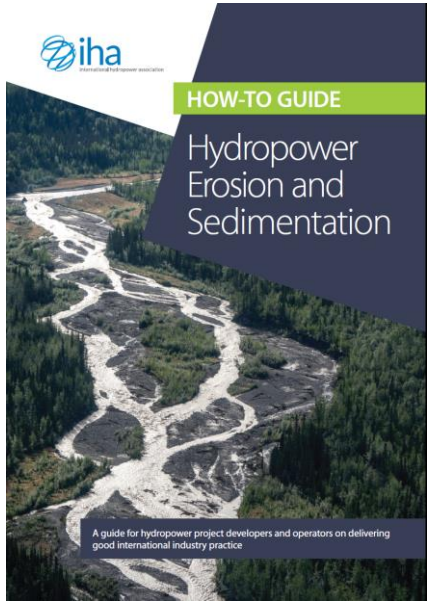
QUENCHING THE THIRST
Sustainable Water Supply and Climate Change


Reservoir Sedimentation Handbook
DESIGN AND MANAGEMENT OF DAMS, RESERVOIRS, AND WATERSHEDS FOR SUSTAINABLE USE
Gregory L. Morris • Jiahua Fan


Dealing with Reservoir Sedimentation
GR Basson • A Rooseboom

Managing Sediment In Utah's Reservoirs
March 2010
UTAH STATE WATER PLAN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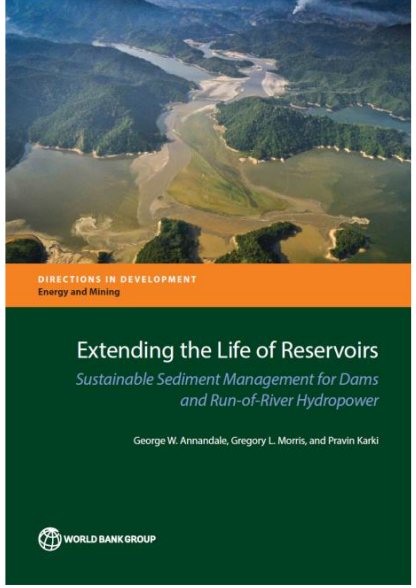
HOW-TO GUIDE
Hydropower Erosion and Sedimentation
A guide for hydropower project developers and operators on delivering good international industry practice


DIRECTIONS IN DEVELOPMENT
Energy and Mining
Extending the Life of Reservoirs
Sustainable Sediment Management for Dams and Run-of-River Hydropower
George W. Annandale, Gregory L. Morris, and Pravin Karki
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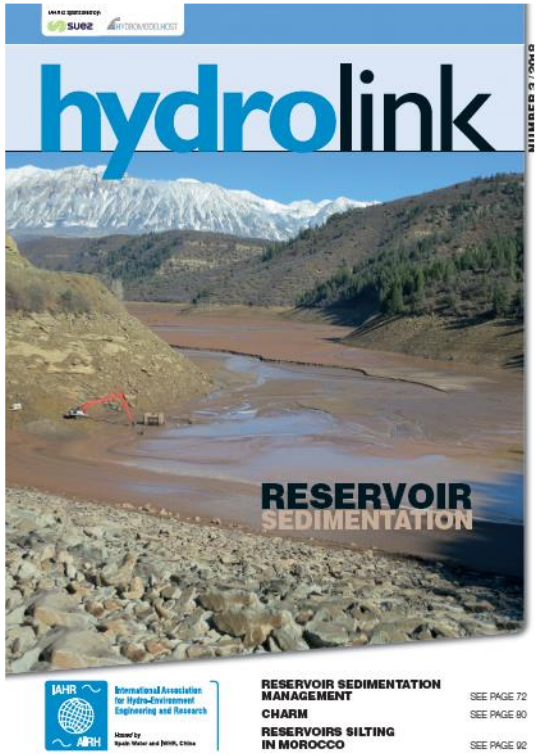
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RESERVOIR SEDIMENTATION
RESERVOIR SEDIMENTATION MANAGEMENT SEE PAGE 72
CHARM SEE PAGE 80
RESERVOIRS SILTING IN MOROCCO SEE PAGE 92

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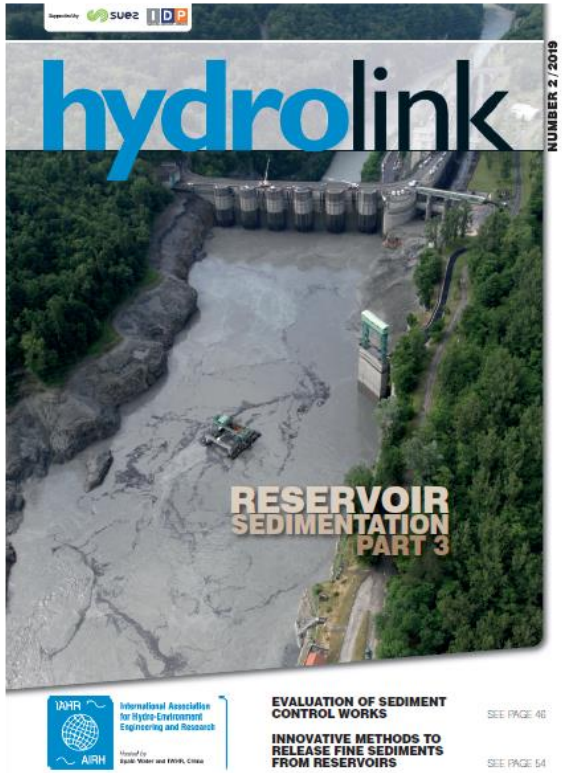
RESERVOIR SEDIMENTATION PART 2
INNOVATIVE STRATEGIES FOR MANAGING RESERVOIR SEDIMENTATION IN JAPAN SEE PAGE 100
SILTING OF RECHARGE DAMS IN OMAN SEE PAGE 115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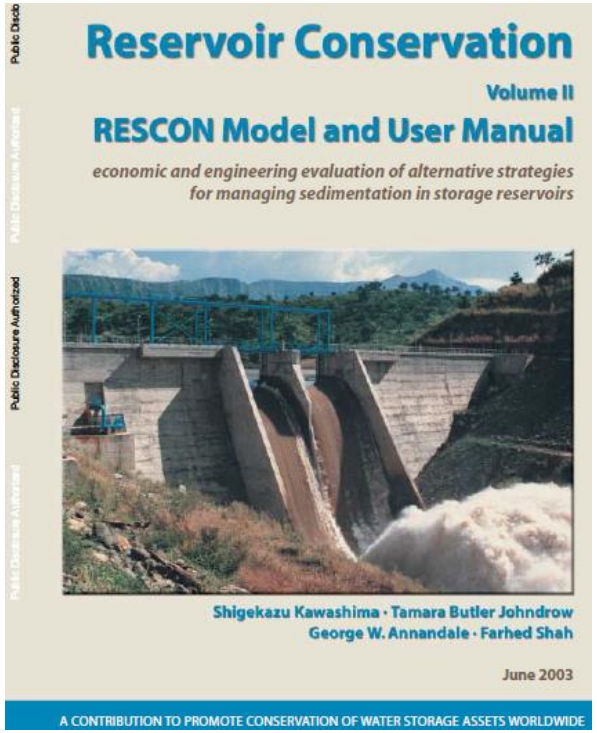
EVALUATION OF SEDIMENT CONTROL WORKS SEE PAGE 46
INNOVATIVE METHODS TO RELEASE FINE SEDIMENTS FROM RESERVOIRS SEE PAGE 54


Reservoir Conservation
Volume II
RESCON Model and User Manual
economic and engineering evaluation of alternative strategies for managing sedimentation in storage reservoirs
Shigekazu Kawashima · Tamara Butler Johndrow
George W. Annandale · Farhed Shah
June 2003
A CONTRIBUTION TO PROMOTE CONSERVATION OF WATER STORAGE ASSETS WORLDWIDE

# WEBINARS

**Reservoir Sedimentation Management – Big Deal! Why should we even care about it?**

Dr. George Annandale, P.E.

https://cires.colorado.edu/events/reservoir-sedimentation-management-big-deal-why-should-we-even-care-about-it

**Sedimentation Management Alternatives at Reservoirs**

Dr. Greg Morris, P.E.

https://cires.colorado.edu/events/reservoir-sedimentation-management-options-and-data-needs

**Sedimentation Management for Multi-Purpose Reservoirs: A Federal Perspective**

Dr. Tim Randle, P.E. and Dr. Paul Boyd, P.E.

https://cires.colorado.edu/events/sedimentation-management-multi-purpose-reservoirs-federal-perspective

# WEBINARS

## Permitting for reservoir sediment management

Dr. Rollin Hotchkiss, P.E. and David Olson

https://cires.colorado.edu/events/permitting-reservoir-sedimentation-management

## Reservoir sedimentation monitoring

Dr. Greg Morris, P.E.

https://cires.colorado.edu/events/sedimentation-monitoring

## Economics of Sustainable Reservoir Sediment Management

Dr. George Annandale, P.E. and

Dr. Rollin Hotchkiss, P.E.

https://cires.colorado.edu/events/economics-sustainable-reservoir-sediment-management

International Commission on Large Dams

www.icold-cigb.net

# WHAT IS THE INTERNATIONAL COMMISSION ON LARGE DAMS (ICOLD) DOING ABOUT RESERVOIR SEDIMENTATION?

BY MARTIN J. TEAL

The International Commission on Large Dams (ICOLD, www.icold-cigb.net) is an organization dedicated to advancing the art and science of dam engineering and promoting the wise and sustainable development and management of world's water and hydropower resources. ICOLD also assists nations to prepare to meet the challenges of the 21st century in the development and management of the world's water and hydropower resources. Presently, ICOLD has 31 Technical Committees. Because reservoir sedimentation is a significant issue for nearly all nations regardless of their position along the development spectrum, ICOLD has made reservoir sedimentation a key issue in its publications and committee work for many years.

The Technical Committee on Sedimentation of Reservoirs is currently composed of 18 member countries, each with a representative from their national committee on large dams, and 4 coopted members with special technical expertise. Many of the committee members have contributed articles to this special edition of Hydrolink (*e.g.* CNR, EDF, DPRI, ETH). In addition, committee members contributed to the organization of and papers within "Question 100" at the recently completed (July 2018) ICOLD Congress held in Vienna, Austria (https://www.icoldaustria2018.com). Question 100 dealt exclusively with the topic of reservoir sedimentation and sustainable development and over 40 works were included. A general report on Question 100 was prepared by Professor Sumi[1].

The committee's current activities are focused on drafting two new ICOLD bulletins. The first of these bulletins is nearing completion and deals with National Regulations and Sediment Management Case Studies. In the first part a summary is given of national regulations, where they exist, that impact sediment management options. The second part consists of case studies from different countries that illustrate sediment management efforts regardless of their degree of success.

The second bulletin was only started last year and is tentatively titled Design of Sediment Bypass Systems. The bulletin will focus on design of sediment bypass tunnels and on continuous bypass systems. Topics are expected to include design, operation, monitoring, ecological impacts and economic analysis. Past bulletins developed by the committee can be found on the ICOLD website: www.icold-cigb.net. ■

**Martin Teal** is the current Chair of the ICOLD Committee on Sedimentation of Reservoirs, which consists of over 20 members representing different countries from all regions of the world. He joined the committee in 2011 as the United States representative and became Chair 2016. He is a Hydraulic Engineer with WEST Consultants in San Diego, California where he serves as Senior Vice President. His experience is in the areas of hydrology, hydraulics, sedimentation and fluvial geomorphology.

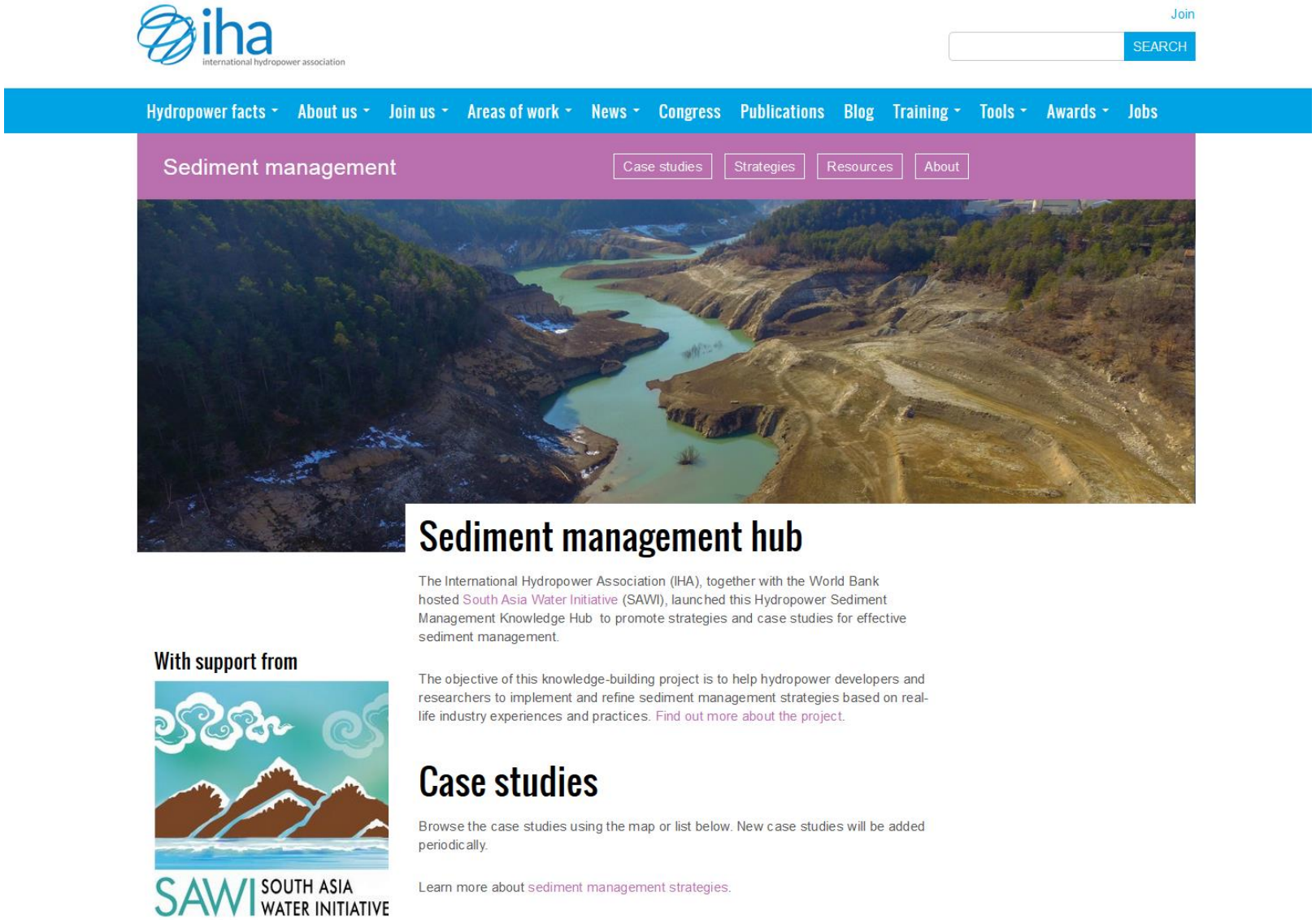
## References

[1] Sumi, T. (2018). "General Report on Question 100" in Proceedings of the Twenty-sixth Congress on Large Dams, ICOLD-CIGB, published by CRC Press.

Hydrolink 2018 (3)

# international hydropower association

https://www.hydropower.org/sediment-management



# New IAHR Group
# Reservoir Sedimentation

## Join us ☺

**Contact: kamal.el-kadi-abderrezzak@edf.fr**

**IAHR Europe Congress** June 30th - July 2nd 2020, Warsaw, Poland

**Special session - Reservoir Sedimentation**

# Acknowledgements

## National Reservoir Sedimentation and Sustainability Team (NRSST)

https://acwi.gov/sos/nrsst/


U.S. Department of the Interior Bureau of Reclamation

GLM Engineering COOP

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US Army Corps of Engineers

GWAI engineering for sustainable development

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Gracias por su atención

شكرا لكم على استماعكم

Thank you for your attention

ありがとうございます

Merci de votre attention