Himalayan Run-of-River Design and Operation: An Engineering Perspective

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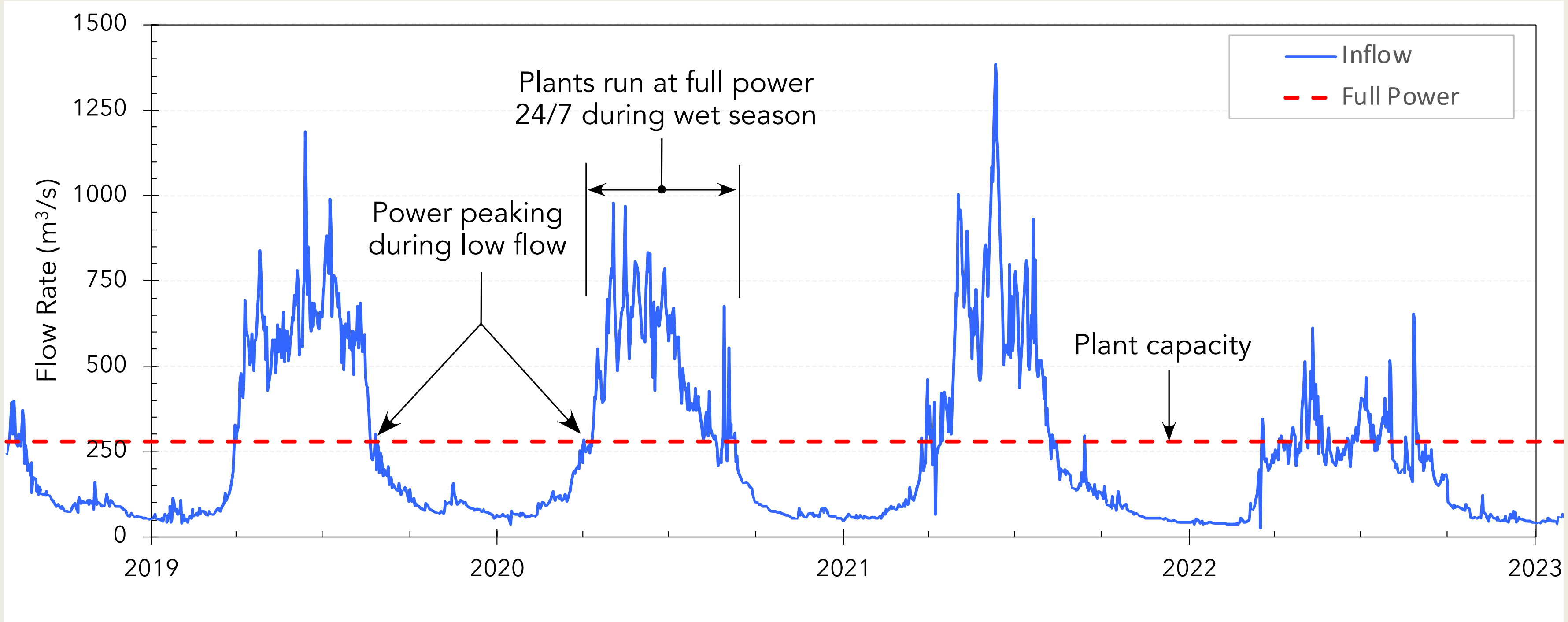
Focus of the Presentation

- This presentation outlines key aspects of RoR hydropower facilities as it relates to the Himalaya.
- A variety of techniques are described which have been used successfully to manage sediment and sustain power production in mountain environments.
- A key focus is to outline strategies which can potentially be employed to design and operate hydropower plants under high sediment loads.
- HEPs do not operate in a void. HEP design is always constrained and molded by:
    - Physical parameters such as topography, geology, hydrology, sediment load, and site access;
    - Social parameters such as laws and regulations (including the Treaty), environmental protection laws, land use and land acquisition, compensation of displaced persons, downstream impacts, etc.;
    - Financial parameters such as anticipated return on investment, availability of equity and credit financing.
- Although the Treaty establishes constraints on certain technologies that India may use in the design and operation of hydropower plants, techniques are available that allow hydropower development to occur despite Treaty limitations.

HYDROLOGY & SEDIMENT

Himalayan Hydrology is Highly Seasonal

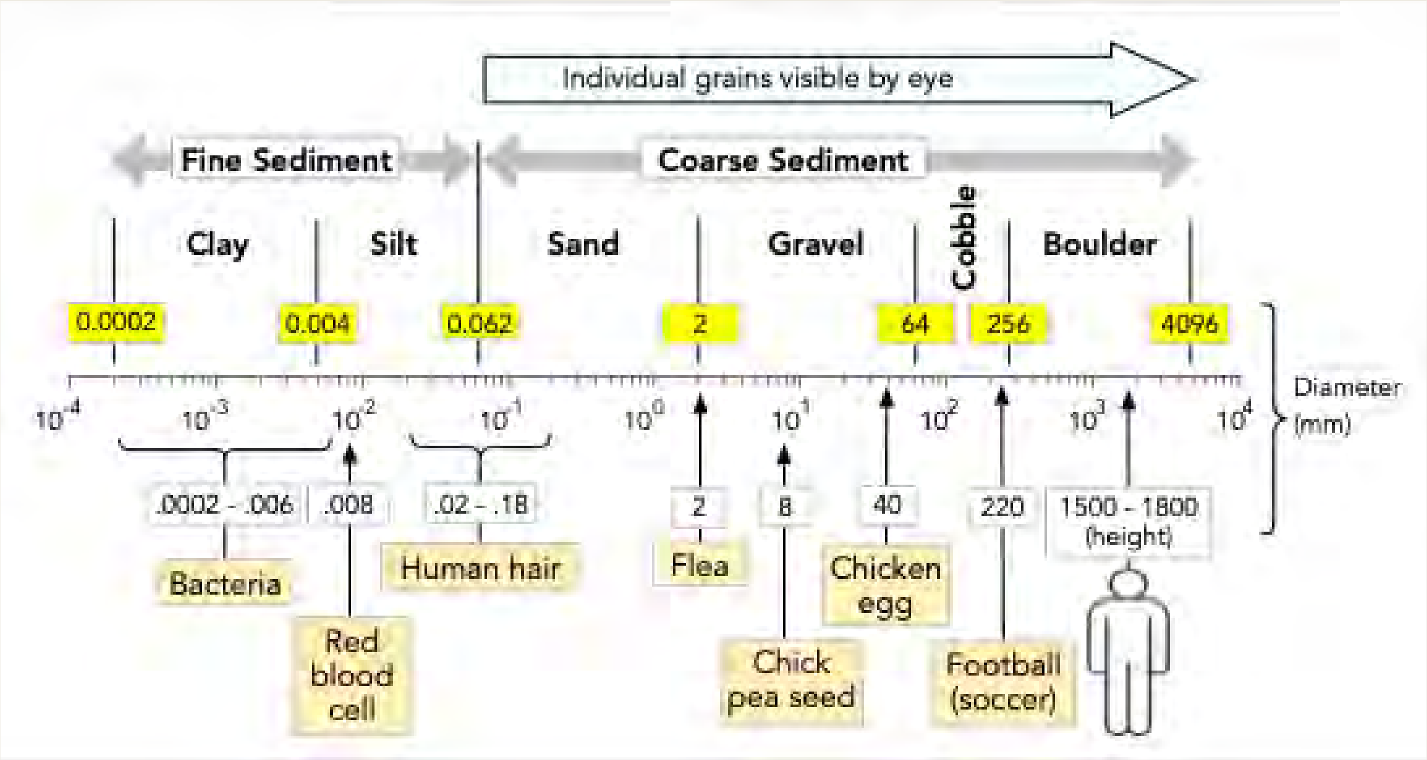
- The graph shows the seasonality of daily flows along the Neelum River at the site of the Neelum-Jehlum dam.
- Winter flows are low because precipitation in the mountains remains locked up as snowpack.
- The early summer high flow is dominated by meltwater (snow and glacier) with monsoon rains becoming more important later in the summer.



Site Visit Presentation 5, Slide 13

Sediment Sizes:

Characteristic range of sediment sizes in Himalayan rivers



Site Visit Presentation 6, Slide 3

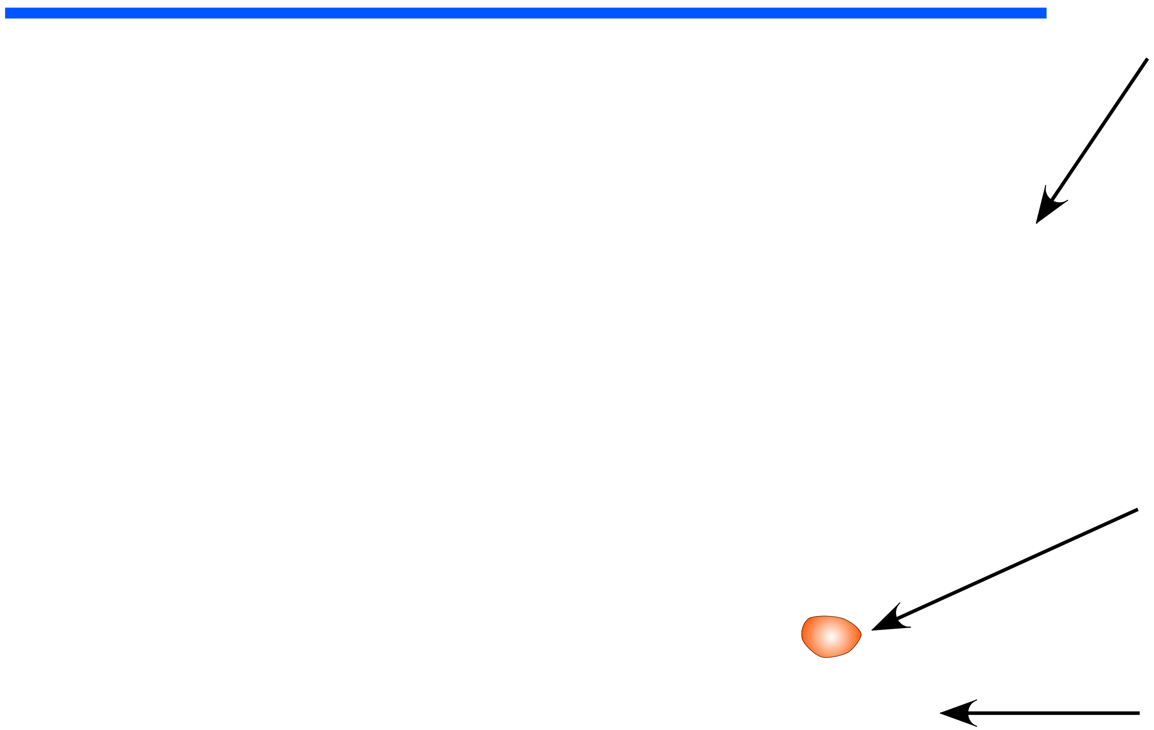
- In Himalayan mountain rivers the suspended sediment grain size ratio typically falls in the general range of

  Silt : Clay = 60:40

- Although sediments of all sizes are damaging to turbines, coarse sediment is much more damaging than fines.

Modes of Sediment Transport:

Most Himalayan sediment is transported as suspended load



city drops.

Bed material: the larger sediment that comprises the river's bed.

Site Visit Presentation 6, Slide 4

Himalayan Sand

Himalayan sands are typically transported as suspended load

Quartz-dominated sand on palm of my hand, Kali Gandaki River, Nepal

Site Visit Presentation 6, Slide 6

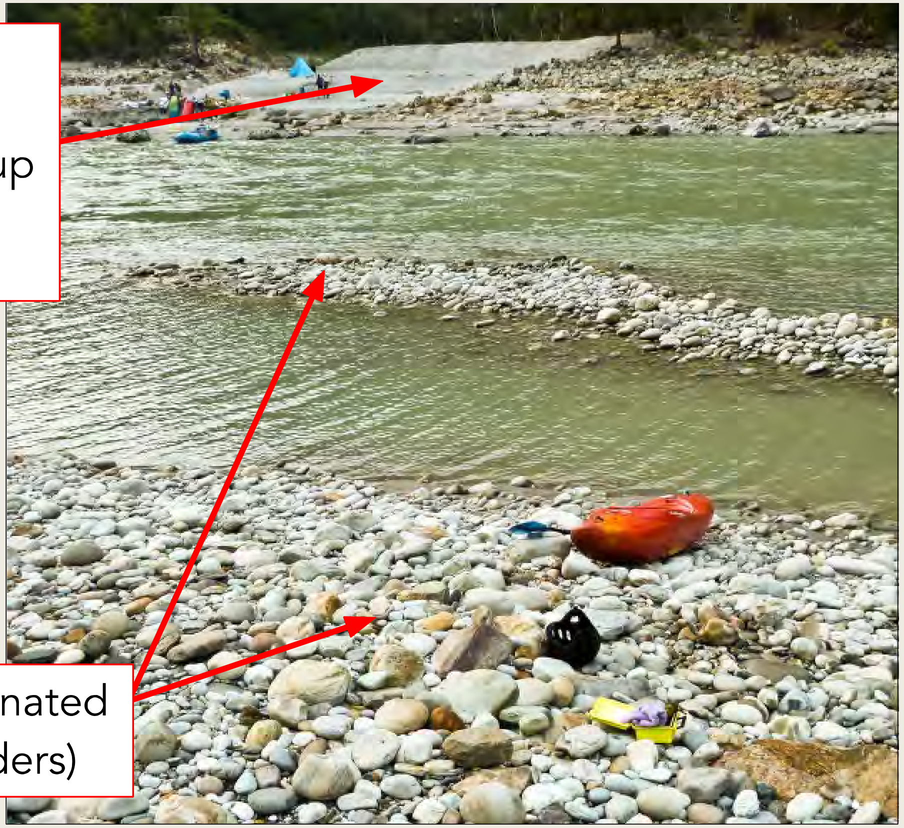
- In Himalayan rivers sand is typically transported as suspended load.
- Suspended load is typically about 60% silt and 40% sand.
- Quartz typically dominates the minerology of Himalayan sands
- Quartz is harder than steel (mhos hardness scale: talc =1, diamond = 10).
  - Sand: mhos = 7
  - Turbine steed: mhos ~ 4.8
- Angularity of sand increases its abrasiveness, but is certainly not unique to the Himalaya.

Himalayan Bed Material and Bed Load Transport

The rate of Himalayan bed material transport (bed load) is typically a very small fraction of the suspended load.

Indus River above Tarbela reservoir at low flow (November)

Notice the men shown for scale



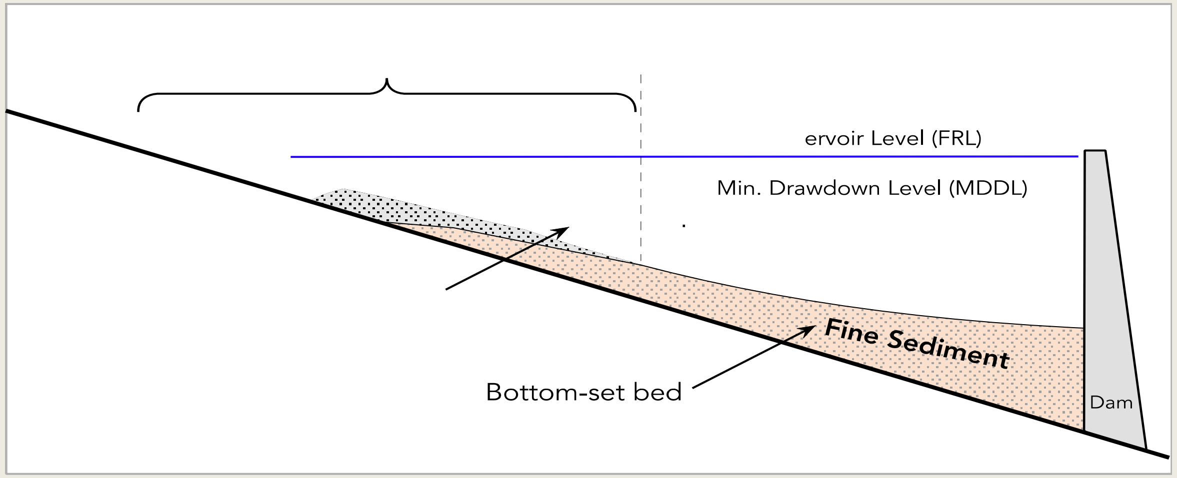
Kali Gandaki River, Nepal, at low flow (January)

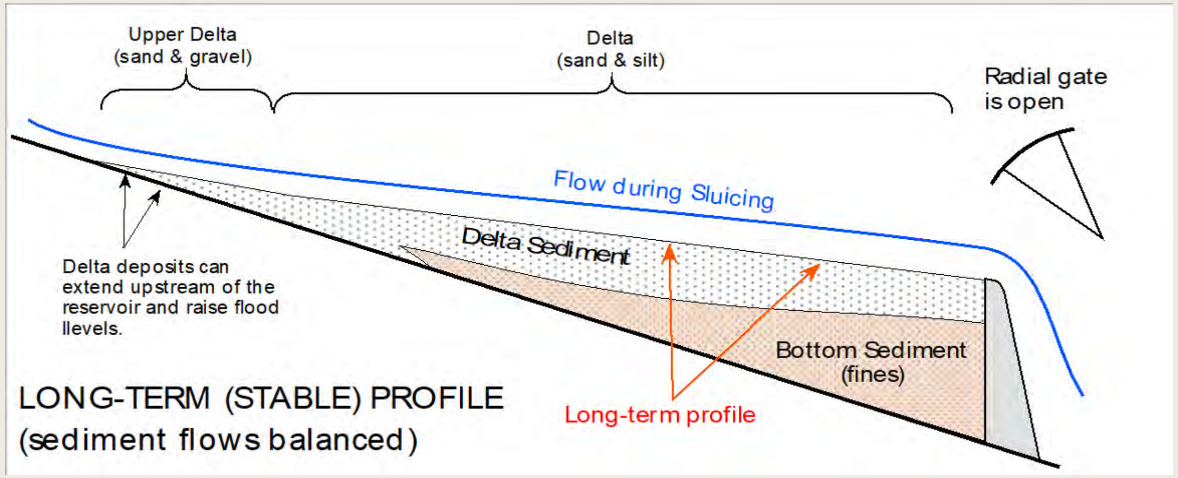
Both images: Site Visit Presentation 6, Slide 5

RESERVOIR SEDIMENTATION PROCESSES

Sedimentation Patterns in Reservoirs

These general patterns apply to both storage and RoR reservoirs, although smaller RoR reservoirs fill more rapidly.

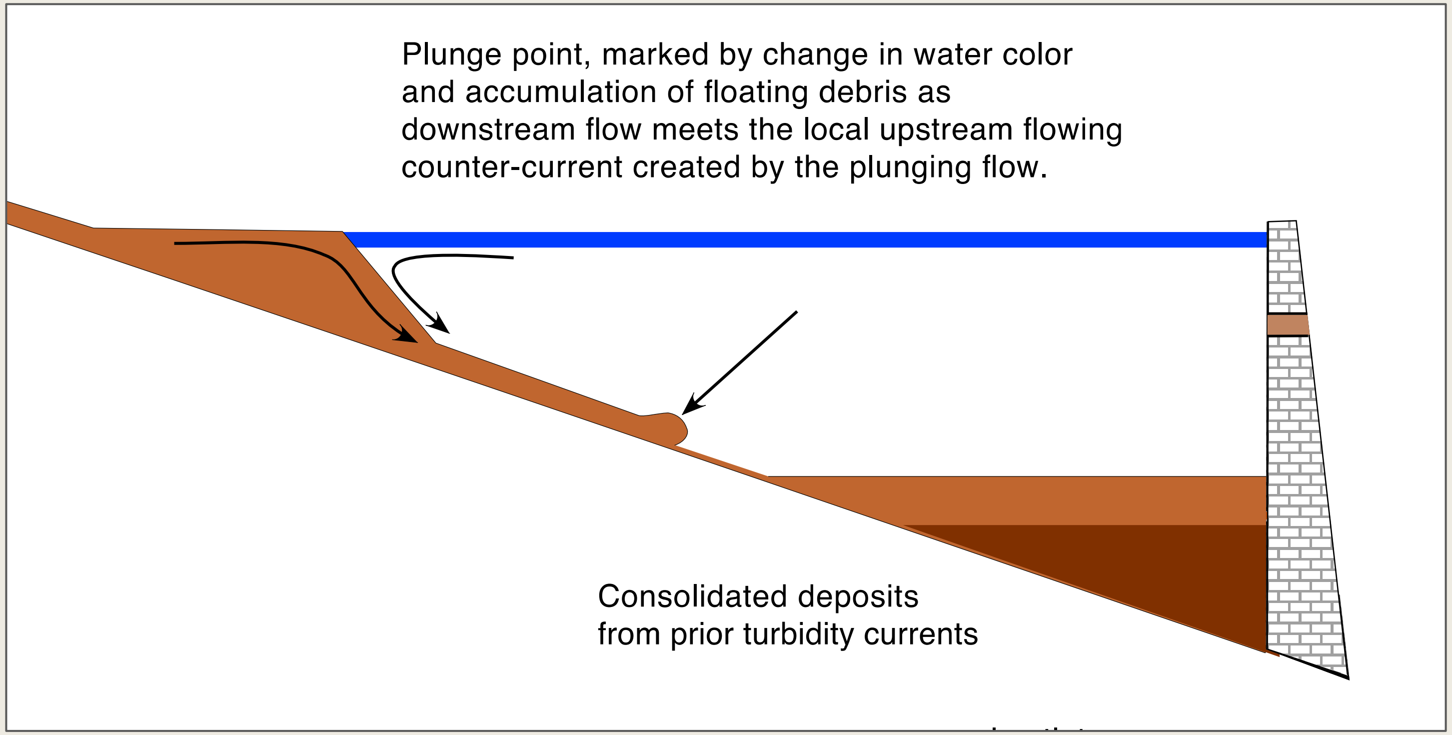




- **Sediments deposit** in different zones according to grain size.
- **Delta deposits:** coarser sediments settle rapidly to form a delta that advances downstream.
- **Bottom-set deposits:** fine sediments settle more slowly and are primarily deposited downstream of the delta.
- **Long-term sediment balance** is achieved when multi-year sediment inflow and outflow are matched.

Site Visit Presentation 6, Slide 8

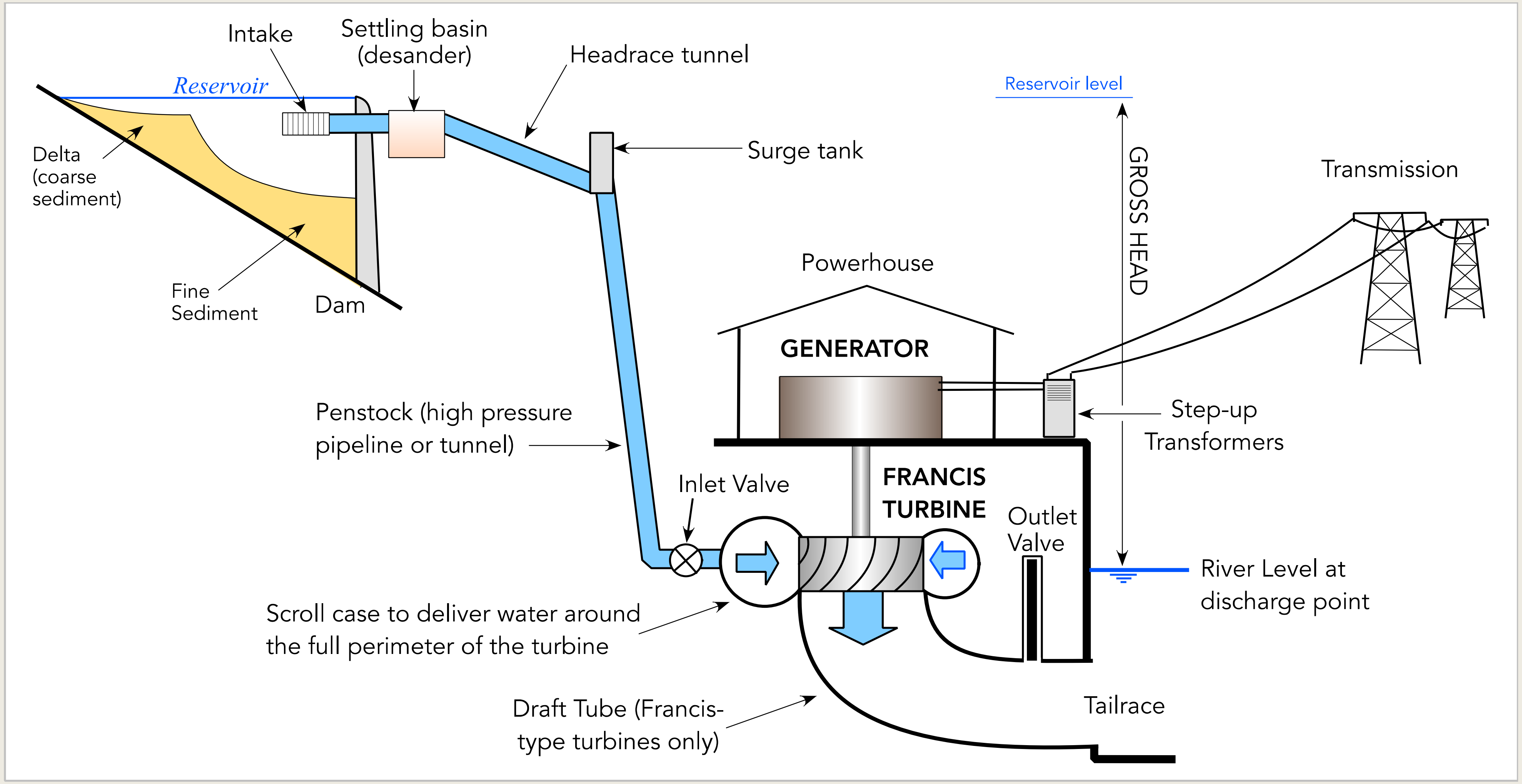
Turbid Density Currents



- In deep reservoirs sediment-laden inflows can enter the reservoir, plunge, and run along the bottom until reaching the dam.
- If not released, the sediment-laden flow will create a submerged muddy lake, and sedimentation from repeated episodes will create horizontal deposits extending upstream from the dam.
- Turbidity current deposits are recognizable in longitudinal profiles from reservoir surveys.
- Turbid density currents normally carry only fine sediments. These fine sediments may be released through turbines to delay the arrival of the much more damaging coarse sediment to the area of the dam and intake due to the advancing delta.

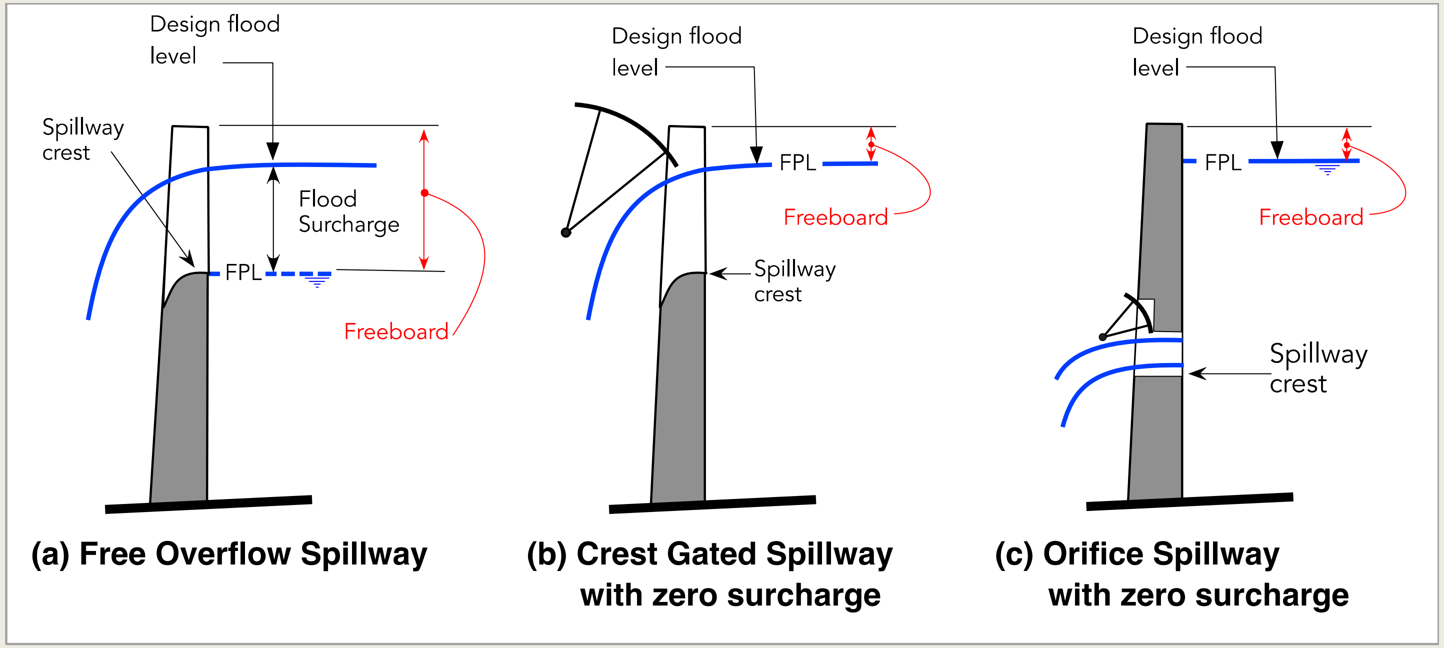
TYPICAL CHARACTERISTICS OF RUN-OF-RIVER PLANTS

Typical Components of A Run-of-River Hydro Plant



Site Visit Presentation 2, Slide 18

Spillway Configurations for Flood Discharge

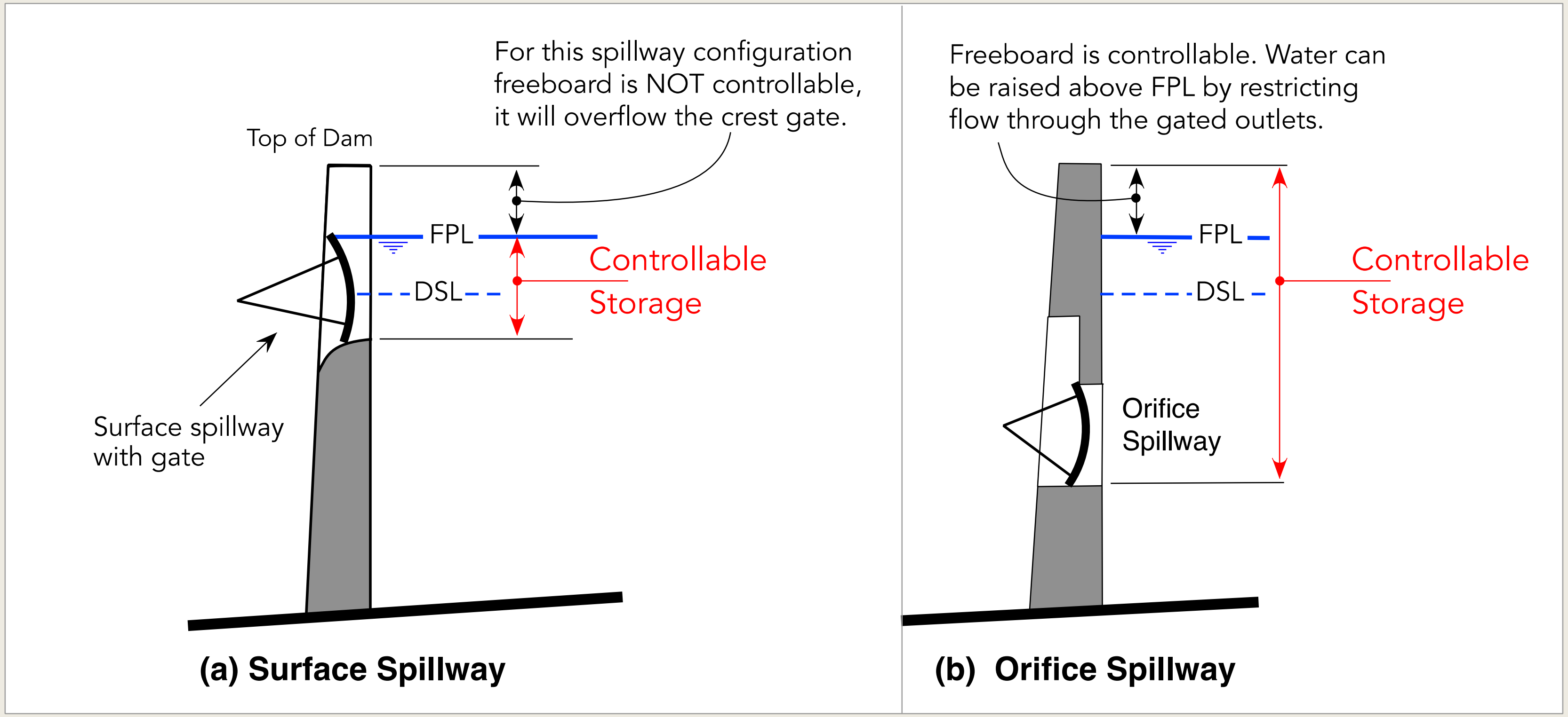


Pakistan's Memorial, Figure 4.2.6

- **"Freeboard"** consists of flood surcharge + the minimum freeboard above the design flood level.
- **"Spillway crest"** refers to the bottom of the spillway opening, whether gated or ungated.

- Spillways are required to safely release floods downstream.
- Different spillway configurations are available.
- Multiple spillways are frequently incorporated into a single dam.
- Surcharge is the additional water level above the maximum operational level that will occur during the design (extreme) flood.
- In the case of gated spillways, if the gates are large enough the design flood can be released without raising the water level above the maximum operational level (i.e. FPL).

Spillway Configurations and Controllable Storage



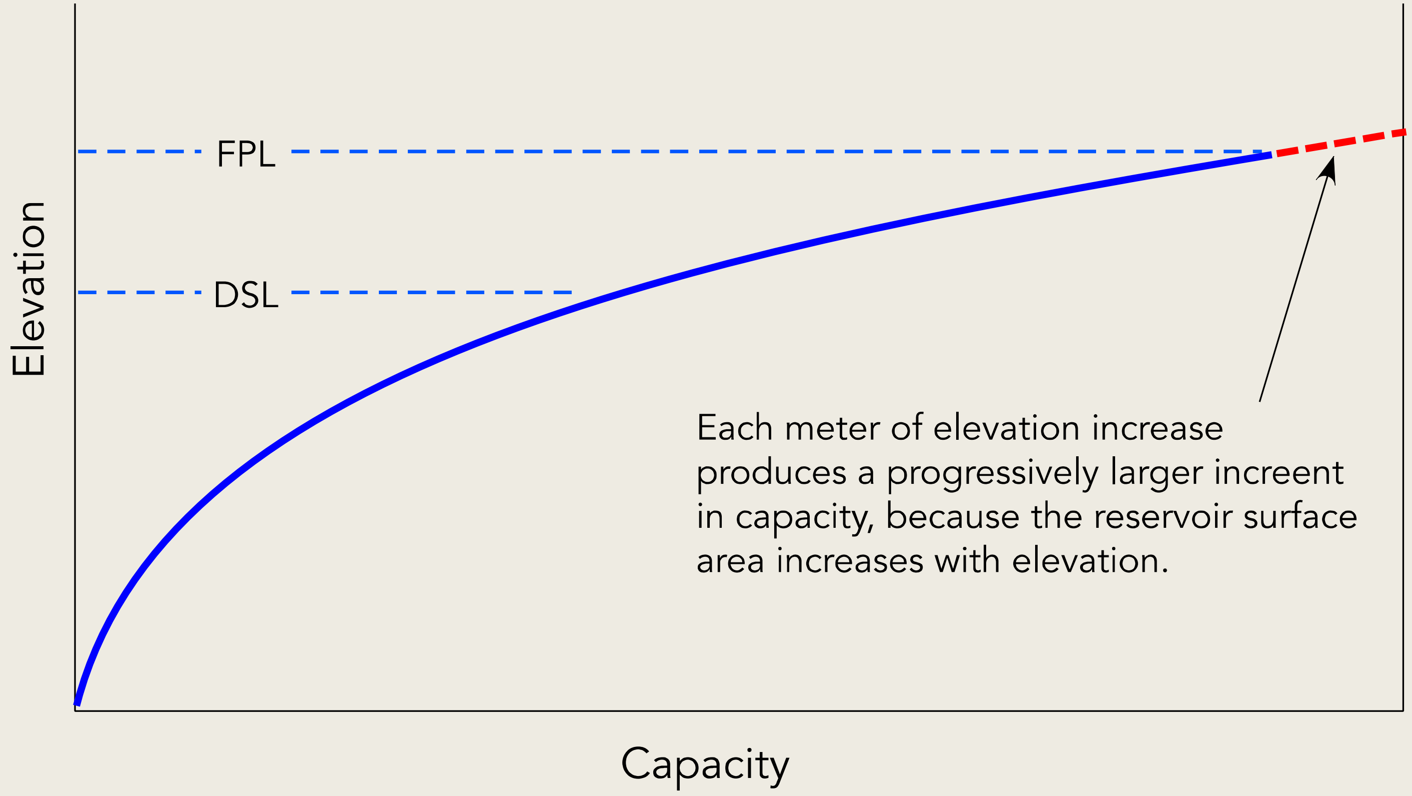
Pakistan's Memorial, Figure 4.20

FPL = Full Pondage Level, the Maximum operating level
DSL = Dead Storage Level (per Treaty definition). It corresponds to the minimum operating level.

- The volume that can be controlled is determined in large part by the placement of the spillway gates.
- In the case of crest spillways, the water will flow uncontrollably over the the crest, or the crest gate (as shown in "a"), rendering the freeboard zone above FPL as uncontrollable storage.
- Use of an orifice spillway increases controllable spillways in two ways:
  - The deeper orifice spillway increases controllable storage below DSL, and
  - The freeboard (including any flood surcharge) is converted into controllable storage if there is no overspill outlet.

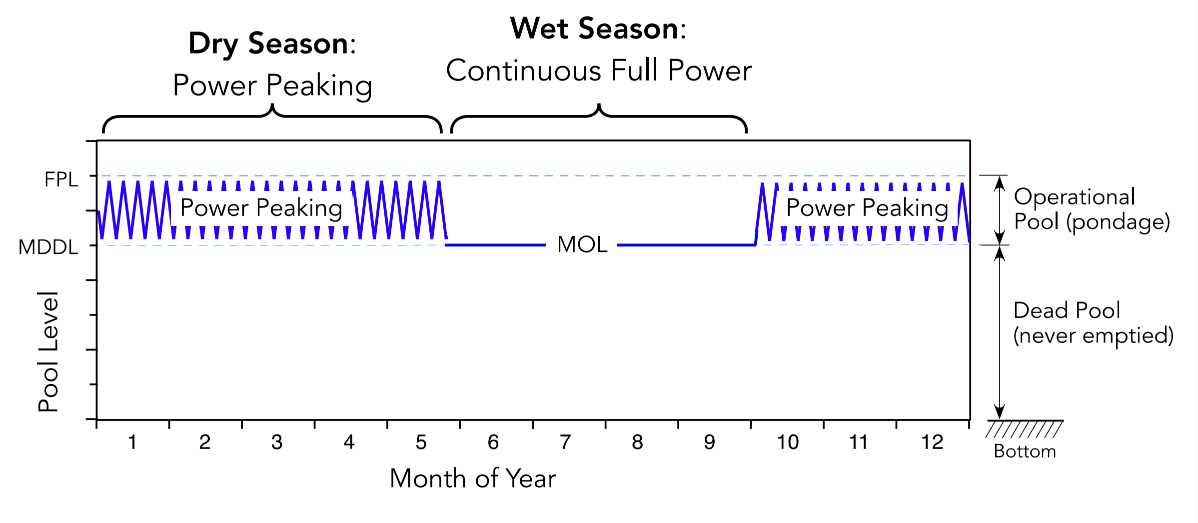
Elevation-Capacity Curve

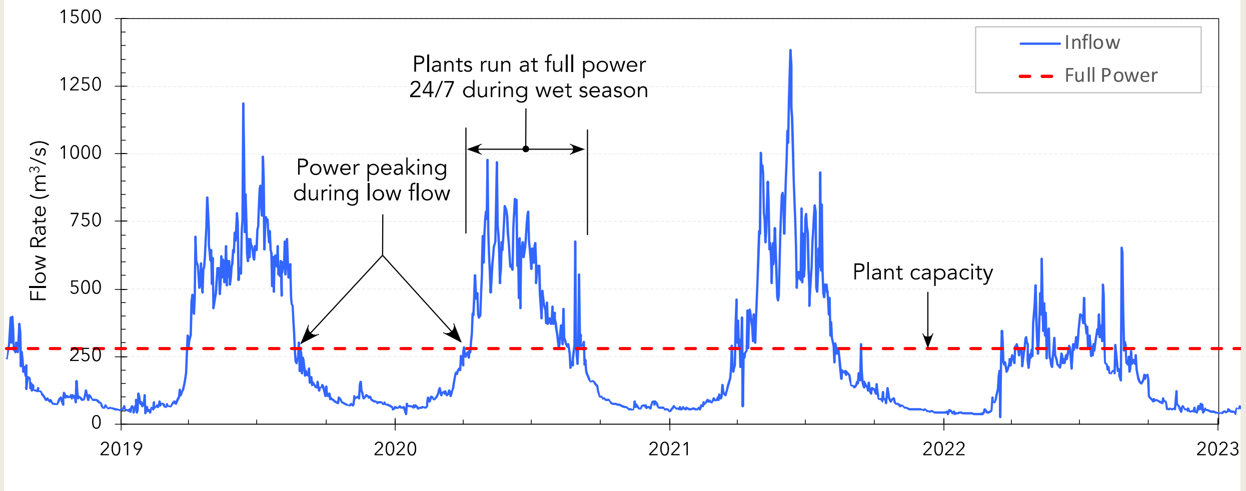
Increases in reservoir level above Full Pondage Level (FPL) produce large increments in storage capacity.



- The storage capacity in a reservoir is highly sensitive to the maximum water level.
- This occurs because the reservoir surface area becomes larger with increasing water level.
- The elevation-capacity curve expresses storage capacity vs. water level.
- Each meter of water level increase above FPL produces an increasingly large volume of additional storage capacity, as seen by the flatter trajectory of the curve at the maximum elevation.
- This makes it particularly important to eliminate the capability to artificially increase the water level.

The Annual Operational Cycle

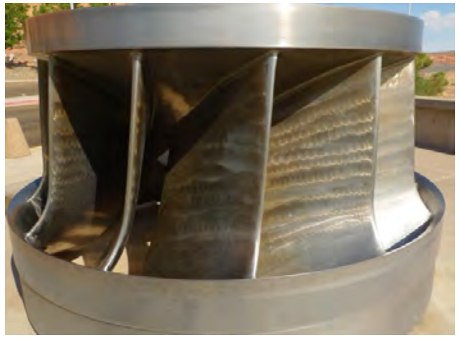


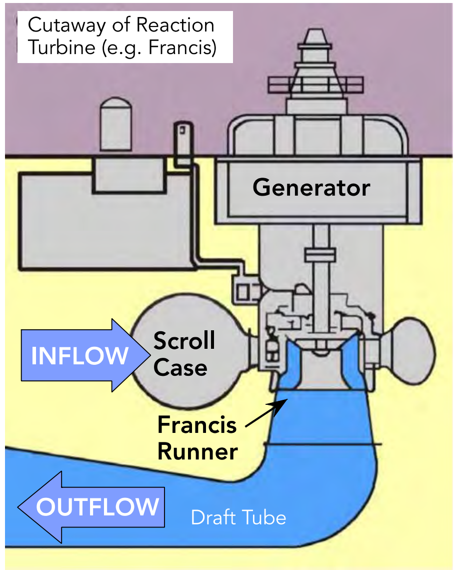


Site Visit Presentation 5, Slide 13

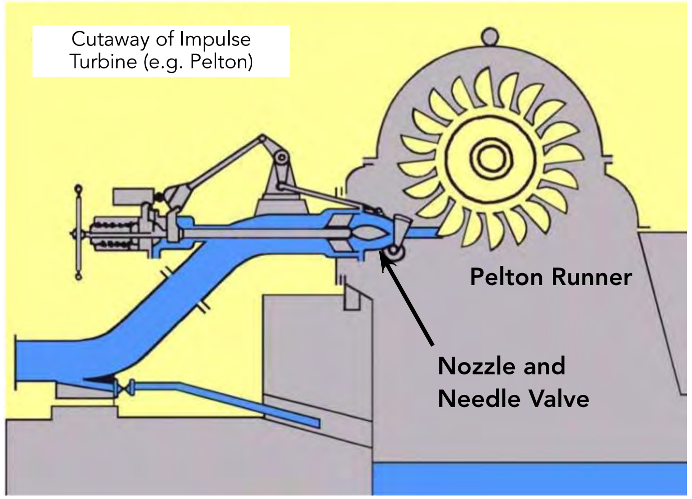
- During the wet season, when water is abundant, the plant delivers “base load”, operating turbines at full power 24/7.
- During winter months with greatly diminished flow, the plant will operate in “peaking” mode.
  - During the nighttime hours the turbines are turned OFF to accumulate water in the reservoir (pondage).
  - During peak hours (typically morning or evening) the turbines are turned ON to produce power when it is most needed.
- Thus, the operational mode of the plant depends on the seasonality of water inflow

Hydropower Turbines: Main Types





Francis Turbine
(moderate-head plants: ~50 - 350 m)



Pelton Turbine
(high-head plants: >350 m typically)

- Most Himalayan Run-of-River Plants use either Francis or Pelton turbines.
- The Neelum-Jehlum plant uses Francis turbines.
- Francis turbines are typically used in the approximate range of about 50 – 350 m of head.
- Pelton runners are typically used at operating heads exceeding about 350 m.
- There is a range of conditions under which either turbine might be preferred.
- Both turbine types are susceptible to sediment damage.

Photos: Pakistan's Memorial, Figure 4.7. Images: Site Visit Presentation 2, Slide 28

Sediment Impacts to RoR Hydro Plants

Sediments impact run-of-river hydropower plants in two major ways:

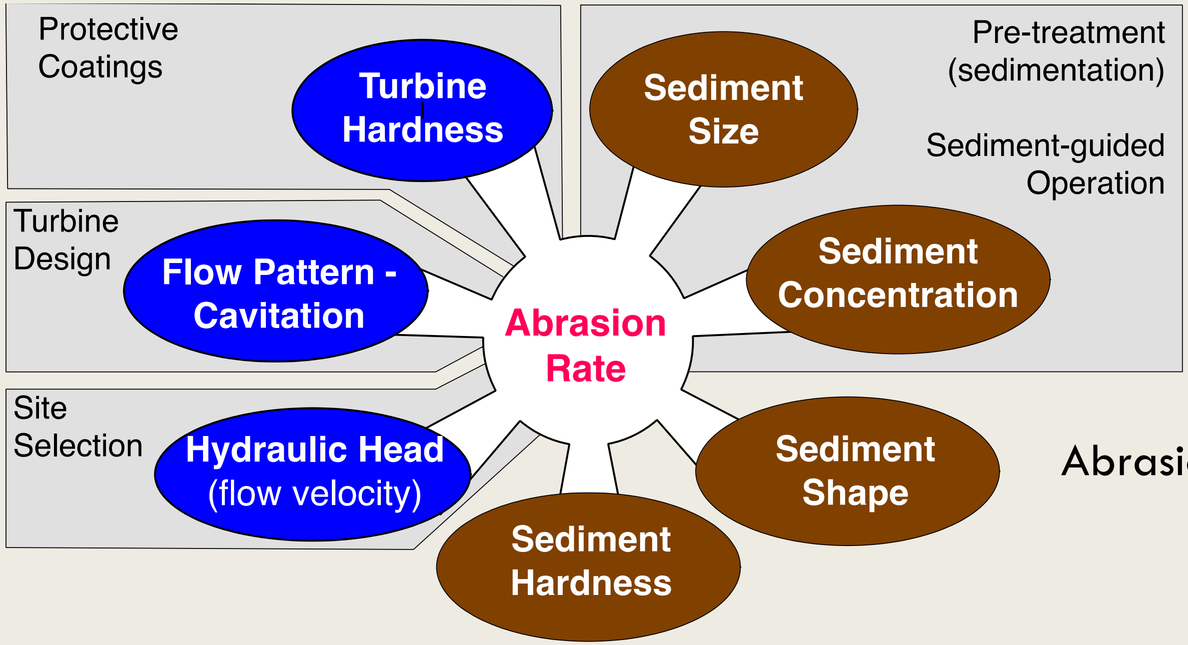
- **ABRASION DAMAGE**. Sediment causes abrasion of hydro-mechanical components, especially the turbine blades (the "runner") and the guide vanes that control both the direction and rate of flow entering the turbine. Problems also arise in the seals, the generator's cooling system, and elsewhere.
- Some structural components at the dam (concrete aprons, gate seals) may also experience significant sediment damage.
- **RESERVOIR STORAGE**. Sediment accumulation in the reservoir displaces usable capacity for water storage.

Plants challenged by heavy sediment loads cannot be designed and operated like a storage plant. It is essential to incorporate both design and operational modifications to manage sediment.

Some components, such as turbines, which may last decades in a sediment-free environment, will experience accelerated wear in a high-sediment environment. These will require more robust construction, special coatings, plus repair & replacement at more frequent intervals (e.g. annual) to function adequately in a high-sediment environment.

SEDIMENT MANAGEMENT TO CONTROL TURBINE ABRASION

Overview of Strategies to Mitigate Abrasion



Abrasion damage

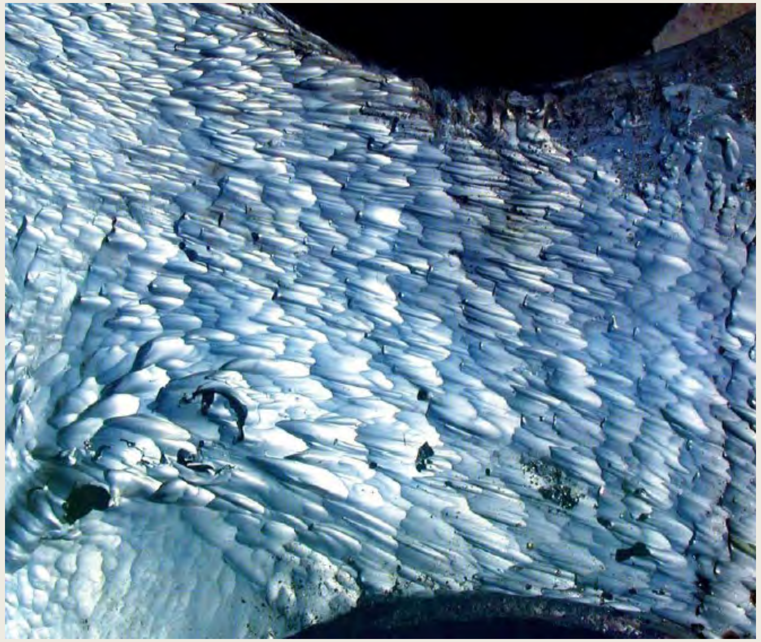
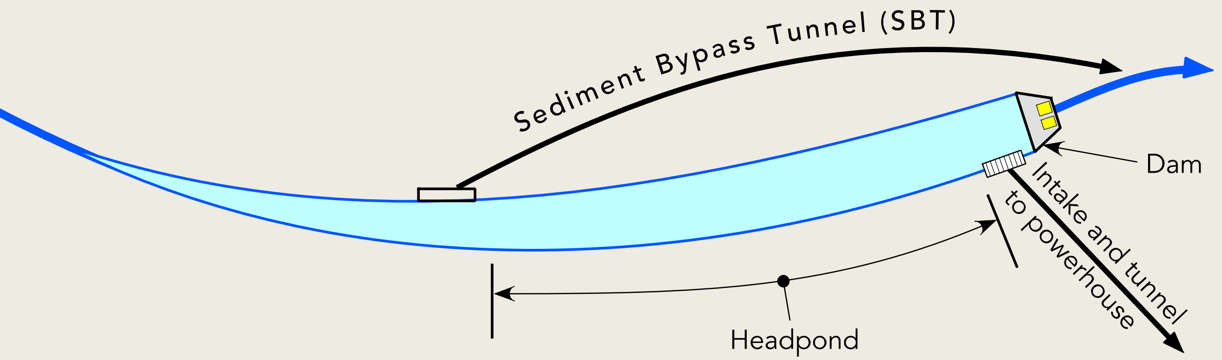
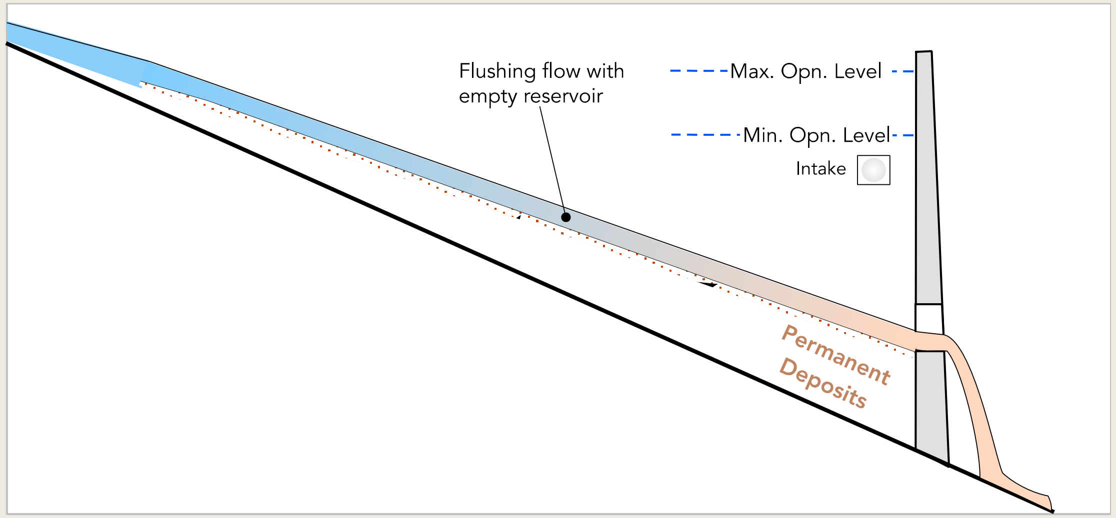


Photo: Site Visit Presentation 6, Slide 30

- Multiple strategies can be applied to mitigate abrasion.
- The graphic on the left shows that the designer and operator are able to influence a variety of parameters to mitigate abrasion damage.

Reservoir Management: sedimentation

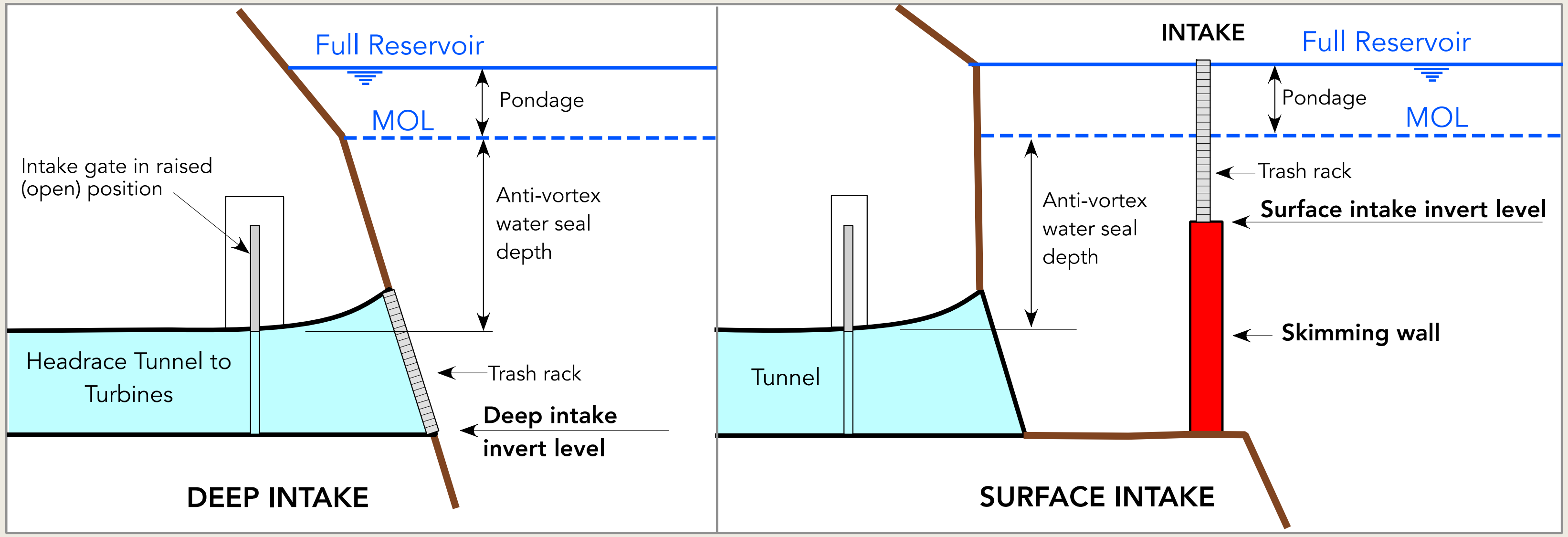




Site Visit Presentation 6, Slides 20 and 26

- The reservoir may be managed to reduce the sediment load reaching the location of the power intake.
- **Sediment Bypass**. One strategy for reducing the sediment load reaching the intake is to construct a bypass tunnel which passes excess flow and sediment around the within-reservoir headpond. This will reduce the hydraulic load on the headpond and increase its sedimentation efficiency.
- **Deep Reservoir**. Another strategy, and one which occurs by default in a storage reservoir until it fills with sediment, is to sustain a large and deep storage capacity to facilitate sedimentation.
- **Flushing**. Both of the above strategies depend on empty flushing to remove the sediment captured in the reservoir and maintain the storage volume.

Intake Configuration

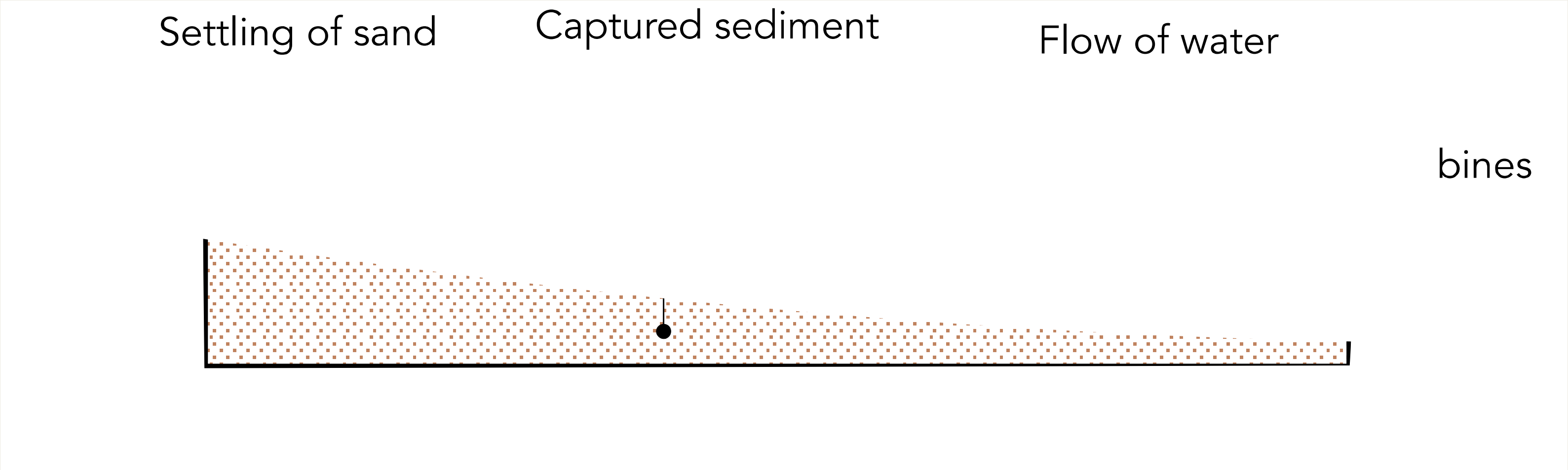


Site Visit Presentation 2, Slide 24

- The intake can be configured separately from the entrance to the headrace tunnel, which needs to have a certain depth to prevent objectionable vortexing.
- Intake design is normally supported by testing in scale physical models.

- Intakes divert water out of the river or reservoir.
- Suspended coarse sediment concentration tends to be highest near the bottom and lowest near the water surface.
- Run-of-River intakes are designed to withdraw water from near the top of the water column, to minimize the coarse sediment concentration.
- Surface intakes are also designed to minimize eddies that can lift sediment off the bottom. This is normally analyzed by physical modeling.
- Deep intakes are characteristic of storage reservoir where there is considerable depth between the intake and the sediment.

Sedimentation Basins (desanders)

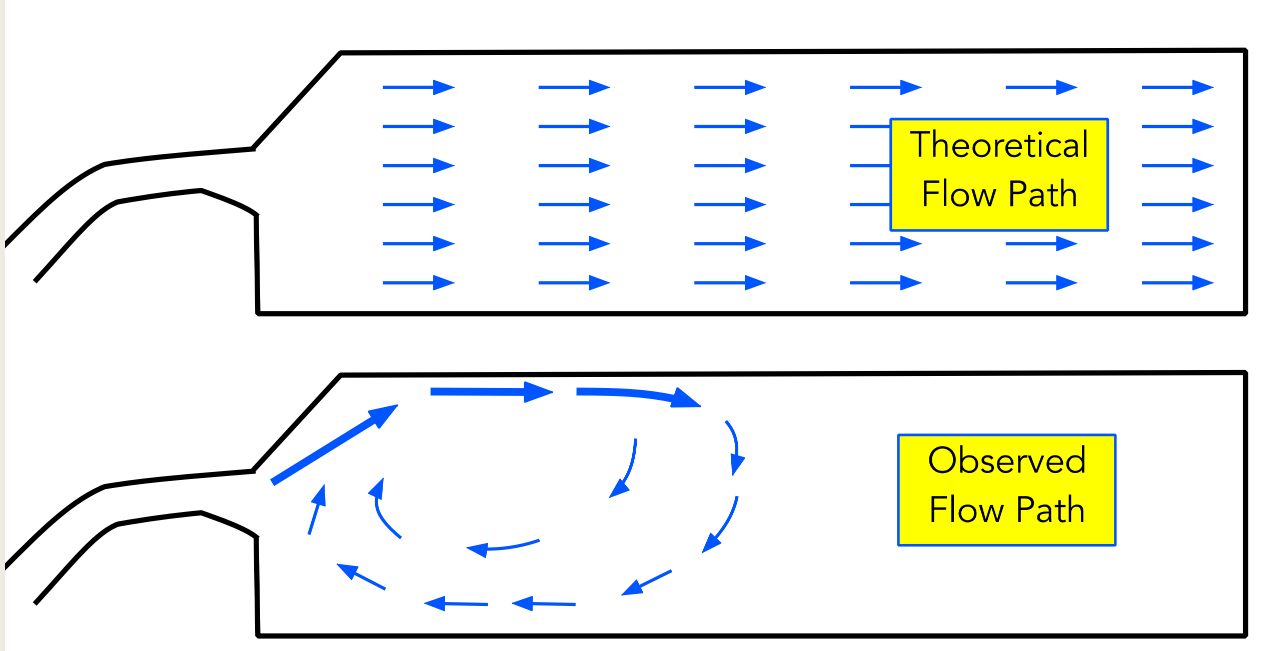


Pakistan's Memorial, Figure 10.2

- Desanders are an effective way to settle out highly abrasive coarse sediments before reaching the turbines.
- Desanders theoretically operate under conditions of uniform and parallel flow paths.
- Notable departures from idealized conditions commonly occur due to poor hydraulic design.
- Designs developed from empirical methods or model studies need to be confirmed and optimized once operational.

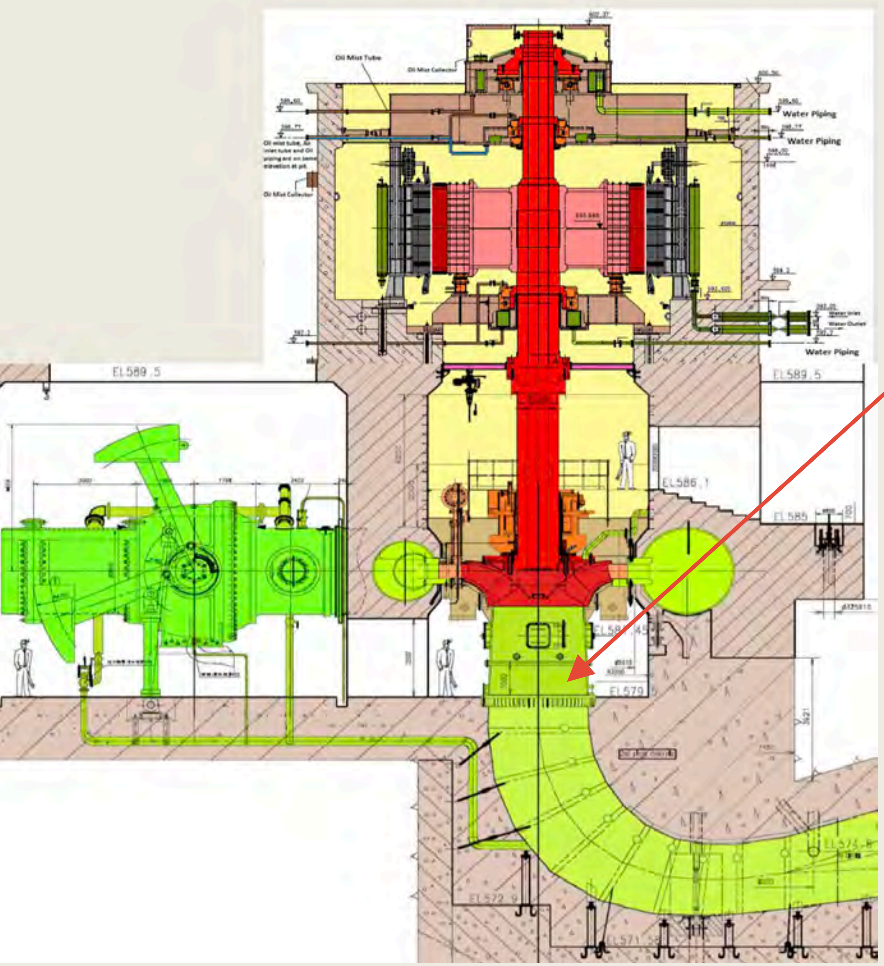
Sedimentation Basins or “Desanders”

Deficient design can result in poor hydraulic performance



- Sedimentation can remove much of the sand load, and should typically remove nearly100% of sands 0.15 mm or larger. Smaller silt particles (<0.062 mm) settle too slowly for effective removal.
- However, desanders frequently incorporate design deficiencies that lead to performance that departs significantly from the intended design condition.
- The following video clip shows a large circulating eddy at the entrance to this desander that is a radical departure from the theoretical flow path on which desander calculations are based.

Sediment Mitigation at the Powerhouse

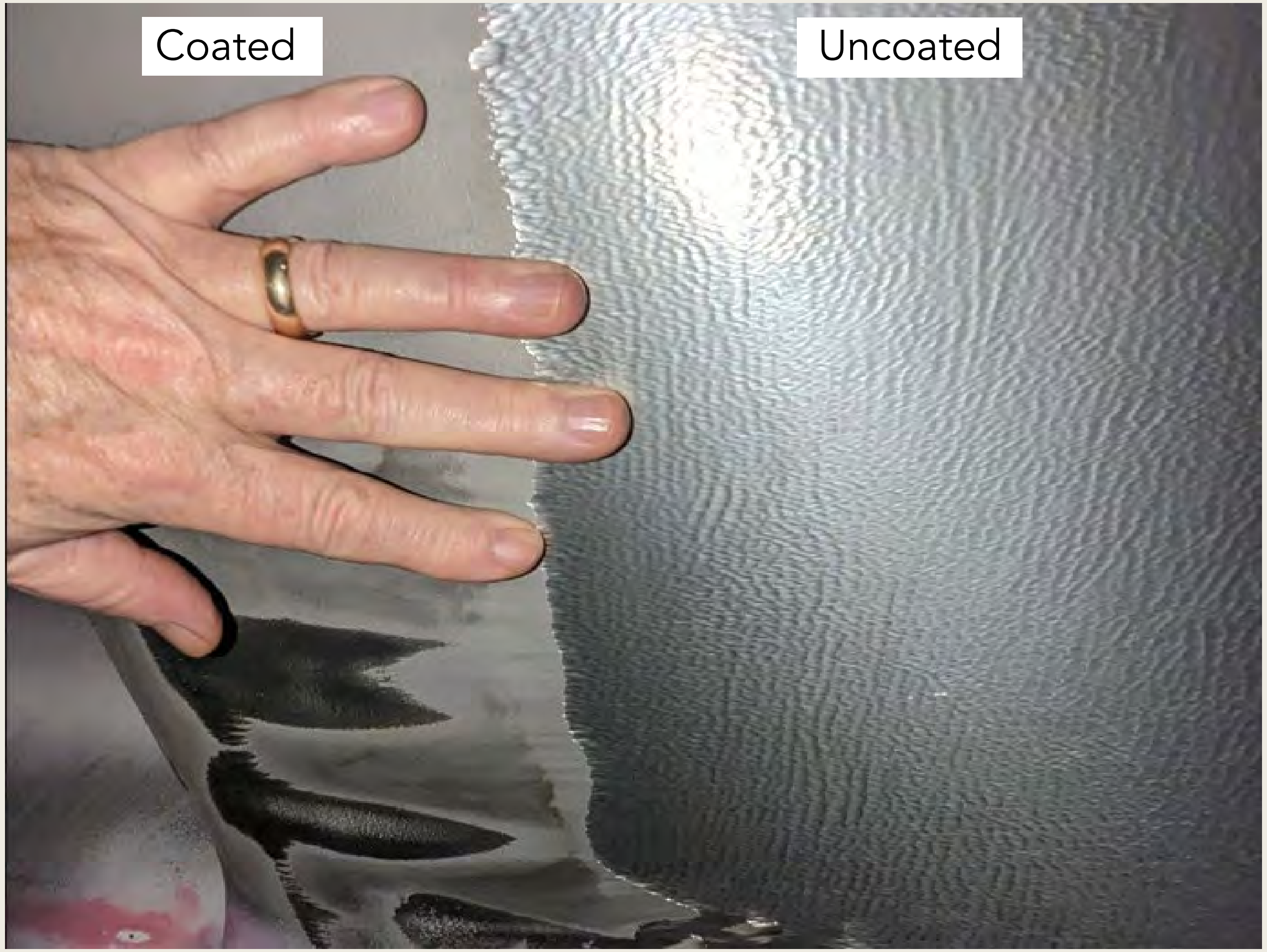


Pakistan's Memorial, Figure 4.6

Multiple sediment mitigation measures may be implemented in the Powerhouse, including:

- Configuration Provide bottom access for rapid removal of turbine for maintenance & repair.
  - For example, the configuration of the draft tube beneath the Neelum-Jehlum turbines allows bottom access. The Francis runner may be removed without removing the generator, which would be the conventional method of accessing the runner.
- Select lower-velocity turbine of more robust construction and less sensitive to sediment damage and which facilitates repair;
- Provide wider spacing between Francis turbine blades to facilitate repair and access by coating robot;
- Provide protective coating (eg. tungsten-carbide);
- Insert pressurized clean water into shaft seal
- Increase Francis turbine submergence to reduce cavitation (abrasion and cavitation are self-reinforcing);
- Avoid low-load operation of turbines.
- Use closed-circuit cooling for generators.

Turbine coatings



- The slide shows the application of a Tungsten carbide coating to a portion of a Francis turbine runner at NJHEP.
- Sacrificial coatings can protect the softer underlying stainless metals from abrasive erosion by small particles for a period of years.
- Effectiveness varies from one site to another.
- Runners can be re-coated at a cost of around USD 0.5 million

Site Visit Presentation 6, Slide 33

Sedimenft-Guided Operation

Regulate plant operation to minimize damage by sediment

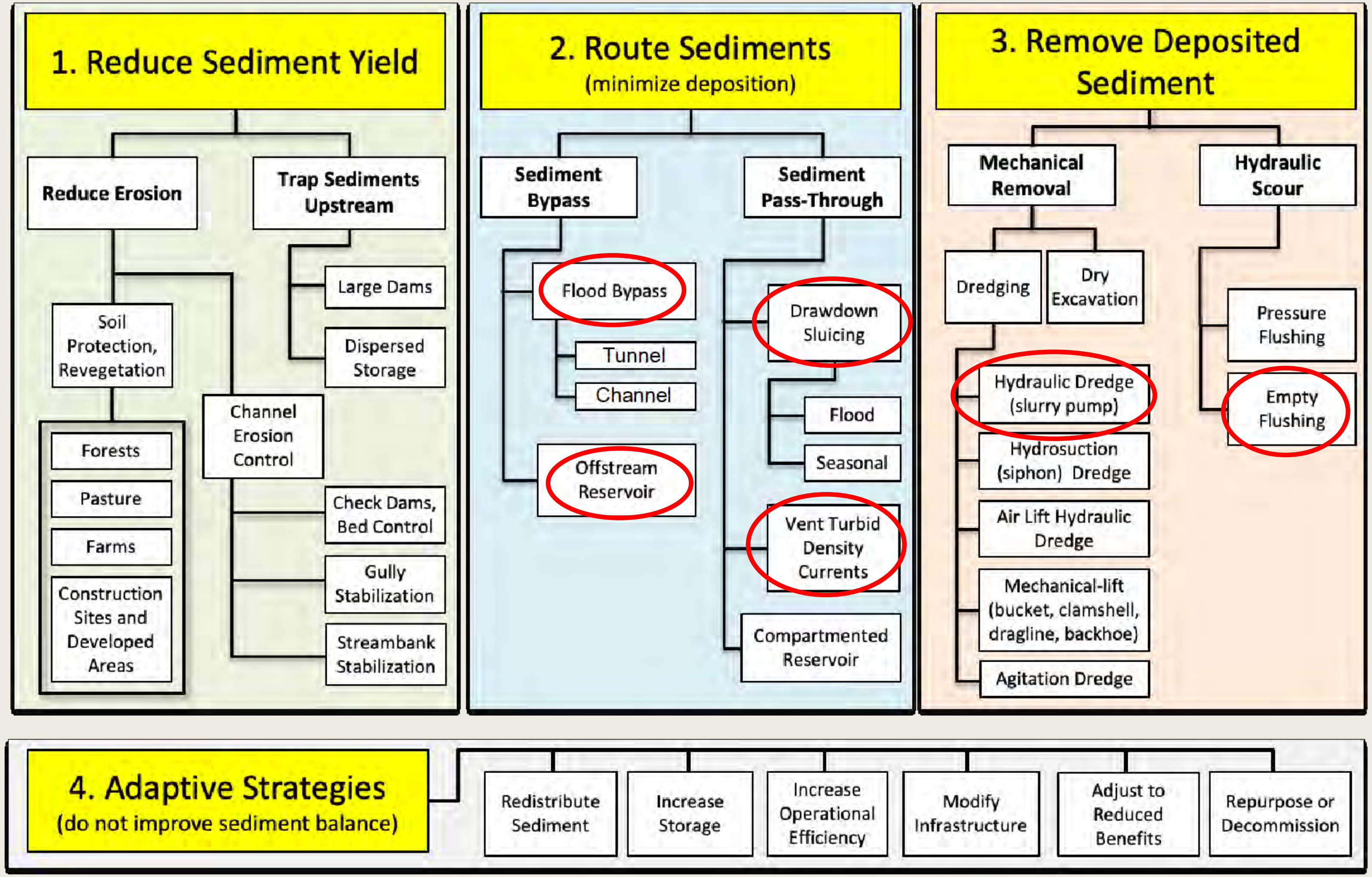
- The analysis of sediment loading on turbines typically reveals that only a few days per year comprise a large percentage of the annual load, and thus account for a large percent of the abrasion damage.
- We have seen this same pattern in Pakistan.
- Under a sediment-guided operating rule, the plant would be shut down on these days of extremely high sediment concentration.
- Alternatively, the plant could be operated at partial capacity, thus reducing the hydraulic load on the desanders and increasing their sediment removal efficiency.
- This operation requires real-time data on sediment concentration at the intake.

Runners are Expendable

- Additional runner repair & replacement costs must be anticipated when operating in a high-sediment environment.
- The most abrasion-prone components, runners and guide vane blades, comprise about 0.5% of the cost of a hydropower plant. By comparison, the cost of tires on an automobile comprise about 2% of its total cost.
- Significant abrasion does not necessarily prevent runners from producing energy.
- During the monsoon, when most energy is produced, the loss in runner efficiency can be compensated by increasing the flow rate.
- High-head plants are much more sensitive to sediment that low-head plants.

MANAGEMENT OPTIONS TO PRESERVE STORAGE CAPACITY

Sediment Management Strategies



- Optimal strategies will vary from one location to another.
- Most locations will incorporate a combination of strategies, employed either conjunctively or sequentially.

Pakistan's. Memorial, Figure 4.2.8. G.L Morris. 2020. "Classification of Management Alternatives to Combat Reservoir Sedimentation." *Water*, 12 (3): 861. https://doi.org/10.3390/w12030861.

Sediment Management Strategies May be Grouped into 4 Major Classes

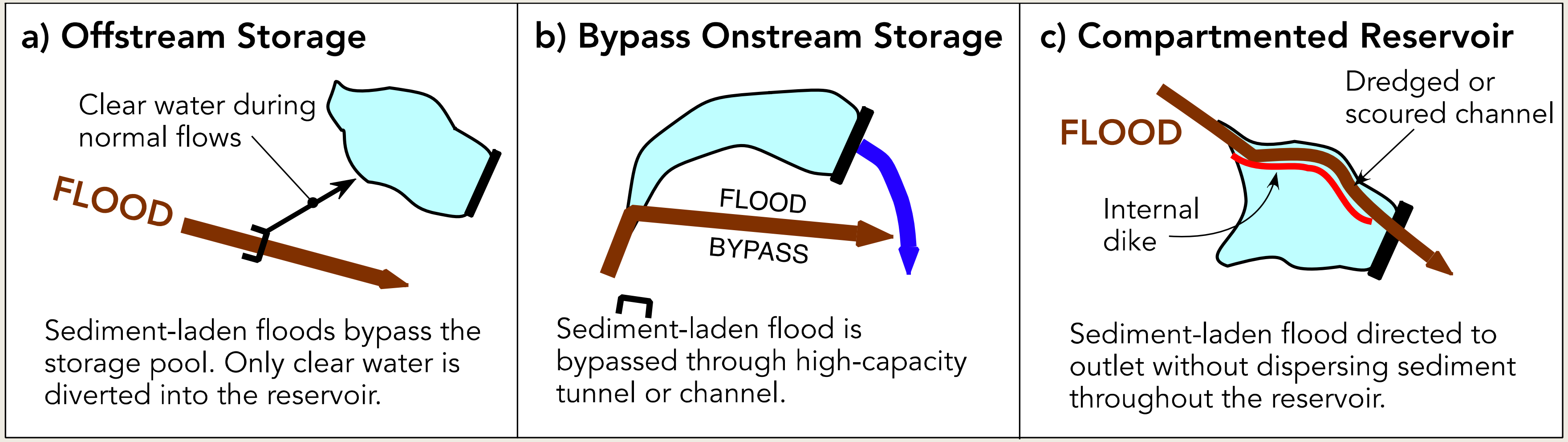
- Reduce sediment yield entering the reservoir from upstream (erosion control, build upstream dams).
- Route sediments by diverting flood-borne sediments around or through the storage pool (drawdown sluicing, sediment bypass tunnel, offstream reservoir, vent turbidity currents)
- Remove deposited sediments by hydraulic flushing or mechanical dredging.
- Adapt to sedimentation by implementing strategies that offset the benefits lost by sedimentation, separate from actions that modify the sediment balance (construct desander, protective turbine coatings, selection of sediment-resistant turbine design, modify intakes, sediment-guided power operations, design plant to facilitate rapid runner replacement, appropriate design of generator cooling system).

1 - Watershed Management

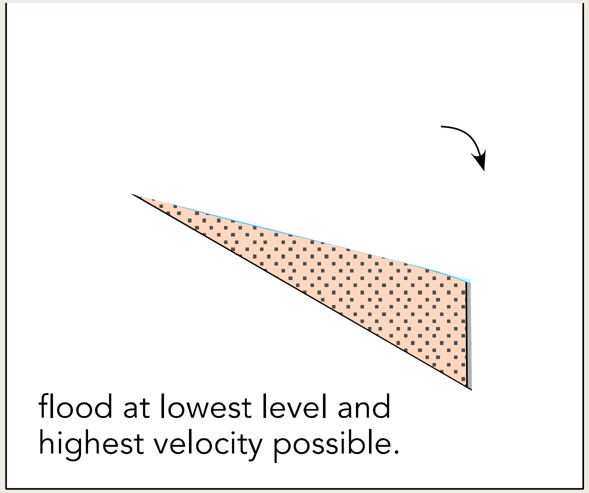
- Watershed management in higher Himalaya has limited potential to reduce loads due to high natural background erosion rates and soils that naturally lack vegetation due to adverse climate.
- Watershed management activities can reduce sediment yield at lower elevations where vegetative cover can exert significant control.
- The construction of additional upstream dams can effectively reduce the sediment yield downstream, until the upstream dam either fills with sediment or begins to be operated to pass sediment downstream.
- Small check dams will have only limited effectiveness due to their lack of capacity and propensity to fail over time, unless they are used to help re-establish vegetation.
- Given the high background level of Himalayan sediment yield, watershed management can represent a partial solution, but will never provide full control of its own.

2 – Sediment Routing Techniques

Sediment Bypass

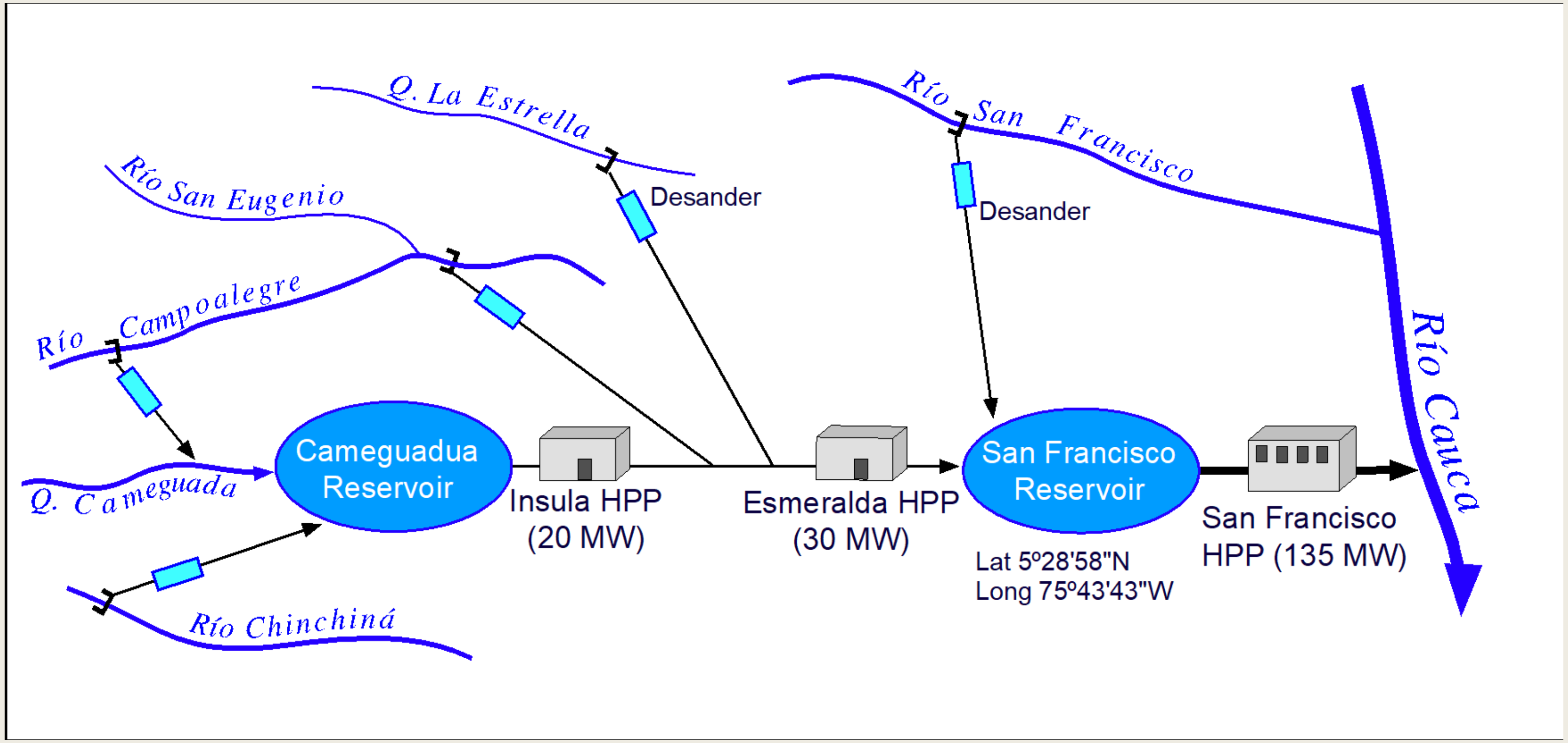


Sediment Pass-through



Off-channel Storage

Off-channel storage may be gravity-fed or pumped storage



Cascade of 2 gravity-fed off-channel pondage reservoirs in Colombia; *Site Visit Presentation 6, Slide 22*

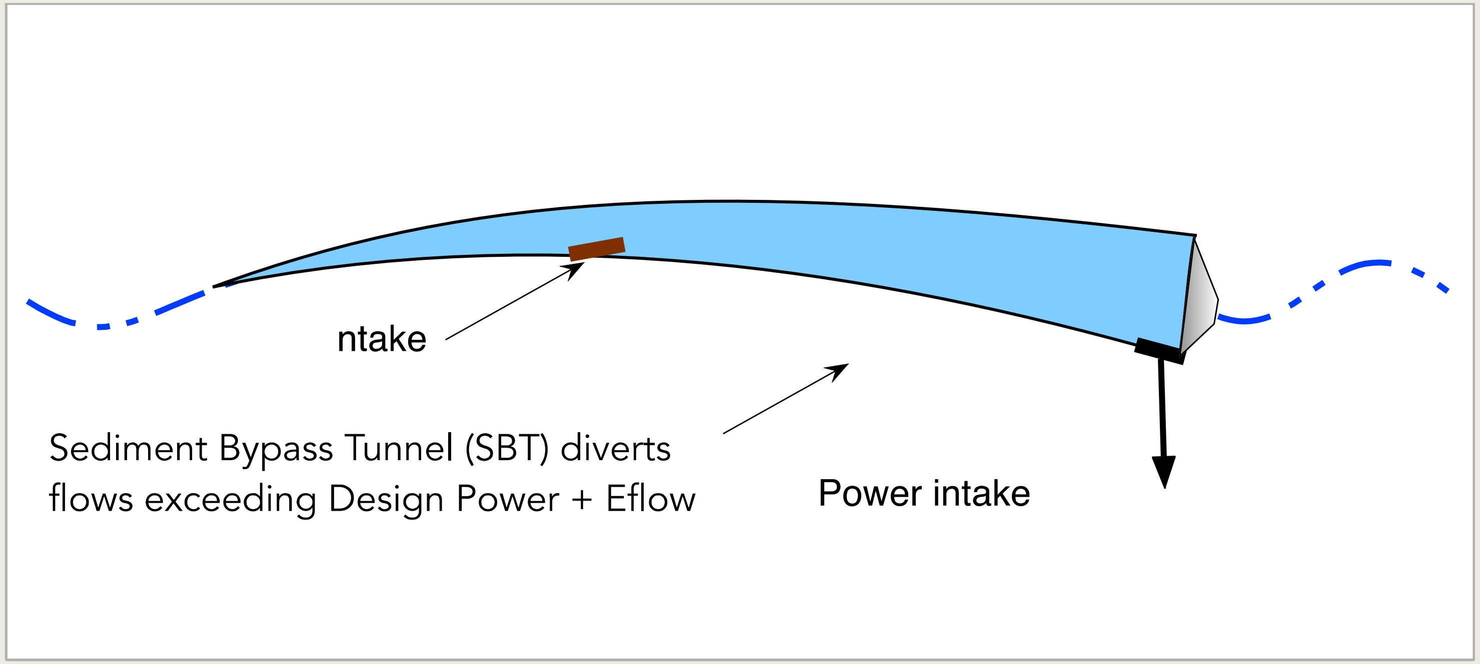
- Reservoir is placed outside the main river and is fed by one or more intakes.
- Water with low sediment concentration is passed into the reservoir.
- Sediment-laden floods run downstream along the river channel.

Examples of Off-channel HEP Storage

- The photo shows an example of off-channel pondage in the Chilean Andes.
- Although opportunities for off-channel pondage in mountain environments are rare, they do exist.
- In Pakistan the Ghazi Barotha plant (1450 MW), downstream of Tarbela, incorporates off-channel pondage.

Tinguiririca, Chile; Site Visit Presentation 6, Slide 23

Sediment Bypass Tunnel (SBT)



Pakistan's Memorial, Figure 10.8

- Bypass tunnel (or channel) passes sediment-laden flows around pondage storage.
- Can bypass suspended load or bed load, depending on the design selected.
- To remove sediment from the sedimentation headpond may depend on empty flushing.

Sediment Bypass Tunnel Examples

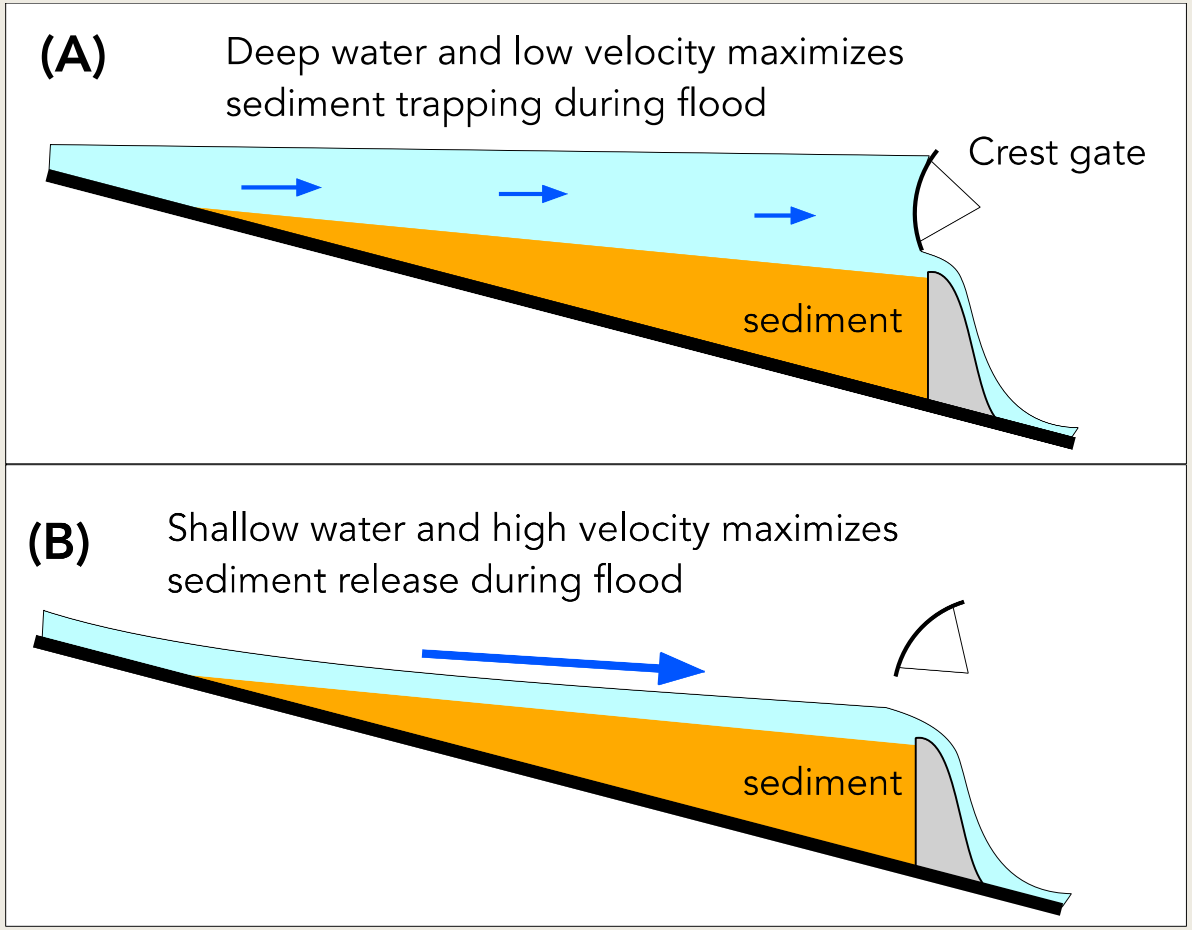
Asahi dam, Japan; Site Visit Presentation 6, Slide 21

Diversion cofferdam (submerged when reservoir full), and bypass tunnel entrance on the right.

- The photo shows the inlet to the bypass
- Although sediment bypass tunnels have been in use for over 100 years, they have been used only infrequently.
- Bypass tunnels are now being given increased attention for both new project design as well as for mitigation of sediment problems at existing plants.
- In Pakistan, the Patrind HEP (147 MW) incorporated a sediment bypass tunnel in its original design.

Drawdown Sluicing

Pass sediment-laden floods through the reservoir at high velocity to minimize sedimentation



Site Visit Presentation 6, Slide 17

- The overall concept is to lower the reservoir to create high-velocity flow which will not deposit sediment.
- Two strategy types are available:
  - **Flood sluicing:** pool drawdown to pass sediment during major floods.
  - **Seasonal sluicing**: pool drawdown to pass sediment during monsoon season.
- Due to hydrology, seasonal sluicing is generally more appropriate strategy for Himalayan HEPs.

Sediment Routing by Sluicing

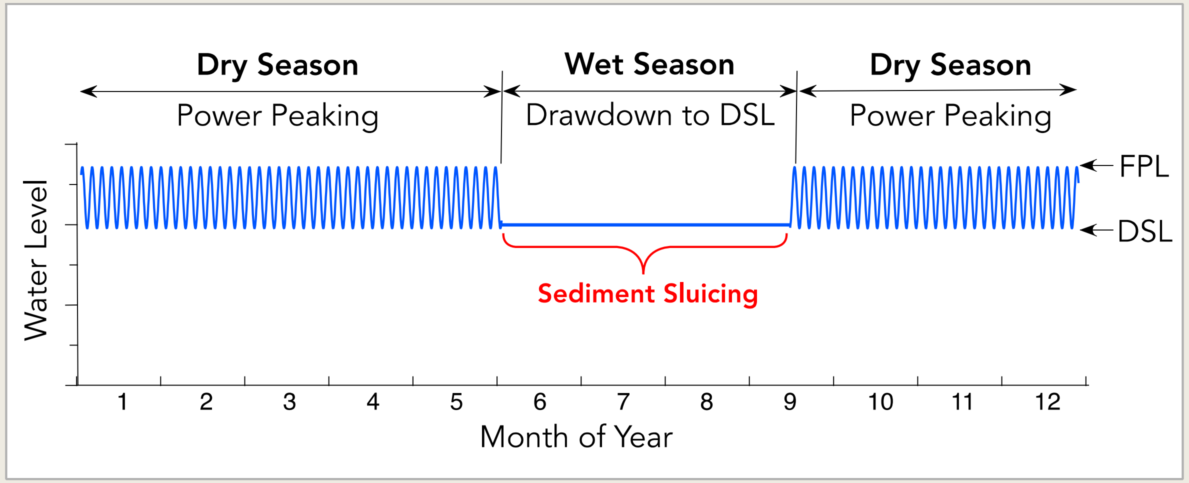
CONCEPT

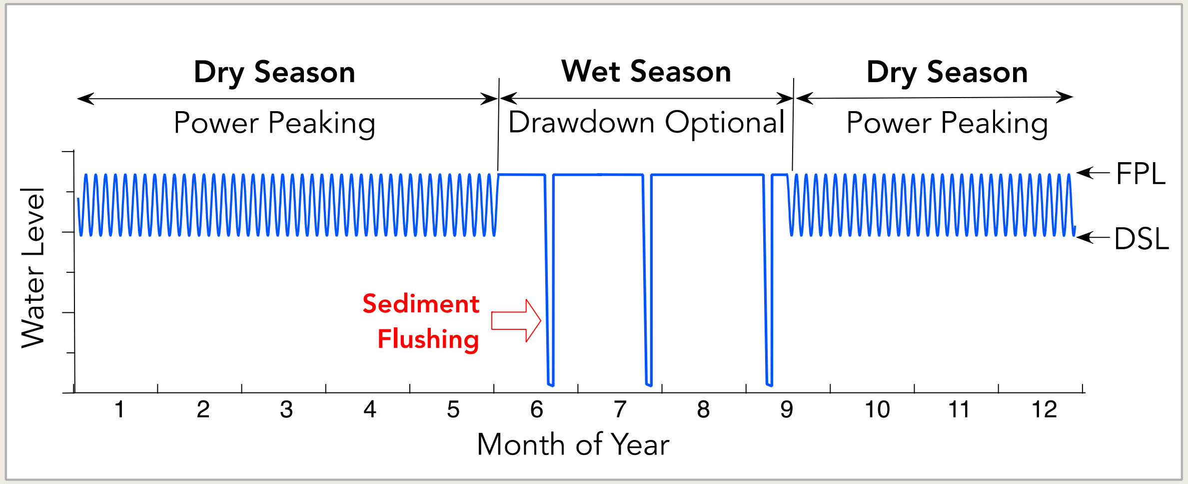
- Operating pool is emptied during floods, maintaining natural sediment flow along the river and minimizing sediment deposition in the reservoir.
- Pass sediment-laden floods through the reservoir at the highest possible velocity to minimize sediment trapping.
- Prior deposits may be scoured, but emphasis is on sustaining sediment transport, preventing deposition.

PROCEDURE (monsoon hydrology)

- Gated opened to lower reservoir to Minimum Operating Level during wet season
- Floods are passed through reservoir with level held at MOL
- At end of flood season, gates are closed to fill pondage and enable power peaking operation.

SLUICING vs. FLUSHING





Capacity Preservation by Sluicing

ADVANTAGES

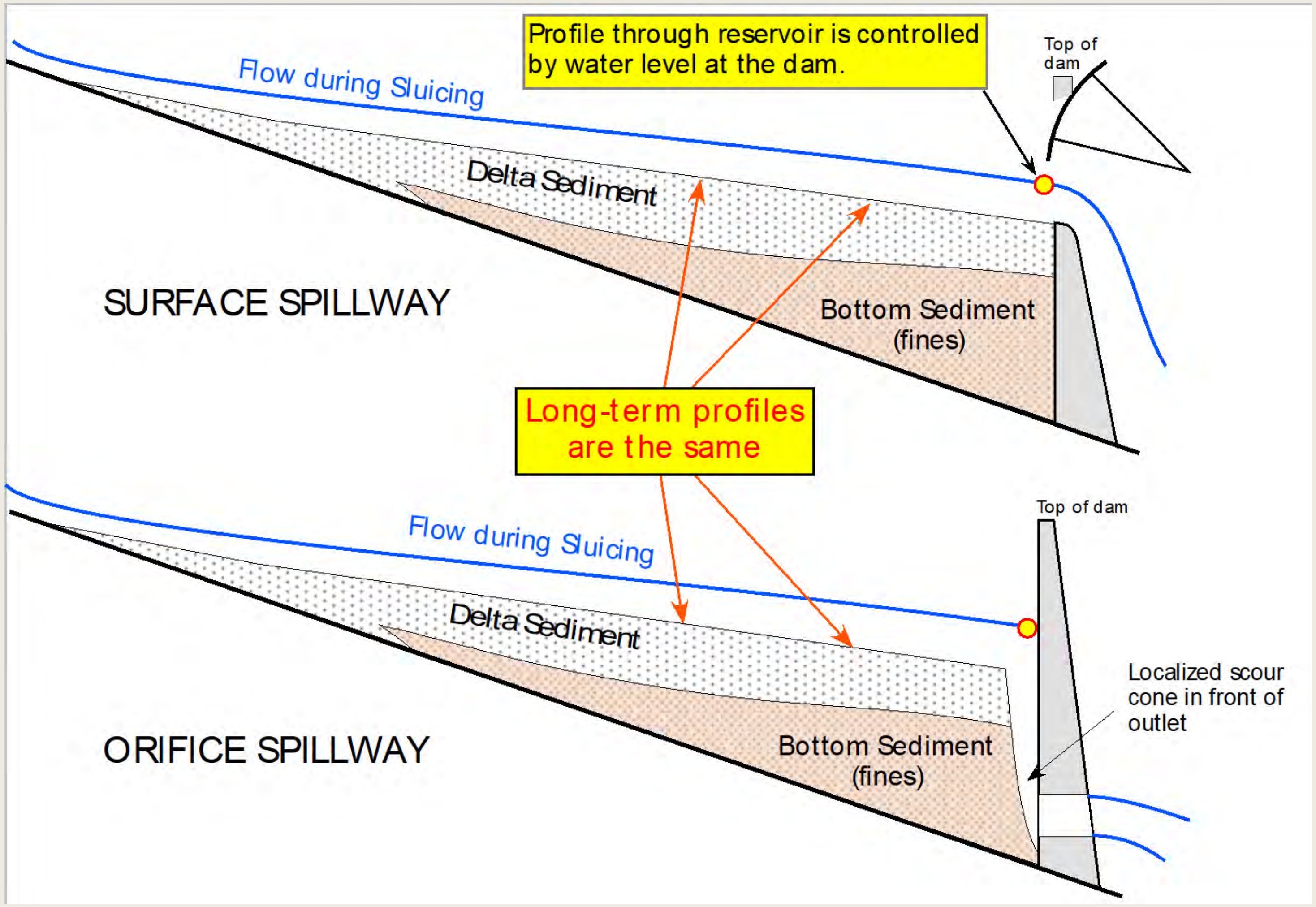
- Power plant can remain in operation, subject to sediment-guided operation.
- Sediment released over time minimizing high downstream concentrations.
- High flows maximize width of scour channel in the reservoir.
- Because operational pool remains empty, sediment deposition outside of the delta area is largely avoided.

DISADVANTAGES

- Seasonal sluicing requires desander (increased capital cost).
- Increased turbine repair costs.

Outlet Placement and Sediment Profiles

Sediment profiles are determined by water level at the dam during floods, not by the location of the outlet.

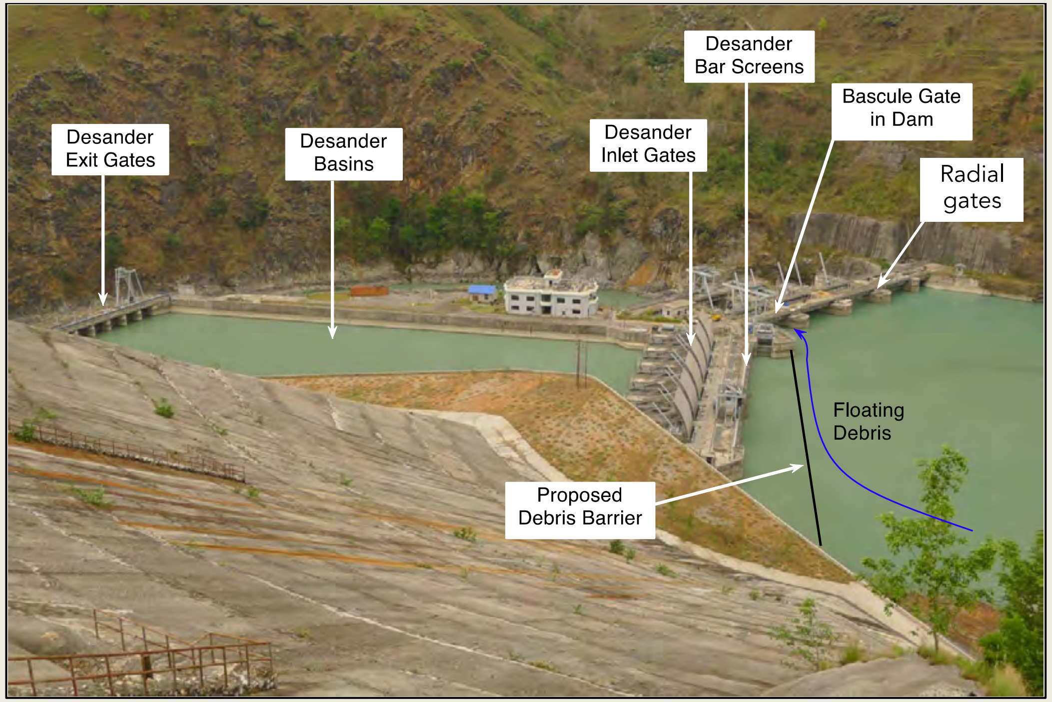


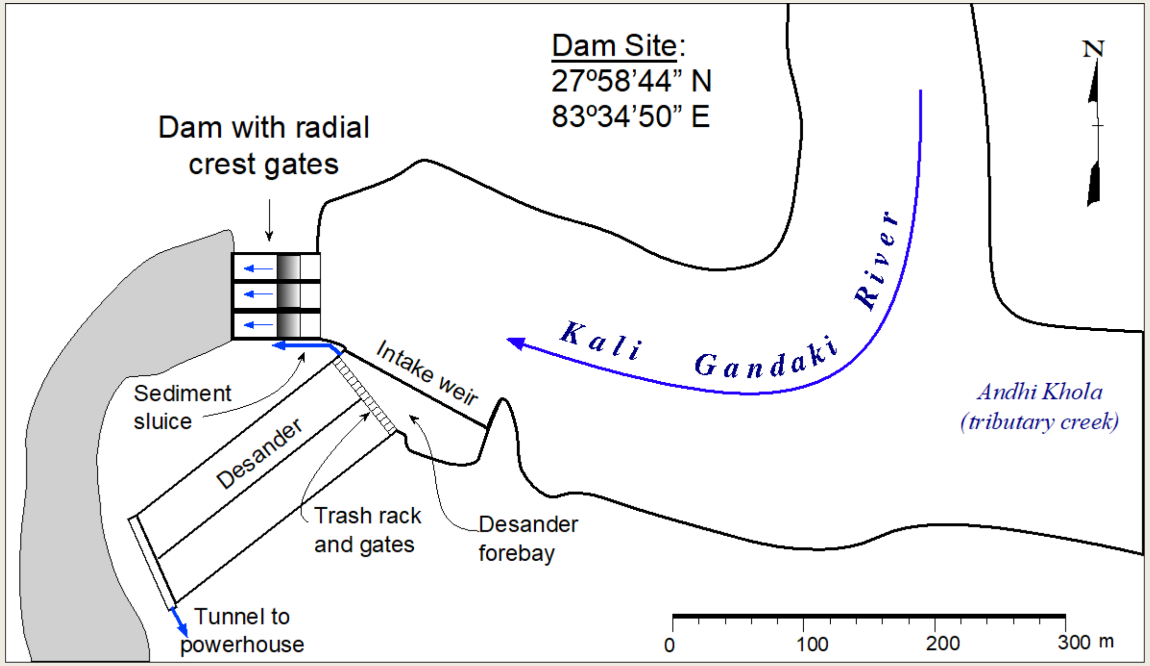
Site Visit Presentation 6, Slide 13

- Water level at the dam during floods is a key factor determining the sediment profile along the length of a reservoir.
- Changing outlet depth will not change the profile if the water level at the dam remains constant.
- A low-level outlet will create a localized scour cone at the upstream side of the outlet.

Seasonal Flushing Example

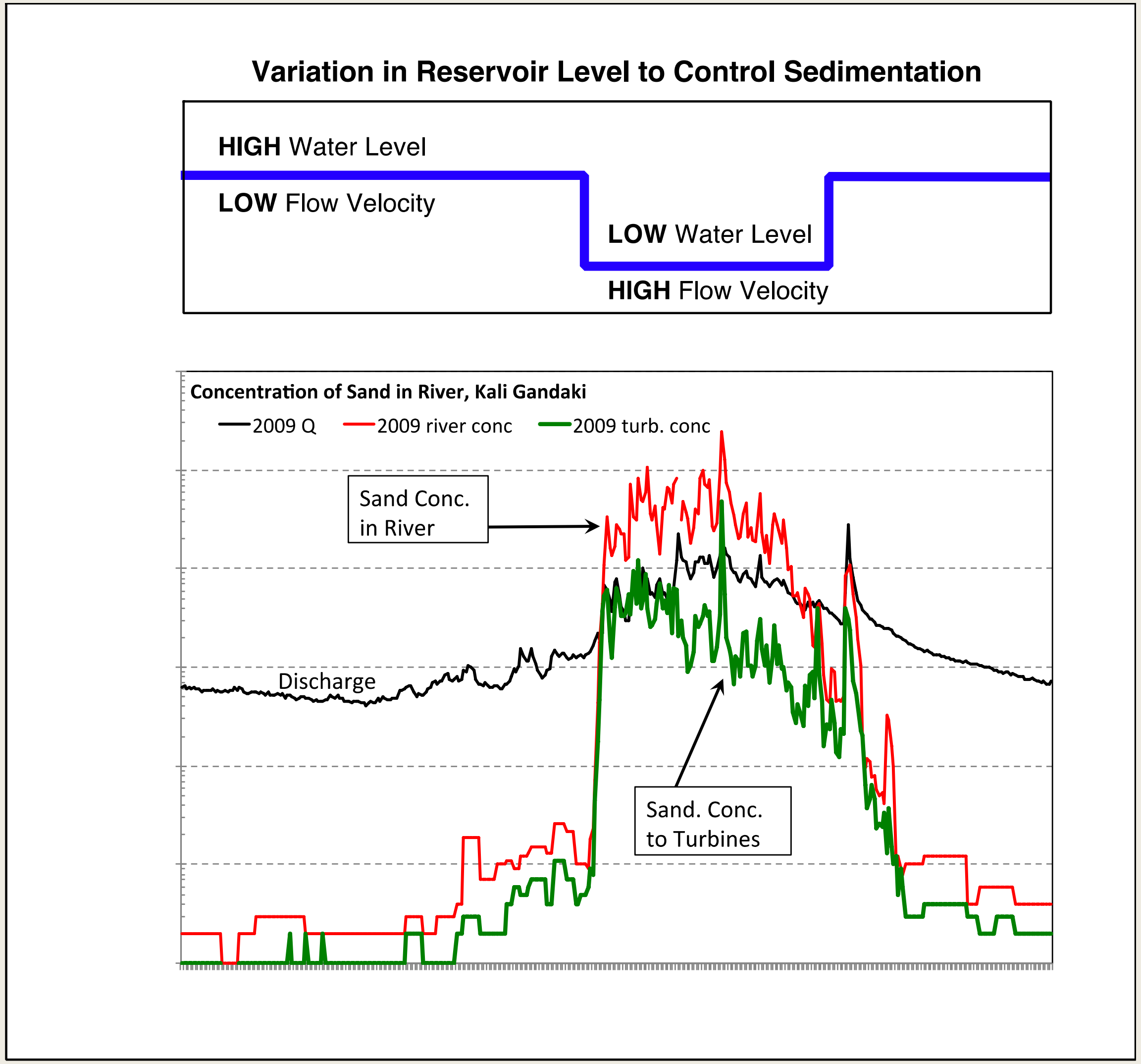
Kali Gandaki, Nepal (144 MW)





- Run-of-River plant with heavy load, operating despite turbine abrasion.
- World Bank financed hydraulic improvements to the intake and desander to reduce abrasion damage to turbines.

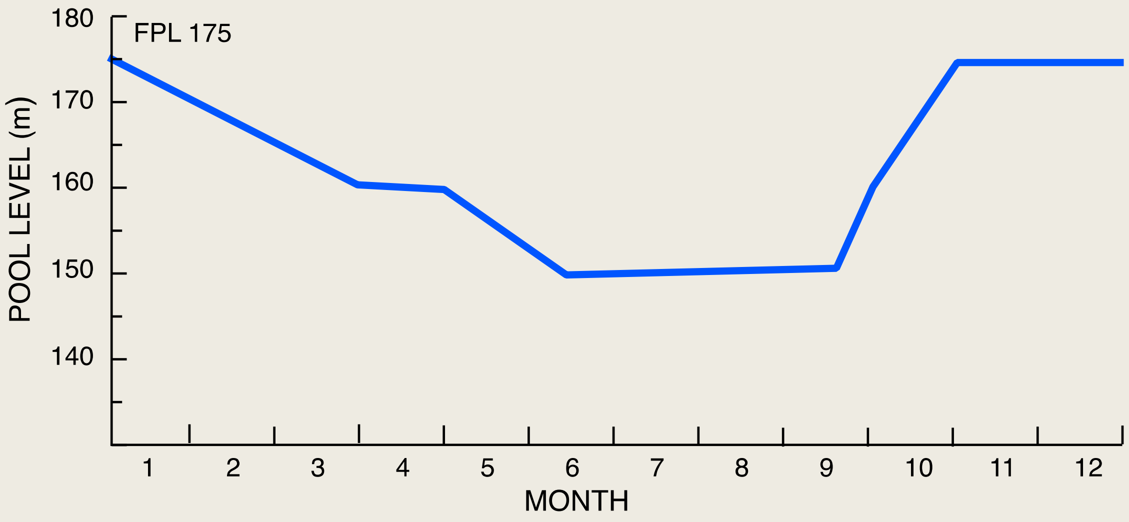
Seasonal Operational Cycle



- Annual sediment load 43 Mt/yr, of which about 25% is sand.
- Pondage ~3.5 Mm^3
- Project operating since 2002
- Reservoir operated in drawdown mode during monsoon to maximize flow velocity and transport sediment.
- Without drawdown, this reservoir could fill with sand in a single monsoon season.

Example of Seasonal Sluicing:

Three Gorges Dam, Yangtze River, China



Optimized operational levels at Three Gorges
Redrawn from Ren et.al. (2021)

- 22,500 MW installed capacity
- Sediment load 405 Mt/year (avg. conc. 940 mg/l)
- 39.3 Bm^3 capacity, 660 km reservoir length
- Regulating rule to pass sediment downstream by reservoir drawdown sustaining pool at or near minimum flood control level.
- Sustains continuous power production.
- Drawdown also used to evacuate pool capacity for flood control and to provide navigational releases.
- Limited dredging occurs upstream to maintain navigation in the delta area.
- Original project design foresaw stabilized capacity in approximately 100 years.

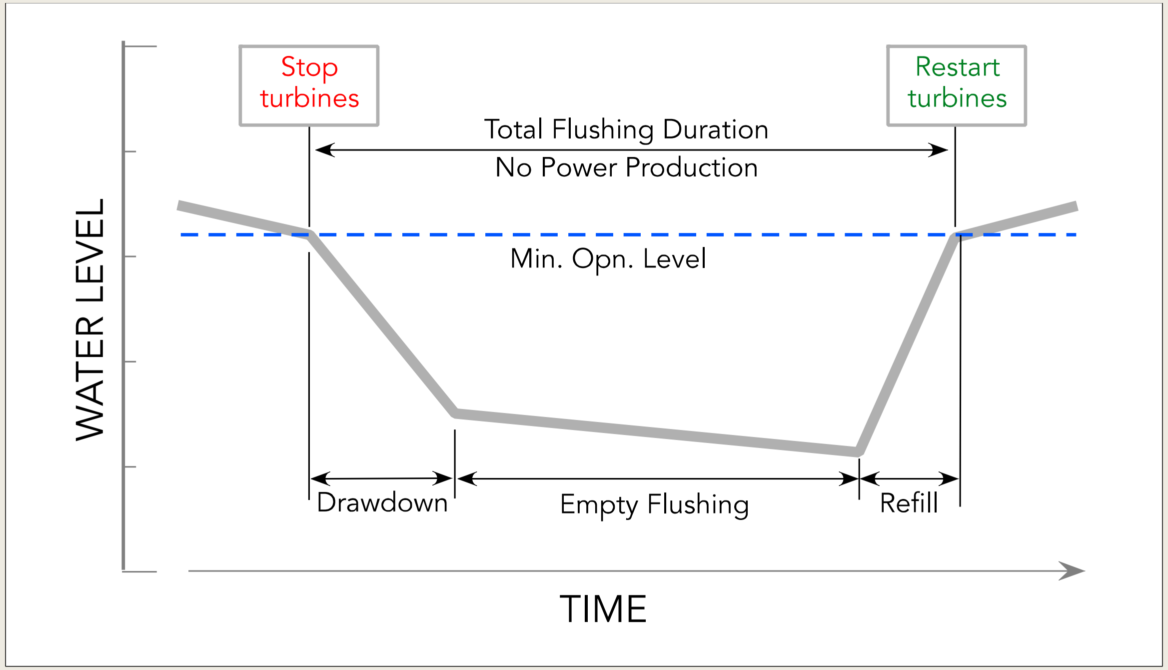
Sediment Removal by Flushing

CONCEPT

- Empty reservoir to scoured and flush sediment deposits downstream over a short period of time.

PROCEDURE

- Inform agencies & downstream users (power plants, water supply intakes, etc.) of pending sediment release operation.
- Deploy monitoring and mitigation team.
- Shut down power plant.
- Open Low Level Outlet (LLO) to lower reservoir at proscribed rate.
- Reservoir remains at flushing level for proscribed duration.
- Close LLO to refill reservoir to minimum operating level.
- Restart power plant.

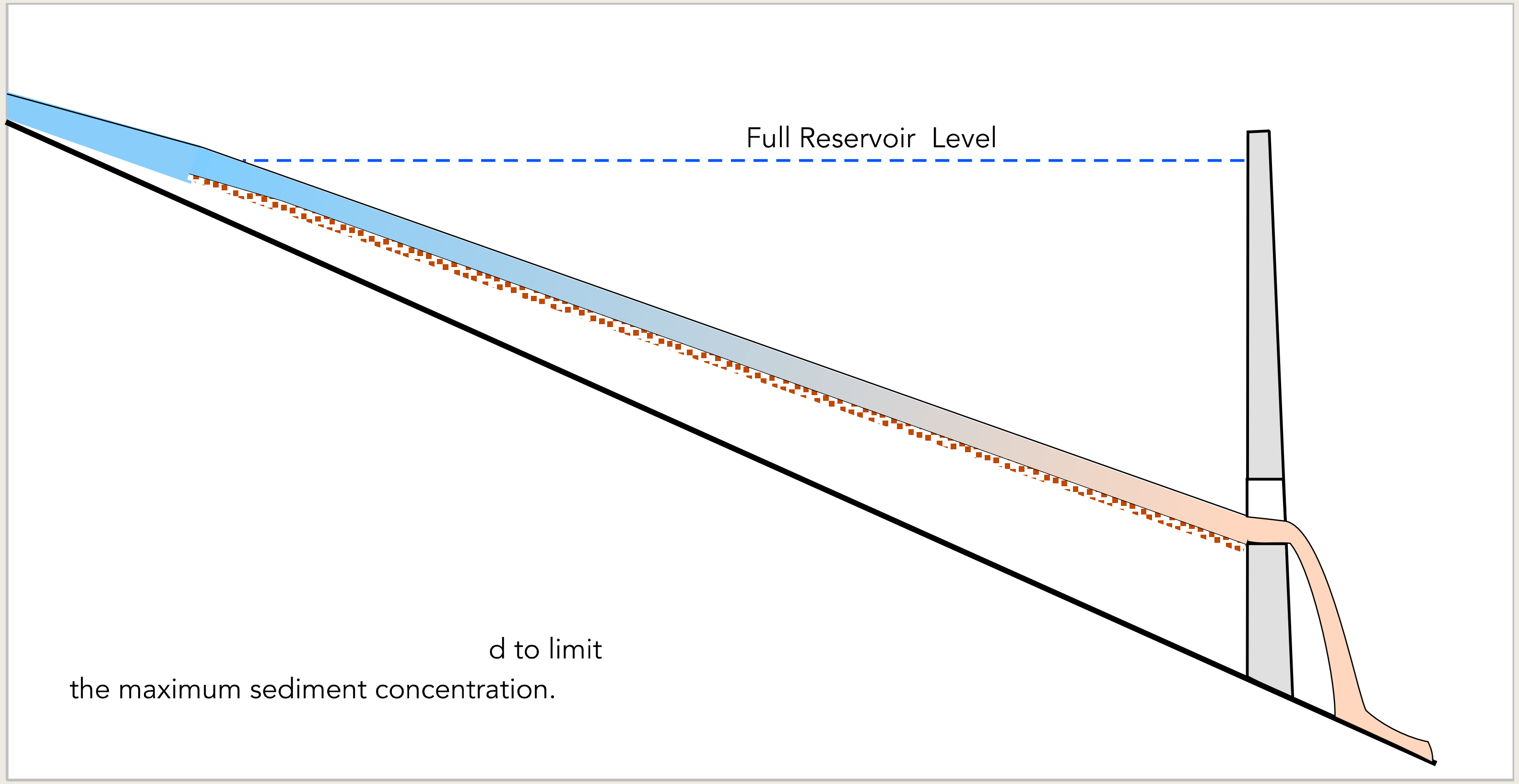


DRAWDOWN RATE:

- May be limited by dam/geologic stability considerations.
- May be limited to control the rate of scour and maximum downstream concentrations (e.g. filter plant intake
- Both of these will increase the total flushing duration.

Empty Flushing

Empty the reservoir to allow sediments to be scoured by river



Site Visit Presentation 6, Slide 26

- Empty flushing empties the reservoir to allow the river to scour the sediment deposits.
- Flushing often has significant downstream environmental impact due to high sediment concentrations (>100,000 mg/l).
- Max. concentration and downstream impacts can be minimized by reducing the drawdown rate (which prolongs flushing duration).

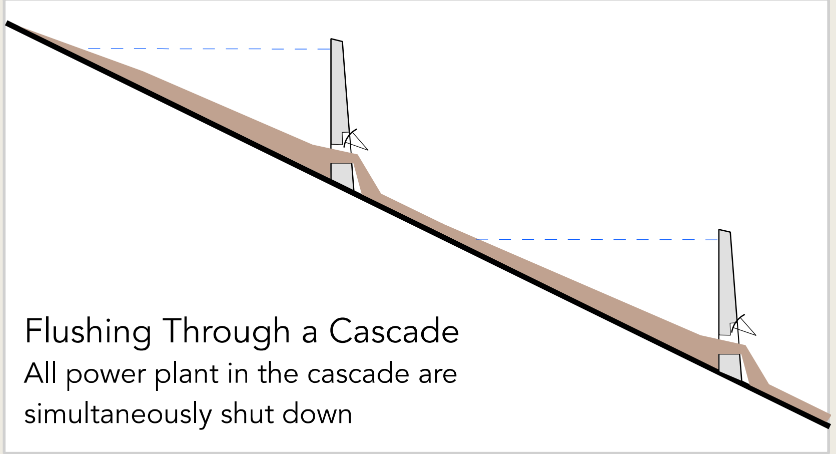
Capacity Preservation by Flushing

ADVANTAGES

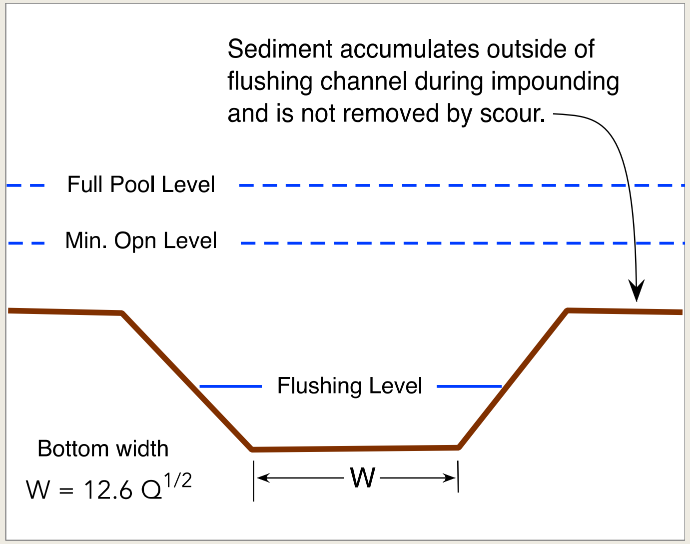
- Can sustain a deep zone near the dam, trapping sediment in reservoir in lieu of using a desander.
- Releases from upstream dams can be used to flush downstream dams.

DISADVANTAGES

- Requires shutdown of power plant in wet season when plant would run at full power, reducing income.
- Can require shutdown of entire cascade, impairing power availability.
- Width of flushing channel is limited.
- Entire year of sediment load is concentrated into a few days, producing extremely high downstream concentrations (>100,000 mg/l) affecting users and environment below the dam. (Many jurisdictions essentially prohibit flushing due to downstream impacts). U.S. Army Corps of Engineers considers flushing a form of "dredging" which requires a permit, whereas sluicing

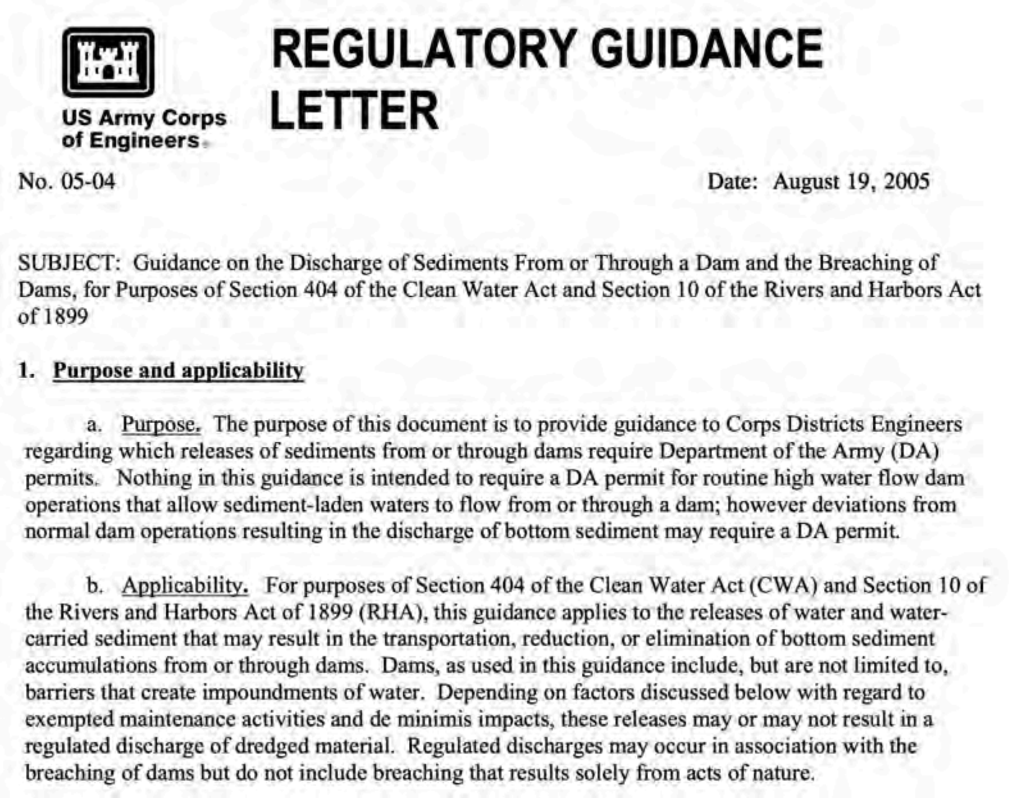


Flushing Through a Cascade
All power plant in the cascade are simultaneously shut down



Regulatory Issues Impacting Flushing

- A prohibition against flushing is actually not an unusual condition, and it is essentially prohibited in many jurisdictions due to the impact of concentrated sediment releases to:
    - Downstream infrastructure such as water supply intakes;
    - Downstream channels, including flood control and navigational channels, and downstream dams, due to sediment deposition;
    - Aquatic ecosystems due to habitat impairment (filling of stream pools, smothering spawning gravel), direct mortality and heightened stress to aquatic organisms; and
    - A wide range of recreational uses.
- For example, the U.S. Army Corps of Engineers considers flushing to be equivalent to "dredging" and thus requires a U.S. Army permit (which characteristically involves a range of both federal and state agencies to sign off, in addition to public review).
- In contrast, and Army permit is not required for "*sluicing structures that mimic the natural increase and decrease of sediment in a stream (i.e., the amount of sediment discharging from or through a structure is comparable to the amount of material entering the reservoir from upstream)*"



US Army Corps of Engineers

REGULATORY GUIDANCE LETTER

No. 05-04 Date: August 19, 2005

SUBJECT: Guidance on the Discharge of Sediments From or Through a Dam and the Breaching of Dams, for Purposes of Section 404 of the Clean Water Act and Section 10 of the Rivers and Harbors Act of 1899

1. **Purpose and applicability**

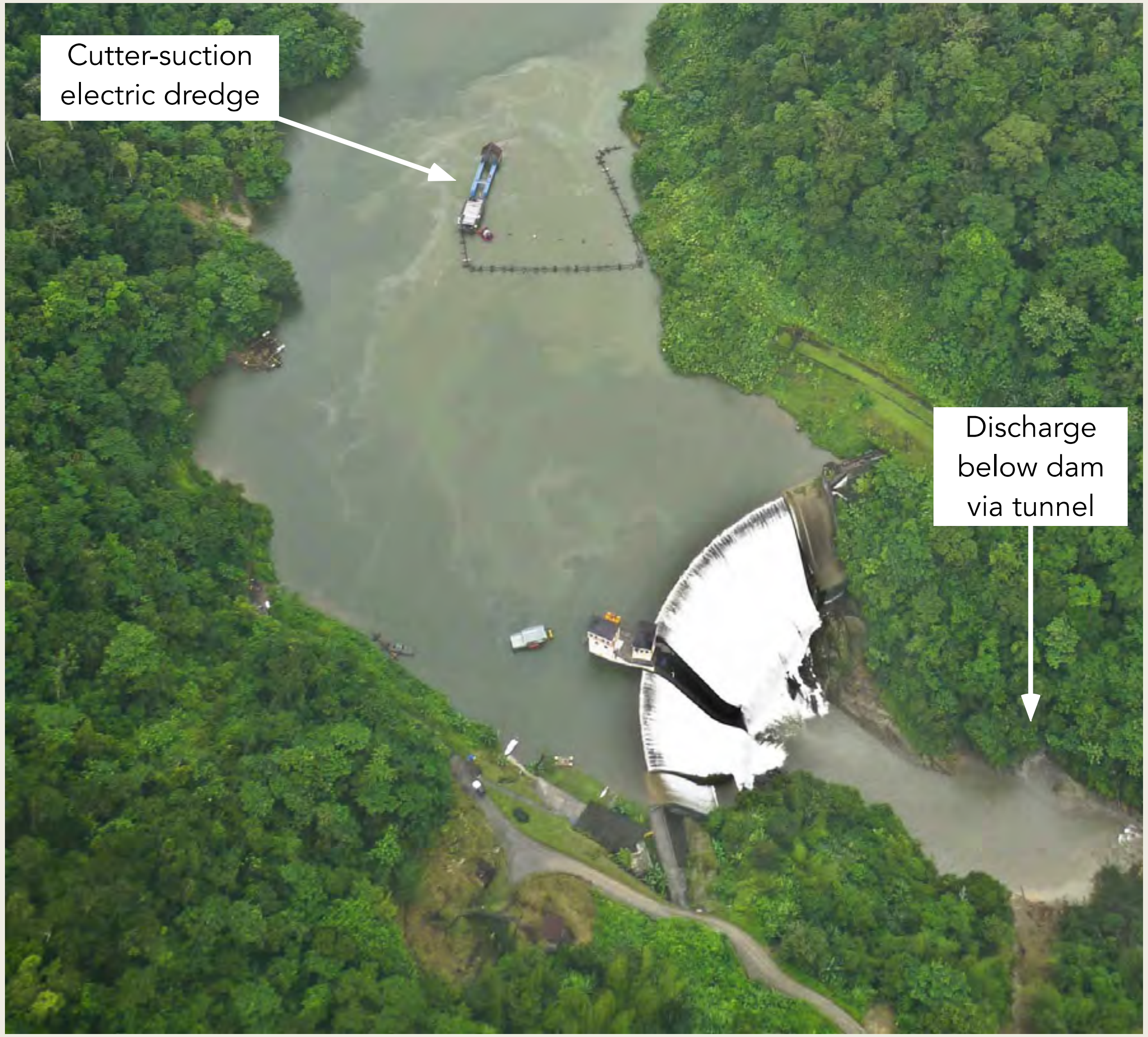
a. Purpose. The purpose of this document is to provide guidance to Corps Districts Engineers regarding which releases of sediments from or through dams require Department of the Army (DA) permits. Nothing in this guidance is intended to require a DA permit for routine high water flow dam operations that allow sediment-laden waters to flow from or through a dam; however deviations from normal dam operations resulting in the discharge of bottom sediment may require a DA permit.

b. Applicability. For purposes of Section 404 of the Clean Water Act (CWA) and Section 10 of the Rivers and Harbors Act of 1899 (RHA), this guidance applies to the releases of water and water-carried sediment that may result in the transportation, reduction, or elimination of bottom sediment accumulations from or through dams. Dams, as used in this guidance include, but are not limited to, barriers that create impoundments of water. Depending on factors discussed below with regard to exempted maintenance activities and de minimis impacts, these releases may or may not result in a regulated discharge of dredged material. Regulated discharges may occur in association with the breaching of dams but do not include breaching that results solely from acts of nature.

United States Army Corps of Engineers, "Regulatory Guidance Letter", **P-0612**

Sediment Removal by Dredging

Example, Bajo Anchicayá, Colombia (74 MW)



Site Visit Presentation 6, Slide 28

- The Bajo Anchicayá hydropower reservoir in Colombia has been dredged continuously since the 1960s.
- Dredging continues to be used at this site due to complicated downstream social issues, lawsuits and governmental restrictions that resulted from downstream impacts (both real and alleged) from an emptying & flushing event.
- The ability of dredging to maintain a power plant in continuous production is an important consideration.

Dredging – Sluicing - Flushing

Accounting for the cost of lost power and sediment release

- Taking a power plant out of production entails the high cost of foregone power production.
- It can also present costly problems with respect to dispatch availability and PPA contractual obligations.
- Planning, monitoring and reporting requirements can also represent significant costs, especially for flushing due to downstream impacts.
- These costs can heavily influence the selection of sediment management measures.

- **Dredging** does not require interruption of power production.
- **Sluicing** at minimum operating level has a power cost in terms of reduced head, but does not require plant shut-down.
- **Flushing** requires shutdown for reservoir emptying, for the duration of drawdown, flushing, and refill back to MOL.
- Drawdown rates can be quite slow for earthen dams or concrete dams with slope stability limitations on reservoir side slopes, which will further extend flushing duration.

Selection of Sediment Management Strategy

Depends on local conditions

PHYSICAL FACTORS

- Site hydrology
- Sediment load & characteristics
- Allowable drawdown rate (flushing duration)
- Plant head and turbine type

SOCIO-ECONOMIC FACTORS

- Legal/regulatory framework (especially relevant to empty flushing)
- Sensitivity of downstream environment (river slope, ecological richness, threatened species, spawning beds, etc.)
- Social sensitivity to sediment
- Impacts to downstream infrastructure (intakes, canals, etc.)
- Cost of lost power

Several Considerations on Climate Change

- The Treaty did not allocate water, rather, it allocated watersheds. The water generated by Eastern watersheds was given to India, and the water of the Western watersheds to Pakistan. This apportionment cannot logically be altered due to climate change.
- Climate impacts will be similar in both jurisdictions, and both can expect to experience increased water demand due to hotter weather, especially for irrigation.
- An increase in overall sediment yield, if it occurs, will not materially change sediment management since management systems should be designed to operate under the highest anticipated loads.
- Where could the Treaty be modified on account of climate change? Perhaps to improve data sharing for better flood warning.

Concluding Remarks

- Sustainable sediment management for HEP development can be achieved by a variety of methods.
- Sluicing and flushing are both viable and proven methods of sediment management for run-of-river hydropower, and both can be made to work in the Himalaya.
- Both methods have important advantages and disadvantages.
- Considerable progress has been made in the past decades improving sediment management strategies and materials. Nevertheless, higher costs will be an inevitable consequence of operating in challenging environments due to the requirement of sediment management including repair & replacement of components subject to wear.

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