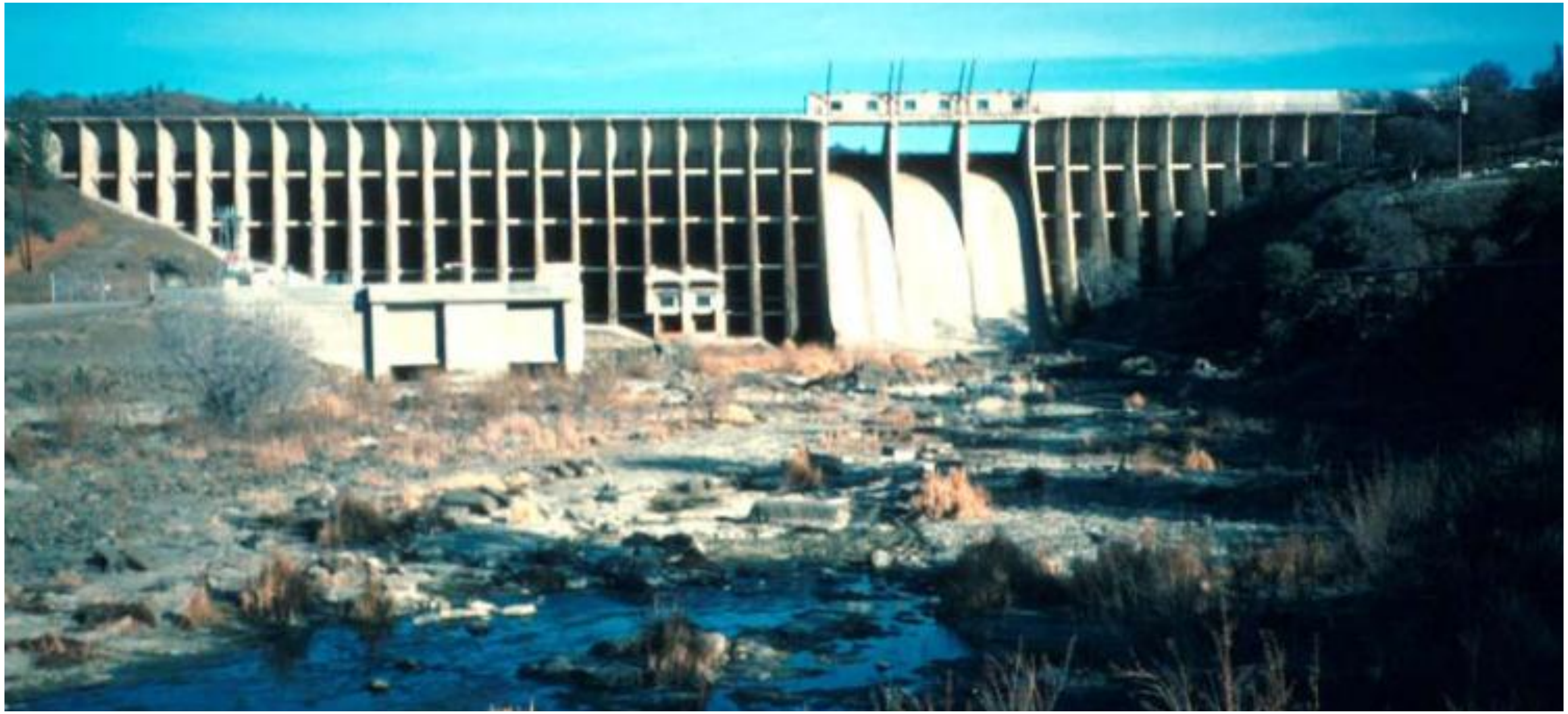
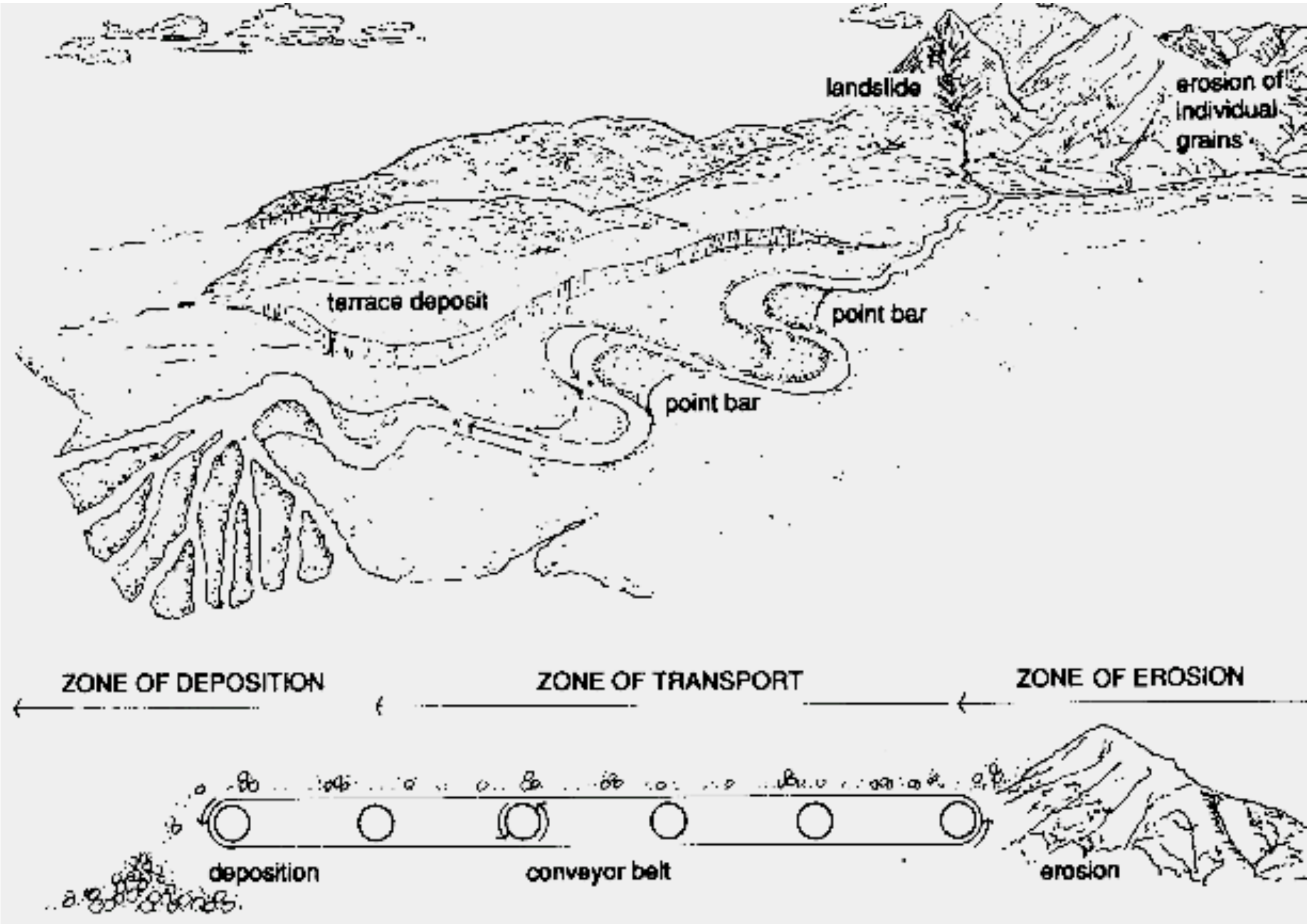
Planning dams for basin-scale sustainable sediment management



G Mathias Kondolf, Rafael JP Schmitt
University of California, Berkeley

SedNet 2017 Genoa, June 2017

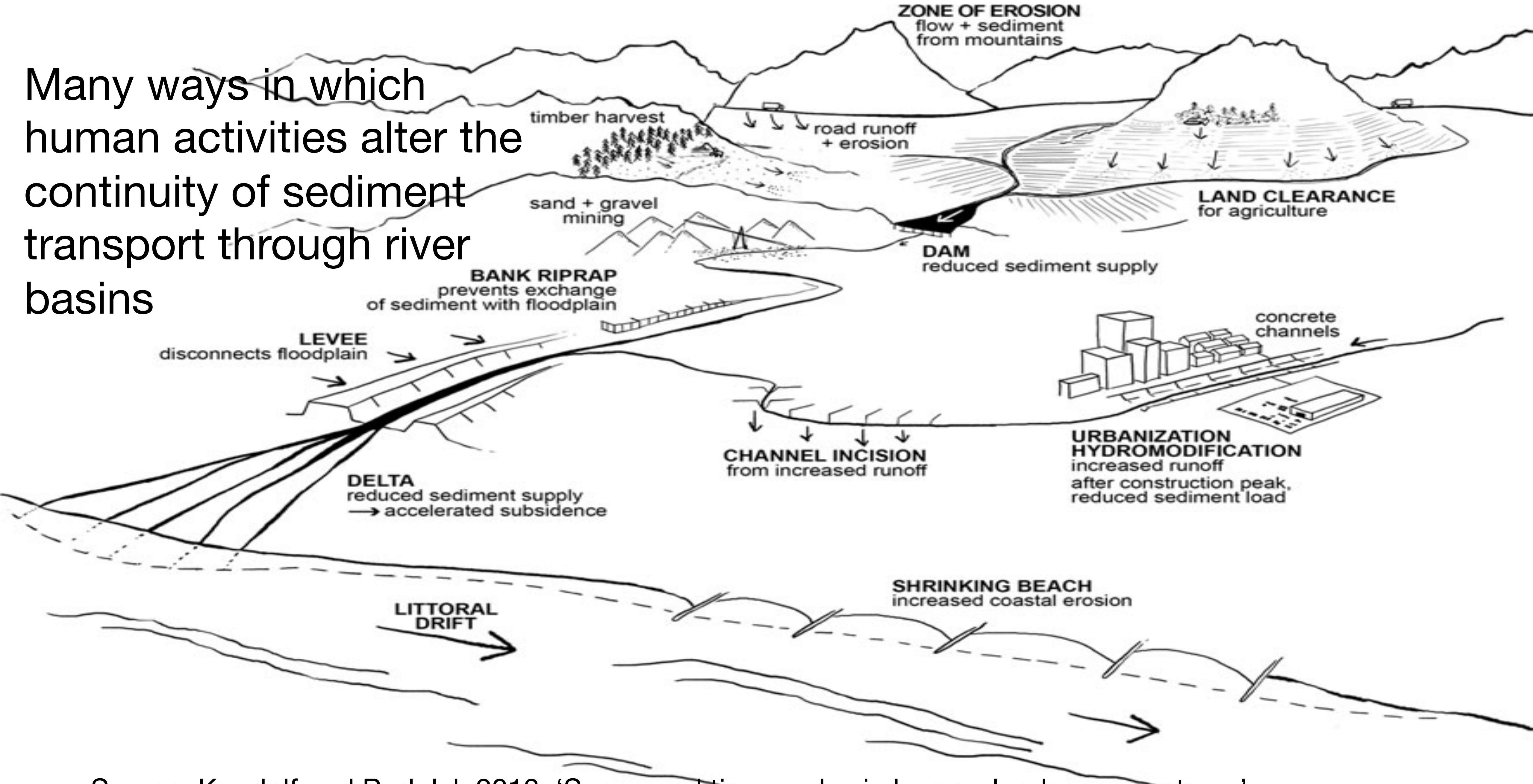
Rivers carry not only water, but also sediment
- an essential component, responsible for channel form



Source: Kondolf 1997 'Hungry Water', *Environmental Management*

The transport zone is like a conveyor belt:
in geologic time, sediment is in motion, temporary storage in bars, floodplains, etc
Dams interrupt this natural continuity of sediment flux.

Many ways in which human activities alter the continuity of sediment transport through river basins



Source: Kondolf and Podolak 2013. 'Space and time scales in human-landscape systems'. *Environmental Management*

As dams trap sediment, 2 problems:

Reservoirs can fill with sediment, lose storage capacity, safety problems

Release sediment-starved water downstream

-- dam

San Clemente Reservoir, Carmel River: $83 million to stabilize

Matilija Dam, Ventura River, California

Filled with sediment, poses safety hazard, blocks fish migration
Will be removed (cost> $100M)
Biggest concern: sediment impacts on downstream channel,
 possible aggradation/flooding
So: mechanical removal and stabilization in-place

This is one of 4 such dams in the Coast Ranges of California that has filled with sediment and poses safety problems.
All of these have expensive houses located on the banks downstream.

Four Dams in the California Filled with Sediment: Safety Hazards, Expensive Decommissioning

Searsville

San Clemente

Matilija

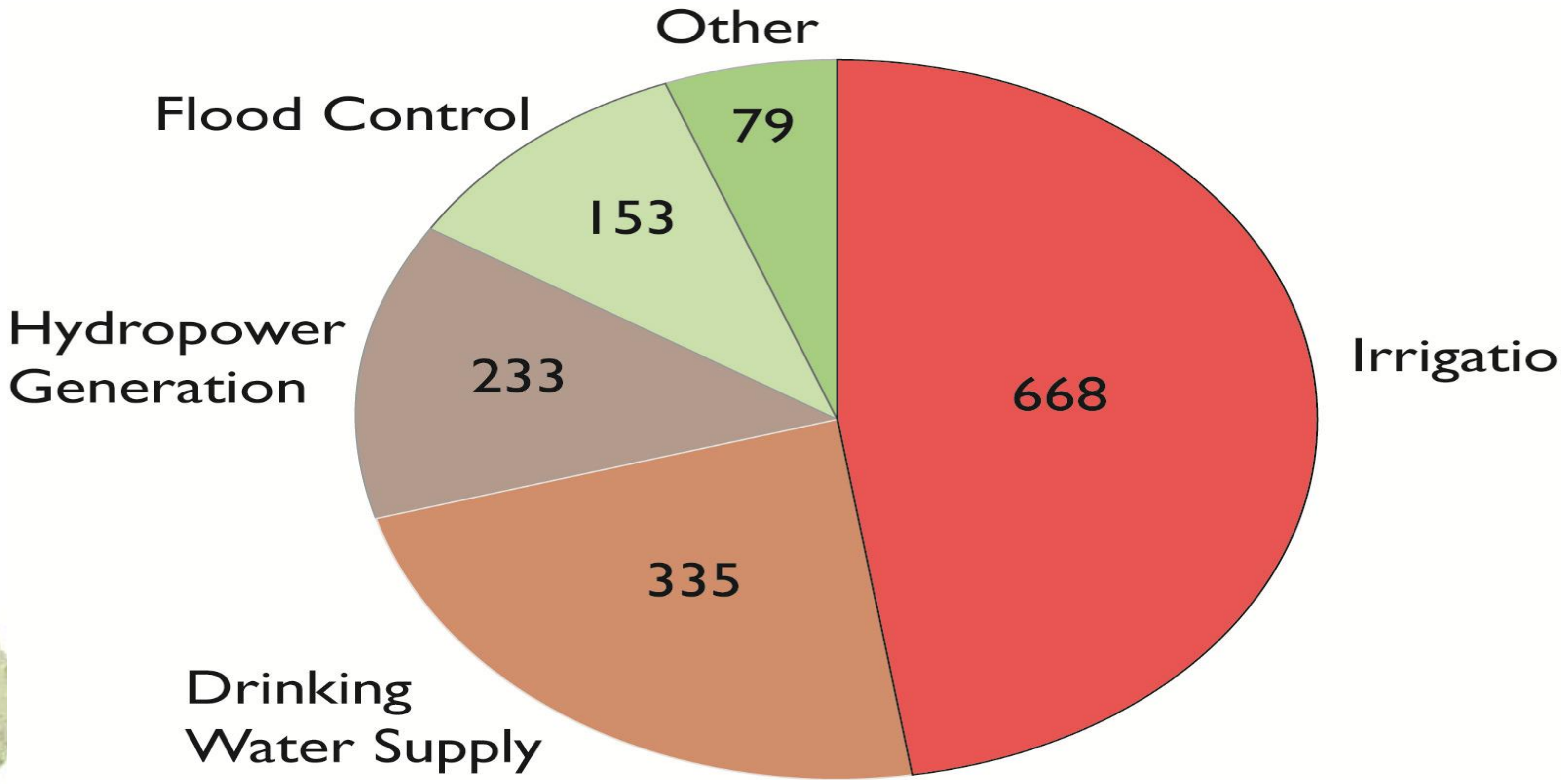
Rindge

Dam North - South CA	**Built**	**Height (ft)**	**Original purpose**	**Original capacity (AF)**	**Remaining Capacity (AF)**	**Impounded sediment (yd^3)**	**Sed. Mgmt.**	**Primary Removal Reason**	**Upstream reach (mi)**
Searsville	1892	68	Drinking Water supply	1,365	~100	~1,000,000	Not slated for removal	Upstream flooding	10
San Clemente	1921	106	Drinking Water supply	1,425	125	2,500,000	Stabilization and river erosion	Dam safety	5
Matilija	1948	168*	Drinking Water supply	7,018	<500	6,100,000	Mechanical removal and upstream stabilization	Dam safety	18
Rindge	1926	90	Irrigation	574	0	800,000	Mechanical removal	ESA - Steelhead	6

Dams in California *How quickly will they fill with sediment?*

1,468 Dams statewide

Source: NID, 2009



Source: CADSOD, 2009

Modeling Reservoir Sedimentation in California

'3W' Model:

Estimates long-term sediment yields from reservoir sedimentation records

Applies these yields to unmeasured reservoirs

Accounts for multiple dams in the same basin

Changes in trap efficiency as dams fill

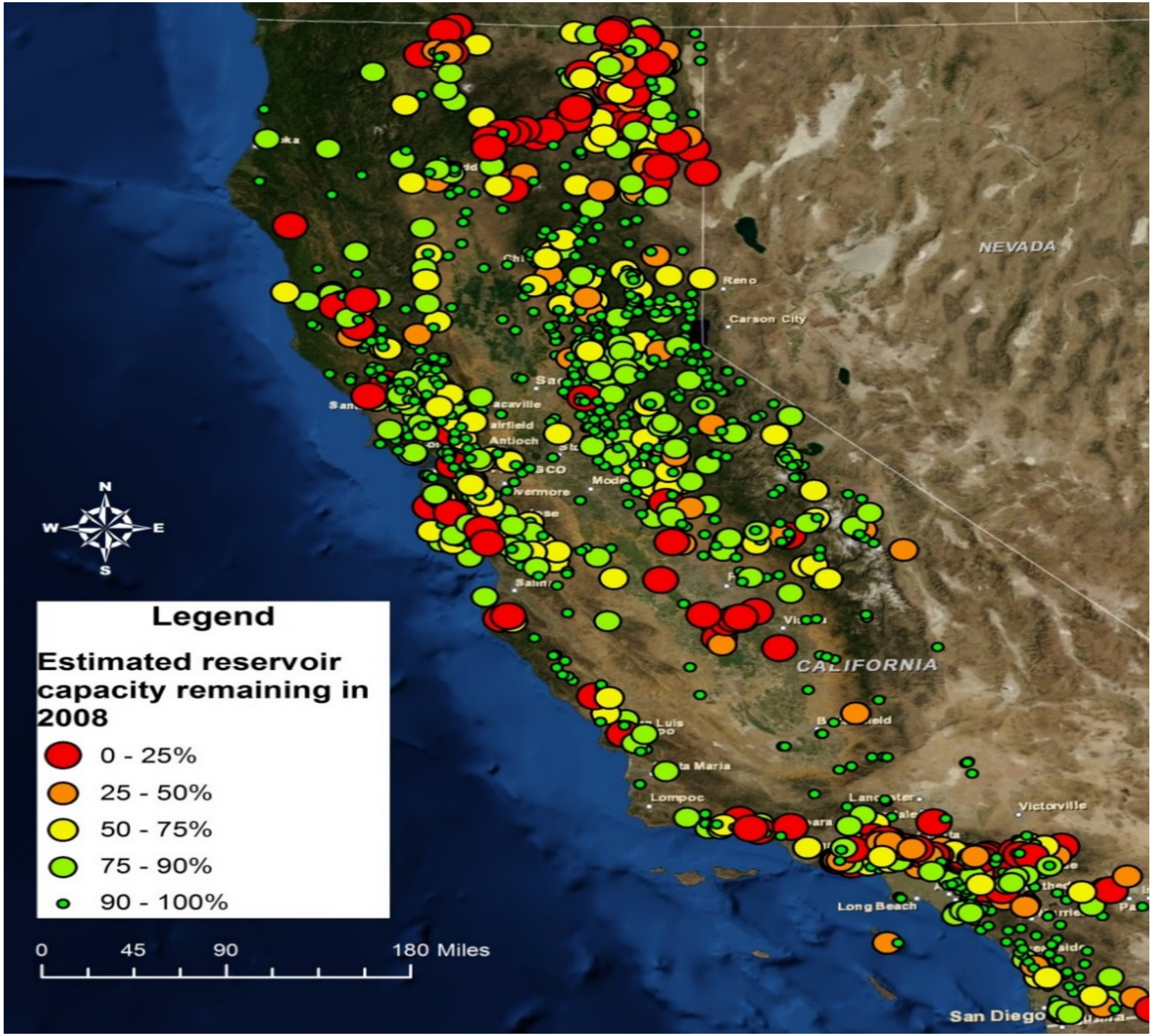
Minear and Kondolf (2009) Estimating reservoir sedimentation rates at large spatial- and temporal-scales: a case study of California. *Water Resources Research*

Sediment Yields Vary by Geomorphic Region

Geomorphic Region	***Sediment Yield (m3 / km2 y)***	
	Median	***Maximum***
Coast Ranges	262	3,419
Central Valley	89	277
Siskiyou	531	711
Peninsular Ranges	130	905
Sierra Nevada	97	1,257
Transverse Ranges	519	5,085

Results highlight where we can expect future problems:
Small water-supply reservoirs in rapidly-eroding Coast and Transverse Ranges

Results:
Estimated reservoir capacity remaining in 2008 (as percent of original)



However: *modeling results*, based on limited data.
There is surprisingly little data on how much reservoir storage we are losing to sedimentation.
In 2014, Senator Pavley introduced SB 1259, directing DWR to collect data on the rate of capacity loss in California reservoirs, but the bill was not adopted.

CALIFORNIA LEGISLATURE— 2013–2014 REGULAR SESSION

SENATE BILL **No. 1259**

Introduced by Senator Pavley
(Principal coauthor: Senator Cannella)
(Coauthor: Senator Wolk)

February 21, 2014

An act to amend Sections 6120 and 10004.6 of the Water Code, relating to water.

LEGISLATIVE COUNSEL'S DIGEST

SB 1259, as amended, Pavley. Dams: sedimentation studies.

Existing law requires the Department of Water Resources to make or cause to be made investigations and gather or cause to be gathered data as needed for a proper review and study of the various features of the design and

So we continue to accumulate sediment in our reservoirs, with little pro-active management or even data collection – it's a legacy we are leaving for our grandkids to deal with!

The reservoir above Englebright Dam on the Yuba River—a third filled up with sediment.

No Joy in Mudville: Amid Drought, California's Reservoirs are Clogged with Gunk

By Glen Martin

As the drought drags on and reservoir levels keep dropping, our politicians predictably are clamoring for new dams. But there may be a better and cheaper way to squeeze more water out of California's desiccated watersheds: Clean out the gunk behind existing reservoirs. That's because dams

Safety Hazards of Sediment-Filled Dams

Barlin Dam on the Dahan River, Taiwan illustrates the safety hazard posed by sediment-filled dams.

Barlin was one of >120 *sabo* dams built upstream of Shihmen Reservoir, most filled with sediment

October 2002

Sept 2004 - dam full of sediment

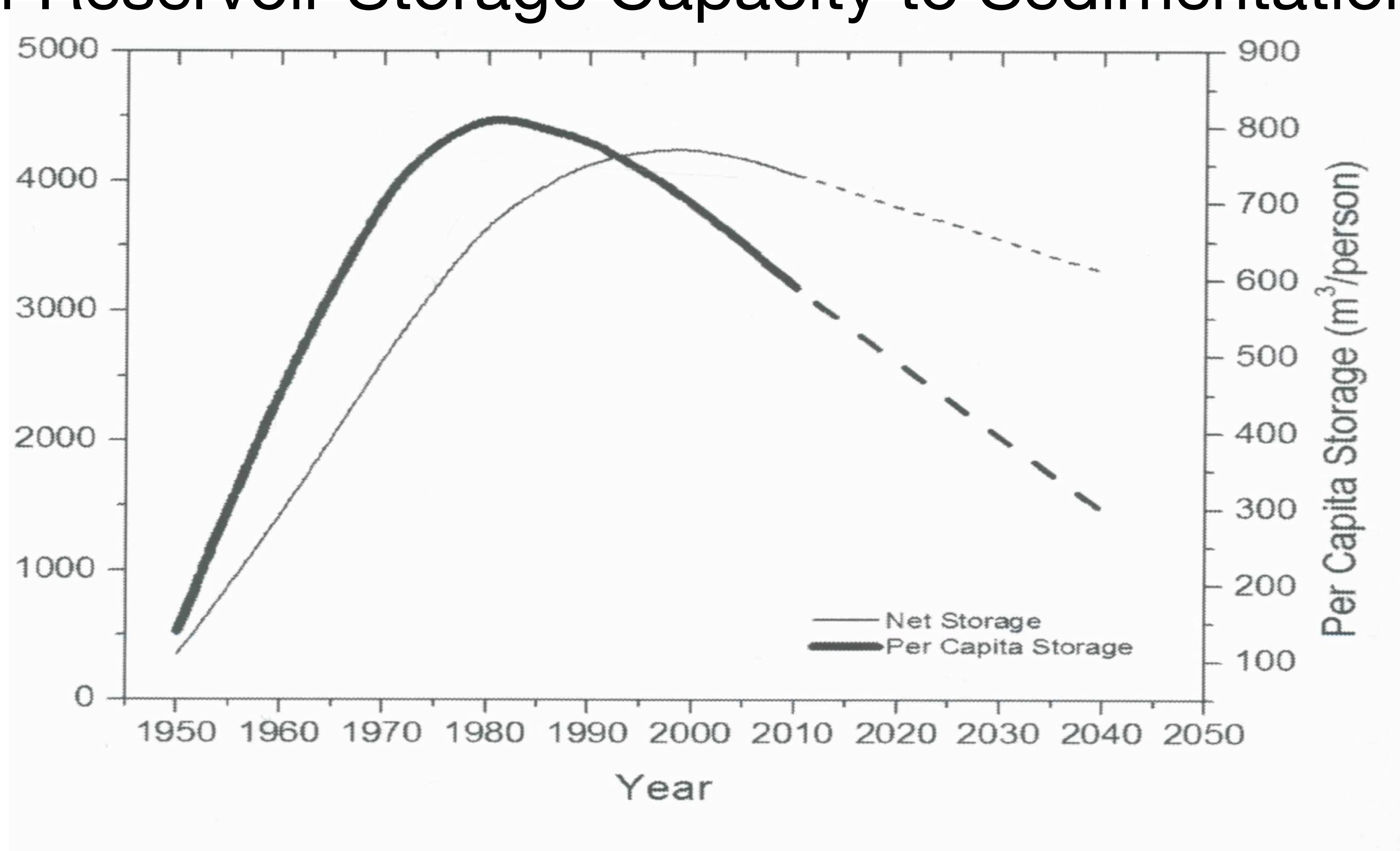
Progressive failure during typhoon in 2007.
Dam stored 10.4 Mm3 sediment. Released pulse of 7.5Mm3 sediment, absorbed downstream in 10-km channel & Ronghua Res. (no lives lost)

9 July 2007

19 Sept 2007

Source: Wang & Kondolf 2013 Upstream sediment-control dams: five decades of experience in the rapidly-eroding Dahan River Basin, Taiwan, *J. American Water Resources Assn*

Loss of Reservoir Storage Capacity to Sedimentation



Since the 1970s, we have lost more reservoir capacity to sedimentation than has been gained by building new reservoirs. Source: Annanndale 2013 *'Quenching the Thirst'*

Downstream Effects of Sediment-Starved Water

Excess energy leads to channel incision (downcutting), which causes:

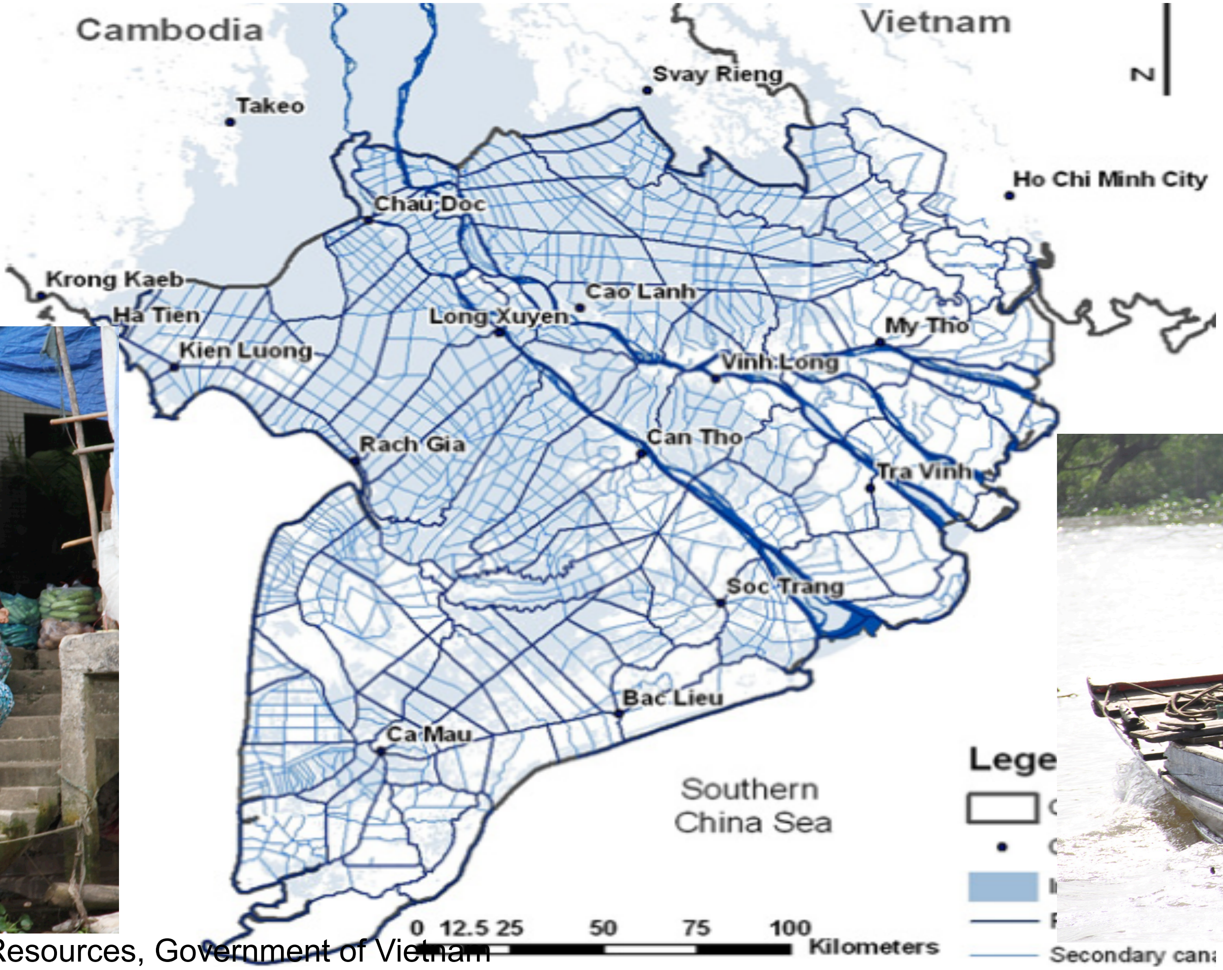
- undermining of infrastructure
- channel widening/destabilization
- drop in water table
- loss of habitats
- coastal erosion

Sediment starvation is commonly exacerbated by mining of sand and gravel from river channels downstream

Downstream Effects of Sediment-Starved Water

Threats to coastal deltas – such as the Mekong Delta in SE Asia

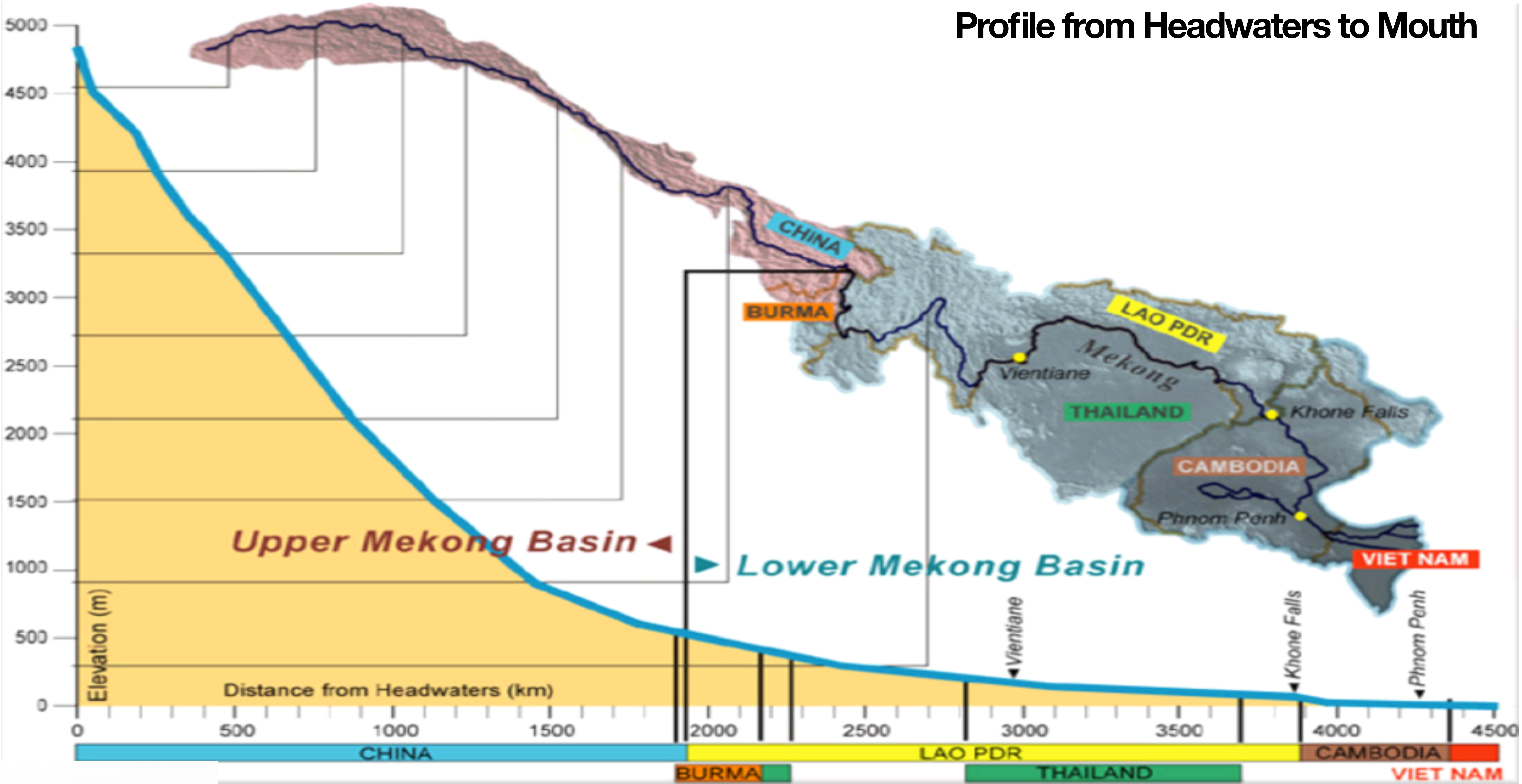
The Delta depends on sediment carried downstream by the river to maintain the delta landform, which results from the balance between sediment supplied and coastal erosion.



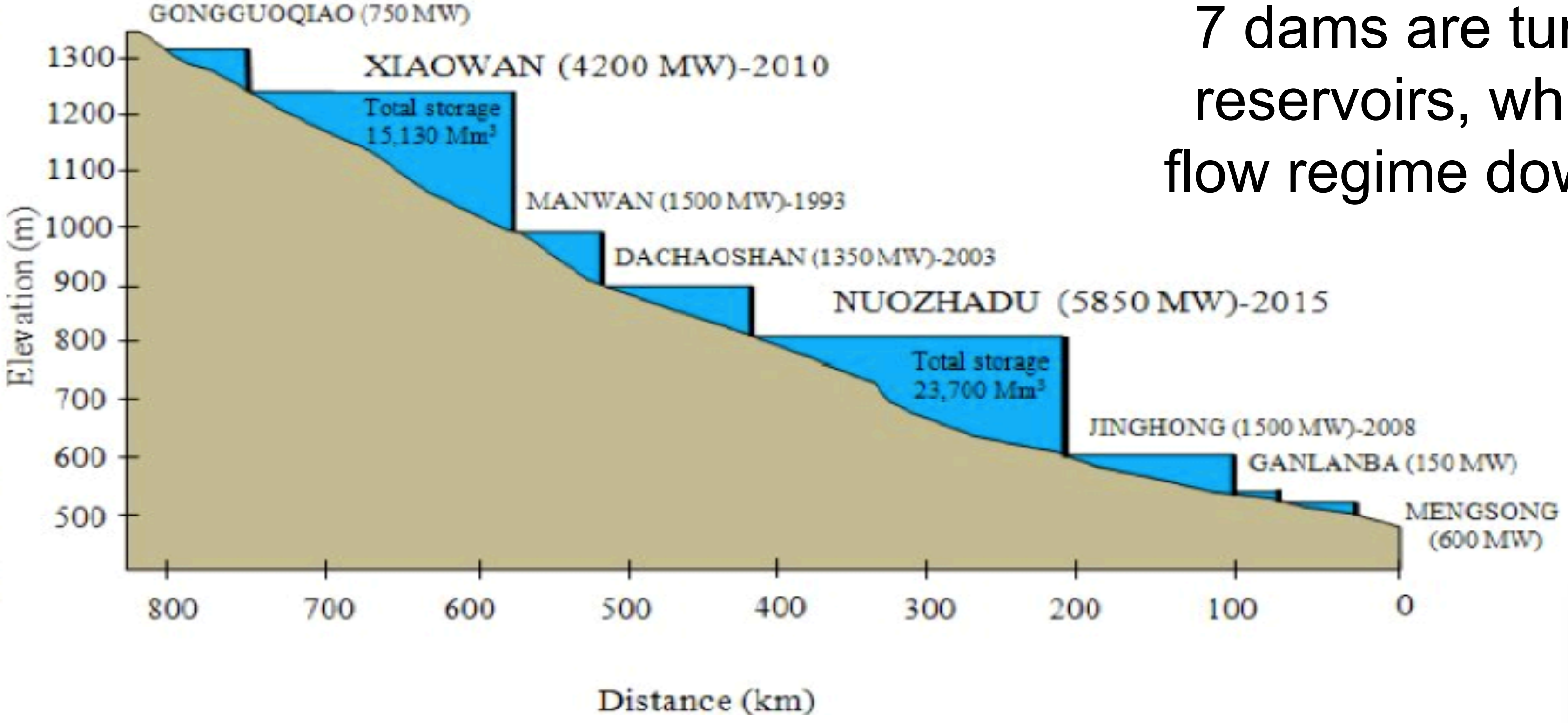
Population: 17M
Agriculture, fishing

Source: Southern Institute for Water Resources, Government of Vietnam

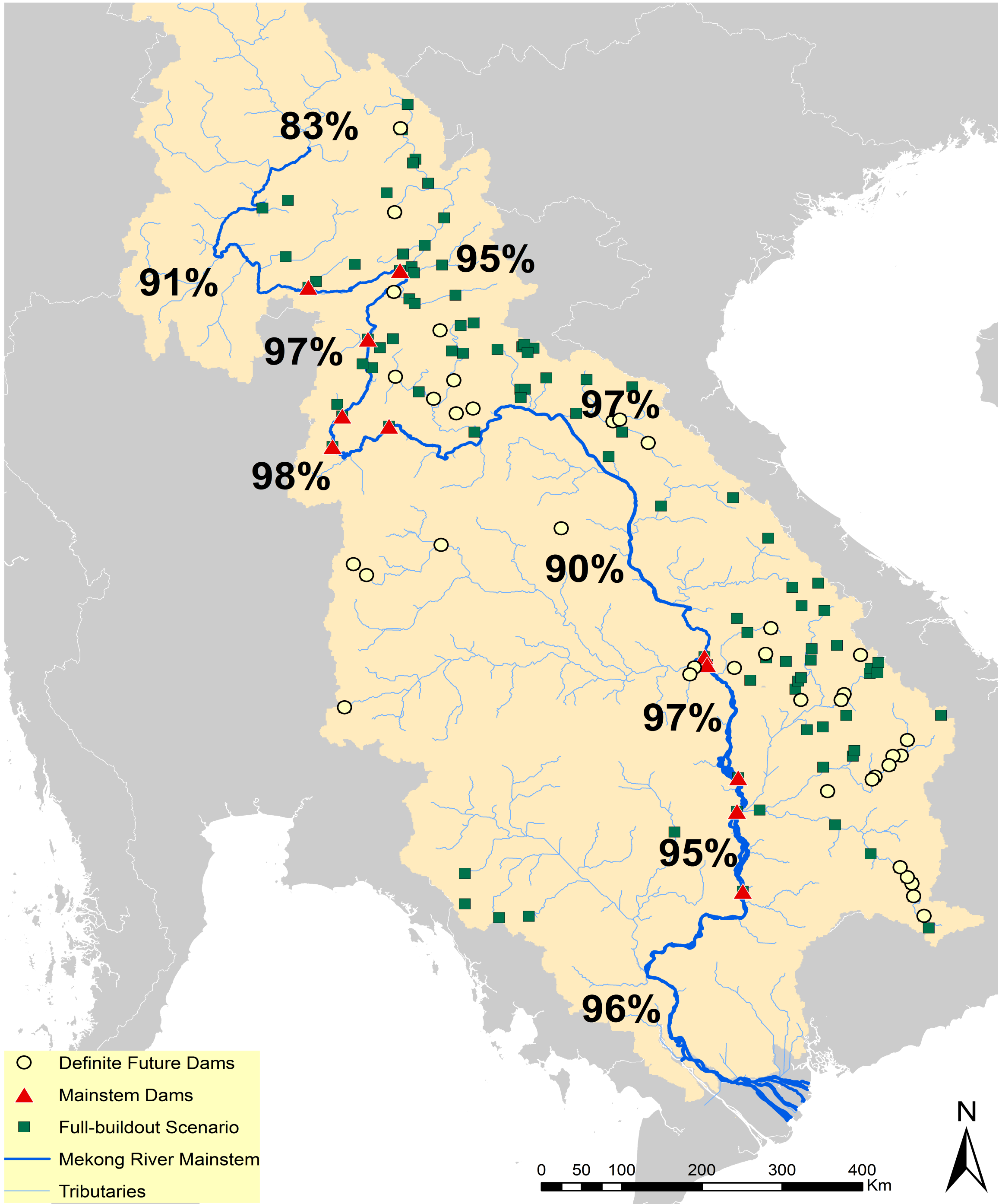
With its drop in elevation from the Tibetan Plateau, the river has potential to generate hydroelectricity



In the Chinese section of the river (upstream), 7 dams are turning the river into a series of reservoirs, which result in small changes in flow regime downstream, but big changes in sediment load.



And another 133 dams are planned or being built on the lower Mekong River, in Laos, Cambodia, and Vietnam, including 11 on the mainstem Mekong itself



We applied the 3W model to the 'full build' scenario (133 dams)
Only 4% of the natural sediment load will reach the Delta –
Severe consequences for the Delta

Source: Kondolf et al 2014 'Dams on the Mekong: Cumulative Sediment Starvation' *Water Resources Research*

Currently working with Laos and Cambodia to relocate or redesign some key dams to minimize downstream impacts.

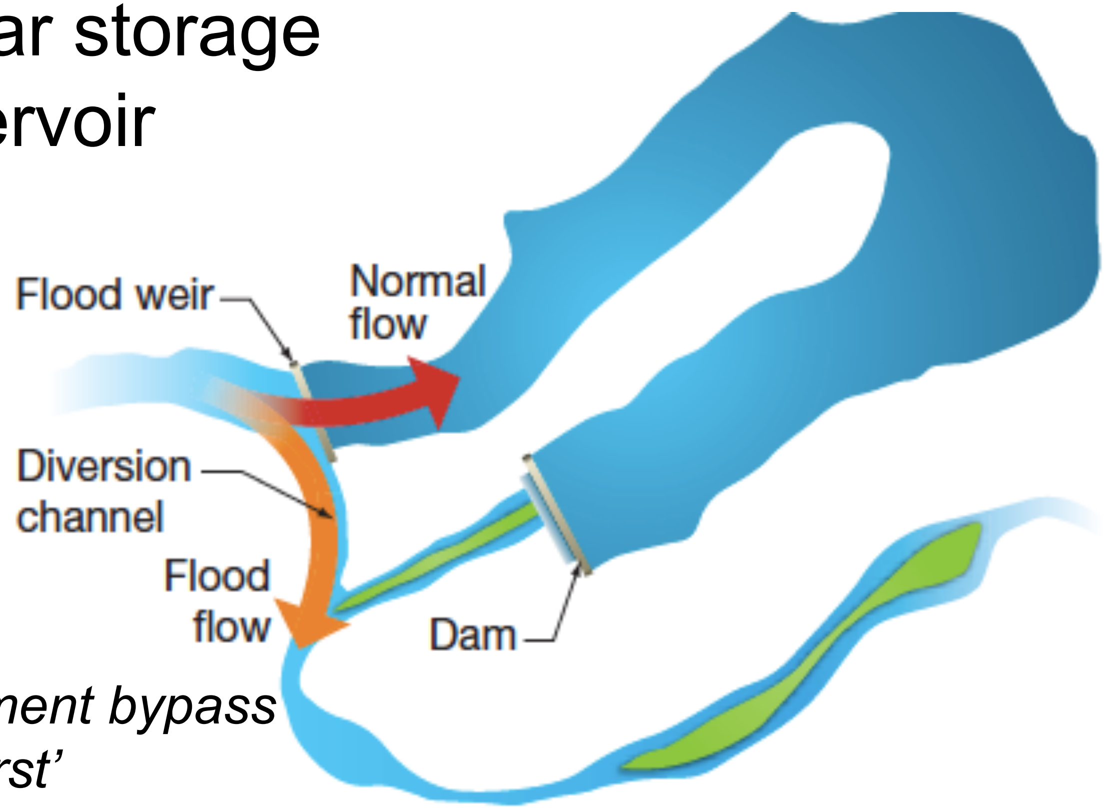
How to manage/mitigate for reservoir sedimentation and for hungry water downstream?

Multiple approaches to pass sediment around or through reservoirs:

- Bypass channels/tunnels
- Pass sediment *through* the dam during floods (sluicing)
  - Need large, low-level outlets
  - Drawdown conflicts with year-to-year storage
- Flush accumulated sediments from reservoir
- Vent density currents

For review of methods, see:

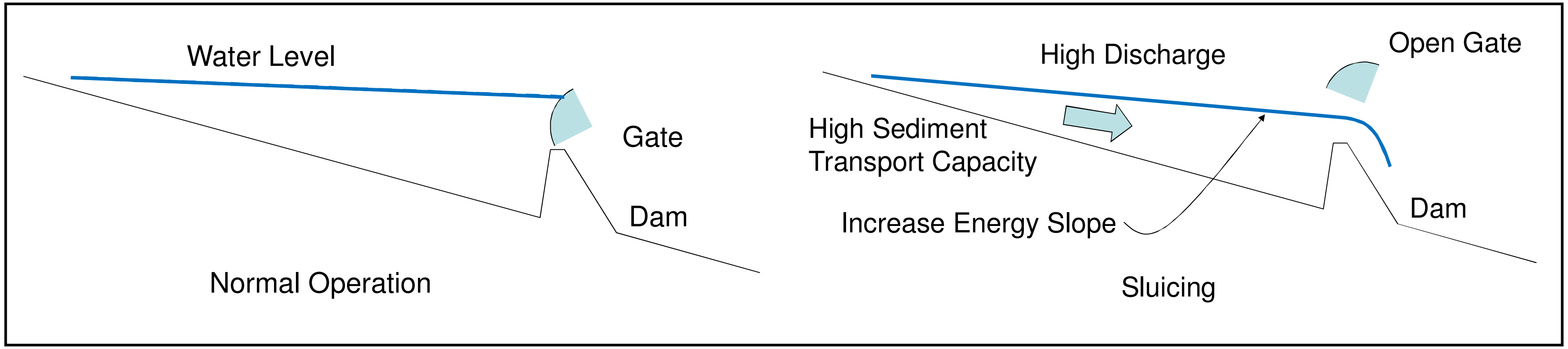
Kondolf et al 2014 'Sustainable sediment management: experience from 5 continents' *Earth's Future*



Nagle Dam, South Africa: *a successful sediment bypass*
Source: Annandale 2013 *"Quenching the thirst'*

Sediment Sluicing (aka Downstream Routing)

Discharging high flows through the dam during high inflows, to permit sediment to be transported through the reservoir and dam *without being deposited*.



Most effective for sand size and smaller sediments.

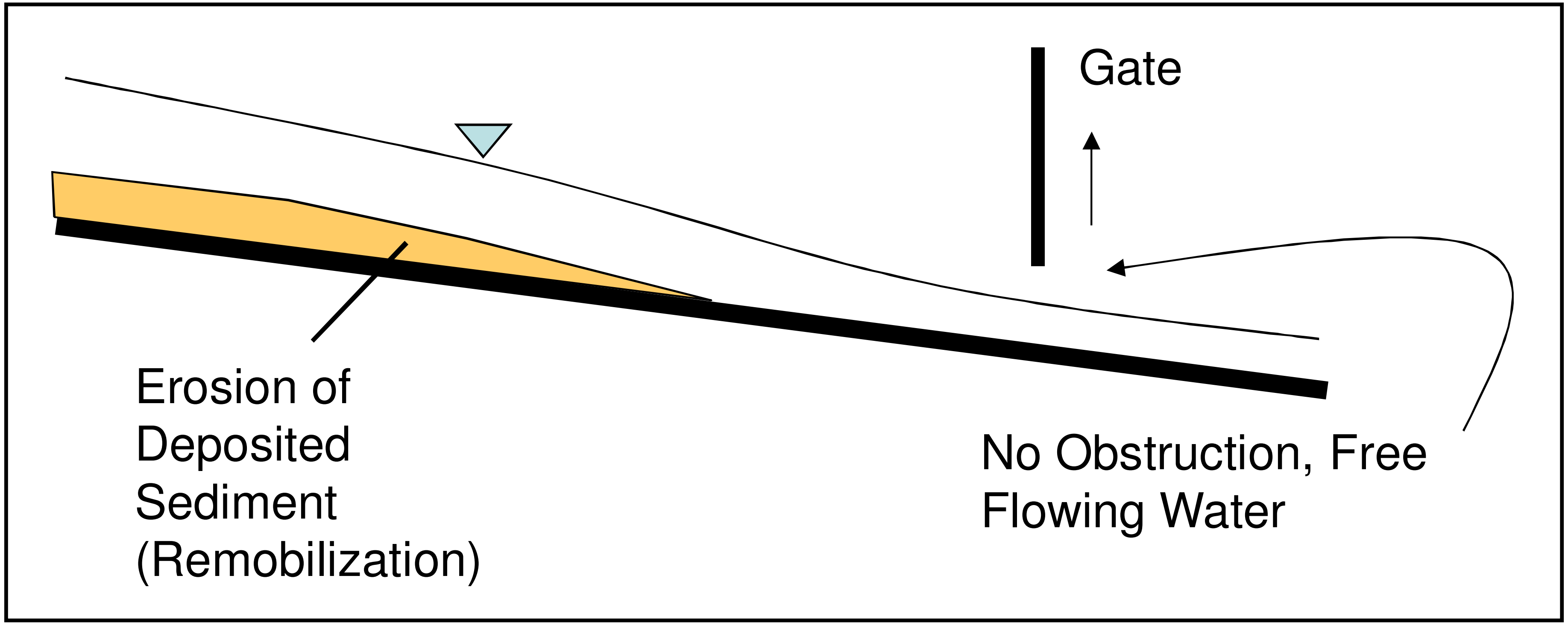
Works best in reservoirs that are long (relative to width, ie narrow), and with steep slopes.

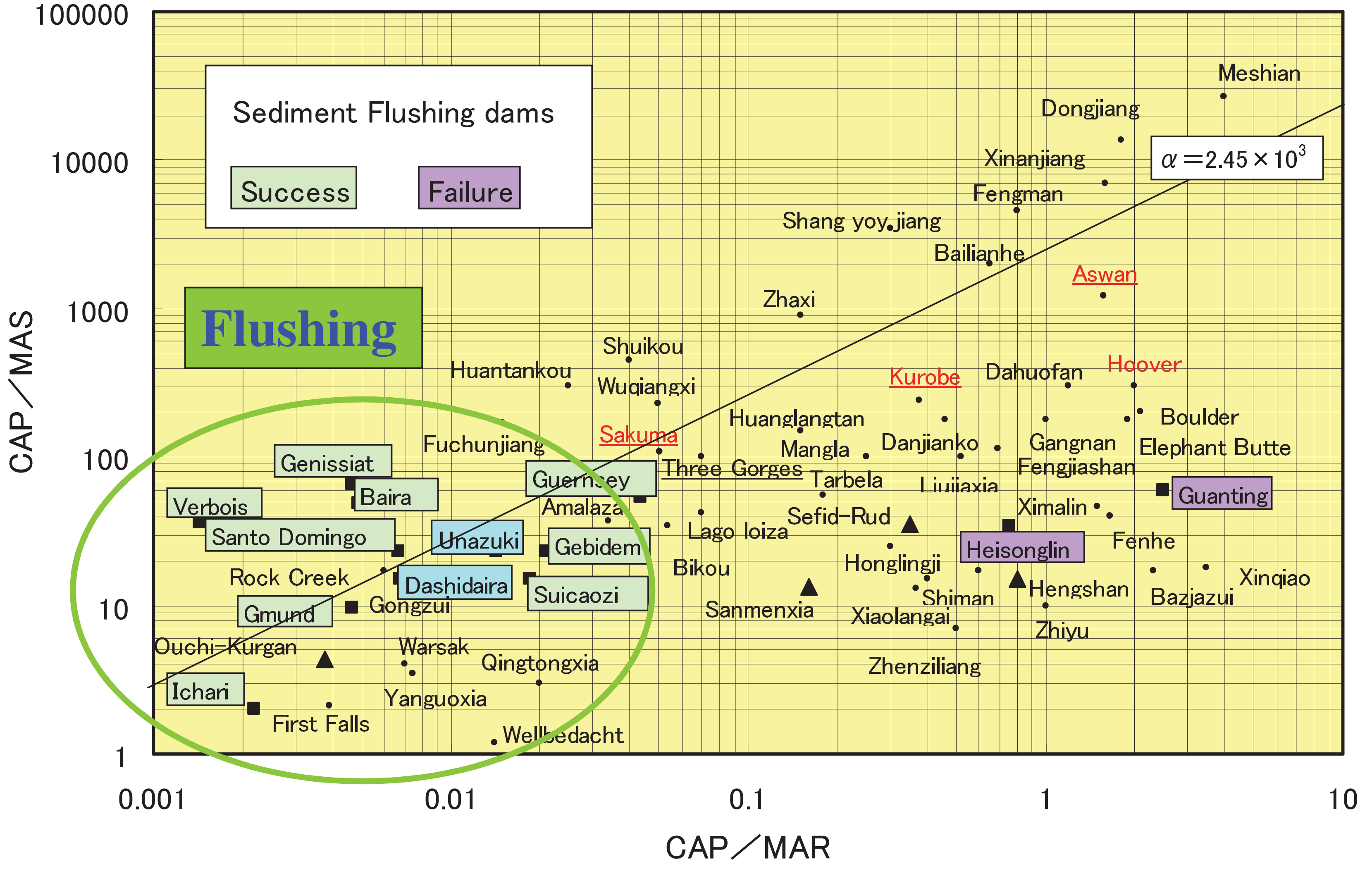
Design for Three Gorges Reservoir: 600km long, <1.5km wide

Drawdown Flushing

Differs from sluicing in that it's designed to mobilize sediment deposited in the reservoir, and transport it through low-level gates.

While sluicing always occurs during natural high flows, flushing can be conducted during low water (with greater environmental impact because sediments deposit on downstream bed).

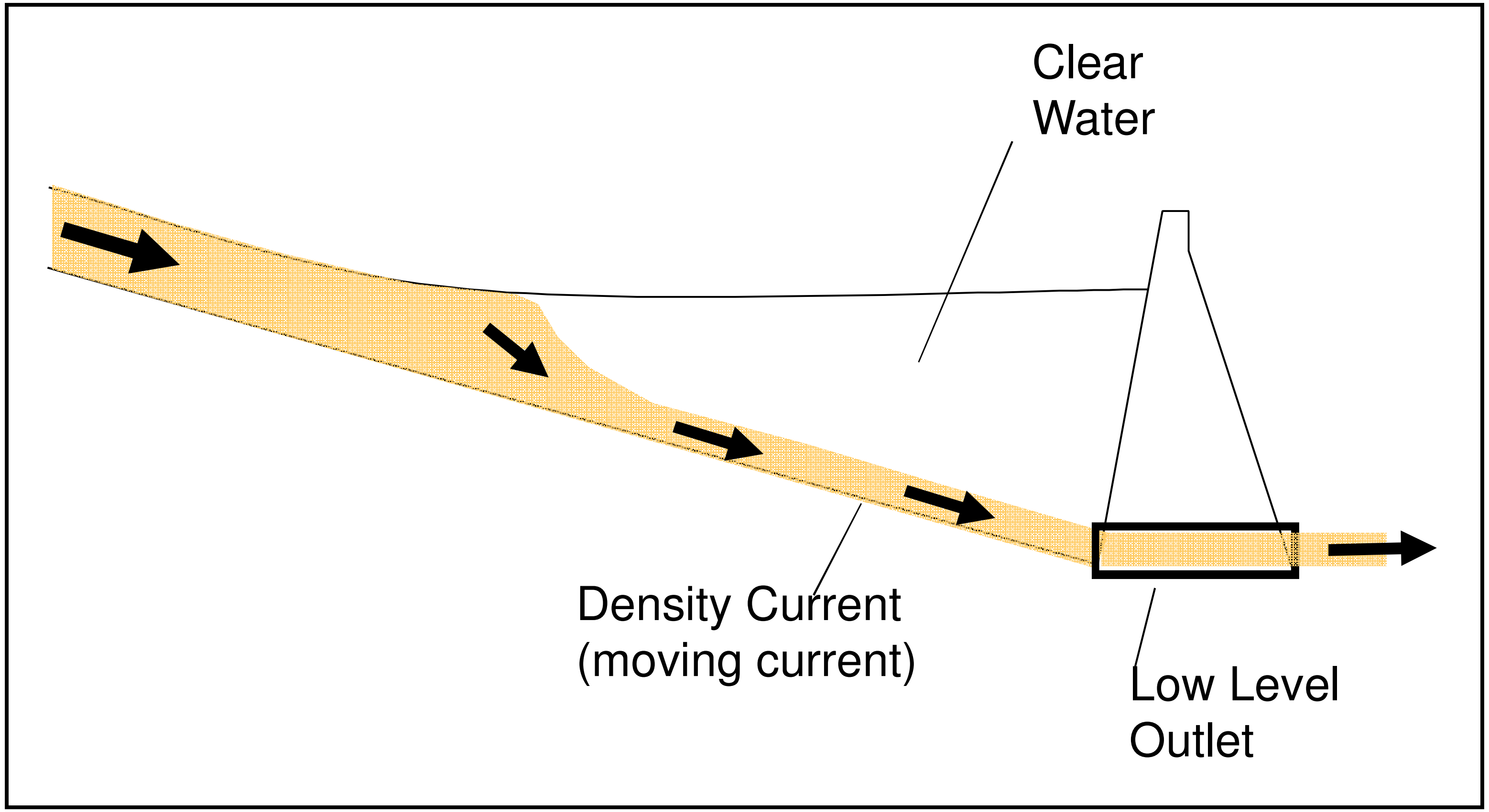




Flushing is most successful in smaller reservoirs, whose capacity is relatively small compared to annual inflow of water (ratio should not exceed 4%), i.e., reservoir should be able to be drawn down. *Plot courtesy of Tetsuya Sumi*

Venting Density Currents

Incoming waters with high concentrations of suspended sediment may behave as density currents, not mixing with clear waters above. It's possible to "vent" them through low-level gates in the dam



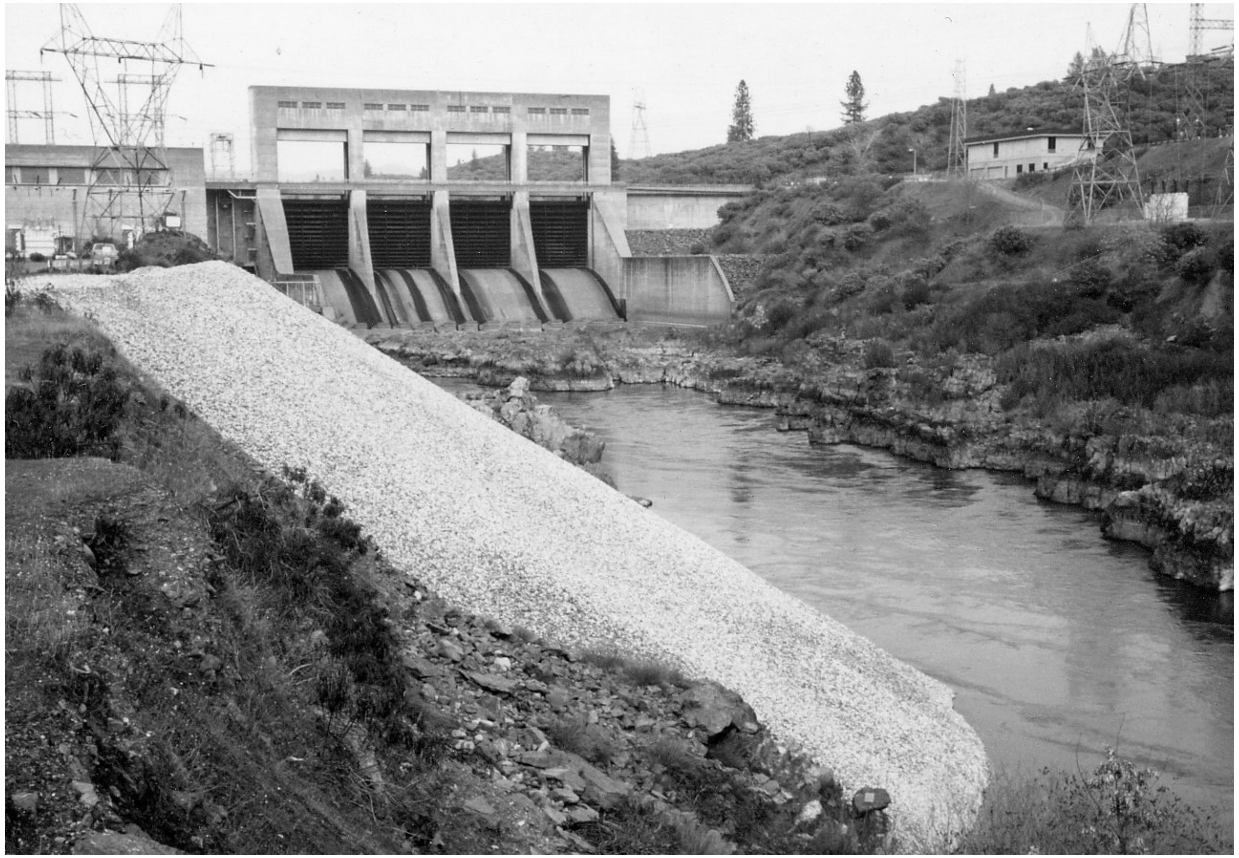
For summary of methods, see:
Kondolf et al 2014 'Sustainable sediment management: experience from 5 continents' *Earth's Future*

Gravel/sediment augmentation

Mechanically add sediment to channel downstream

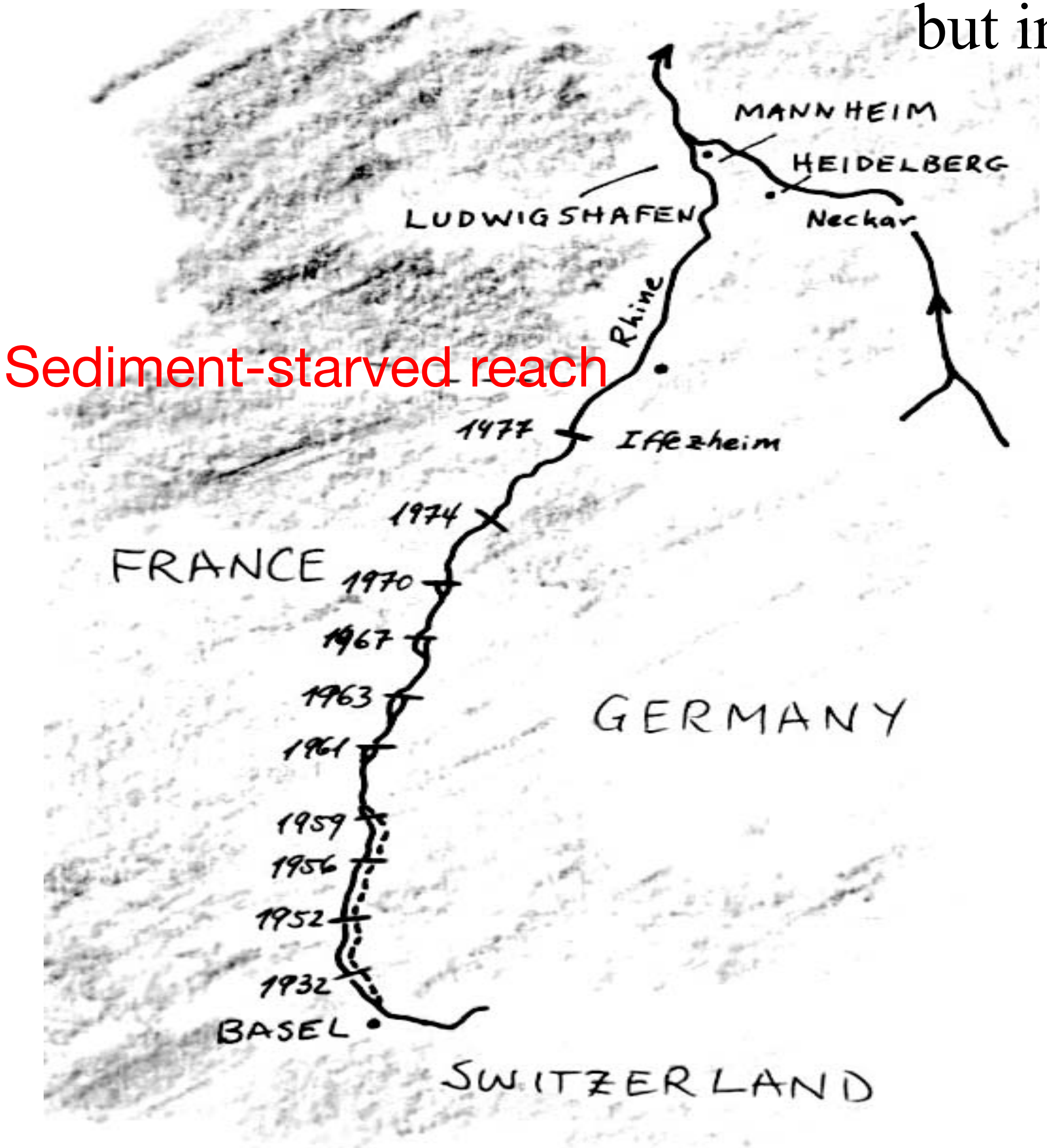
Most examples for fish habitat (except Rhine- infrastructure)

Does nothing to solve problem of sediment accumulation in reservoirs, only mitigates downstream sediment starvation



Adding gravel to Sacramento River, below Keswick Dam, California
Source: Kondolf 1997 ‘Hungry Water’ *Environmental Management*

The largest gravel augmentation project is not for habitat but infrastructure on

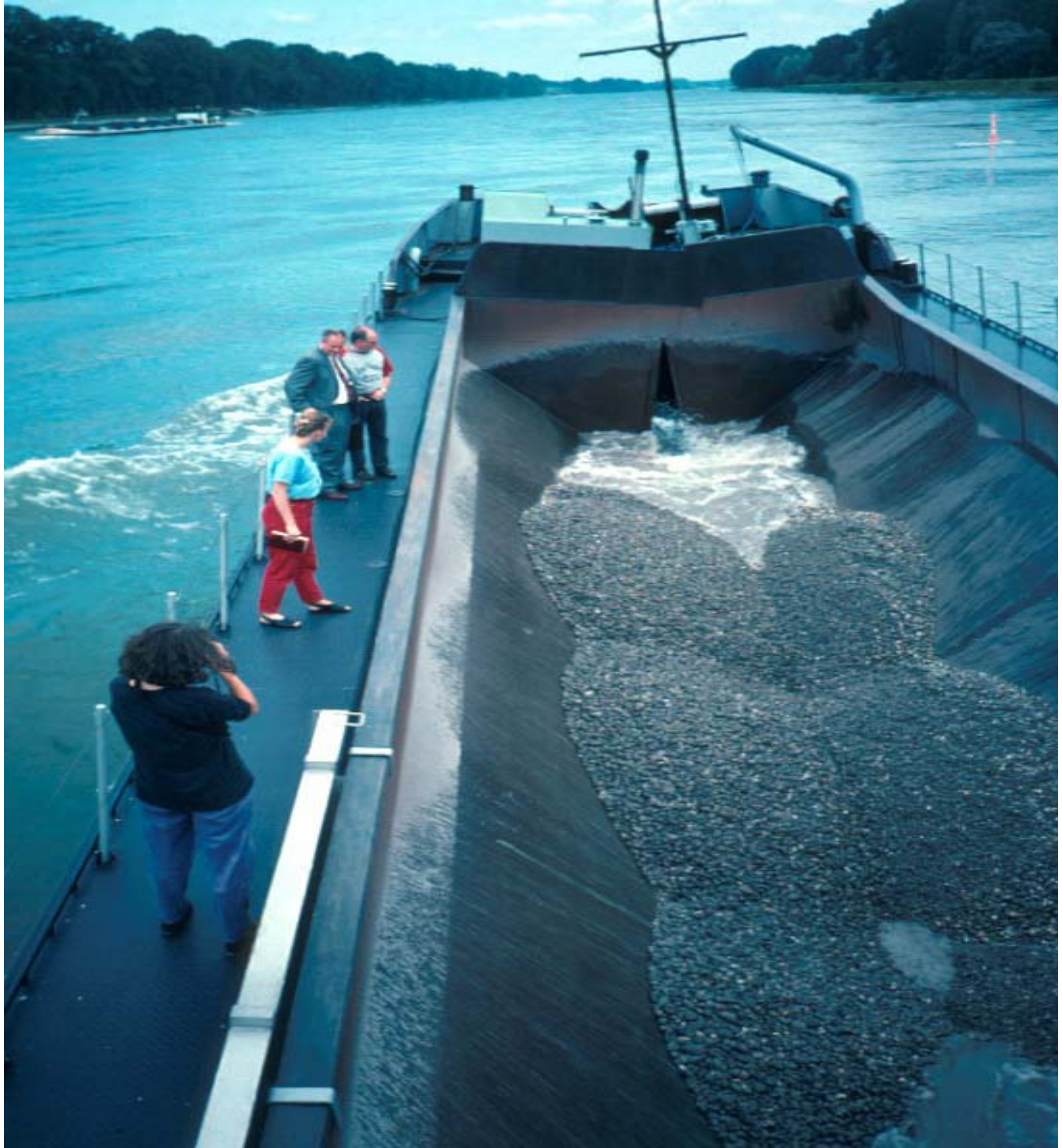


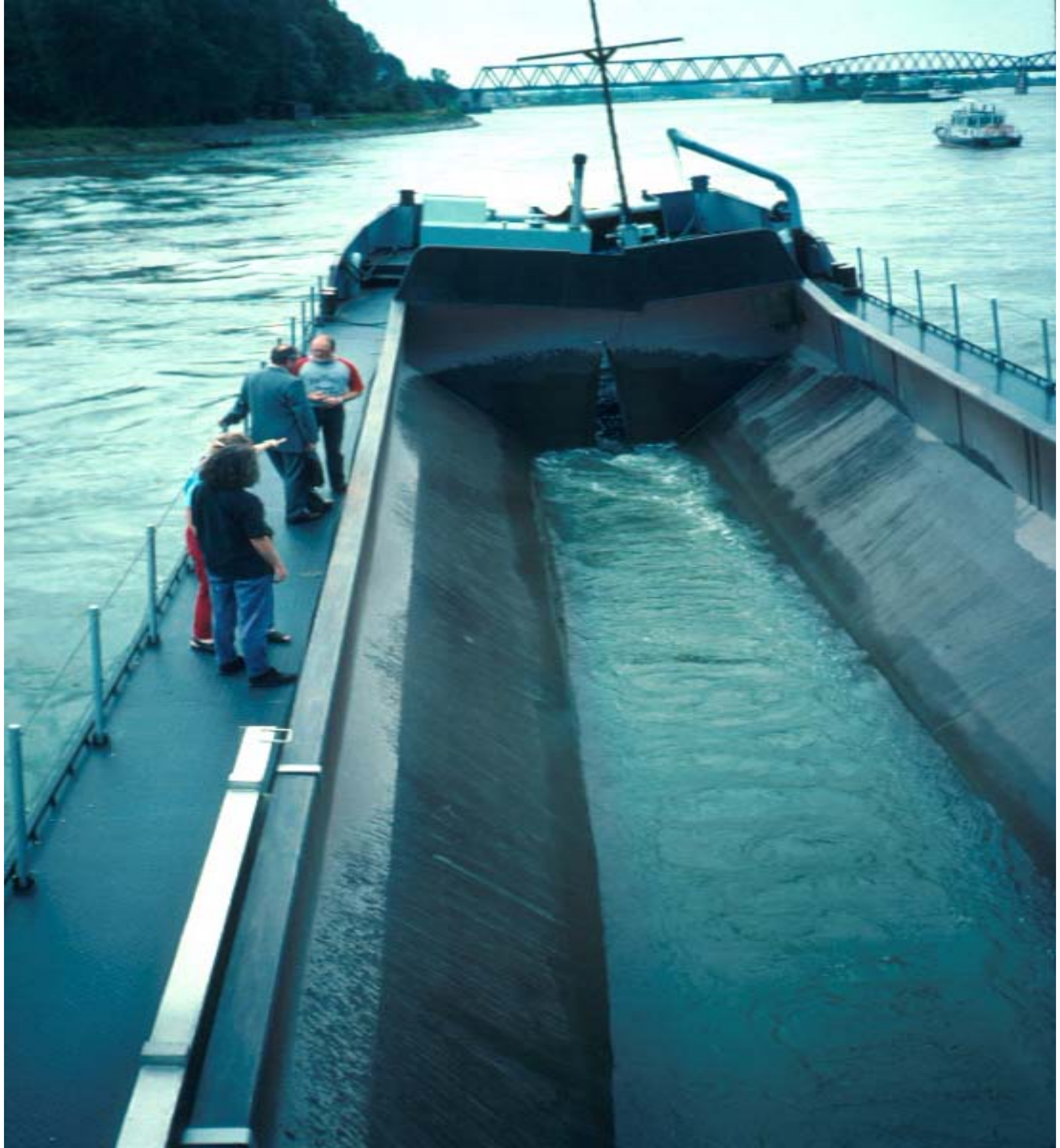
The French-German Rhine

Downstream of Iffezheim

See: poster, talk by Gudrun Hillebrand

Two barges operate
355 days/year
Add avg 170,000m3
gravel&sand





Colorado River downstream of Glen Canyon Dam:

in sediment deficit, hungry water has eroded beaches needed for camping and wildlife

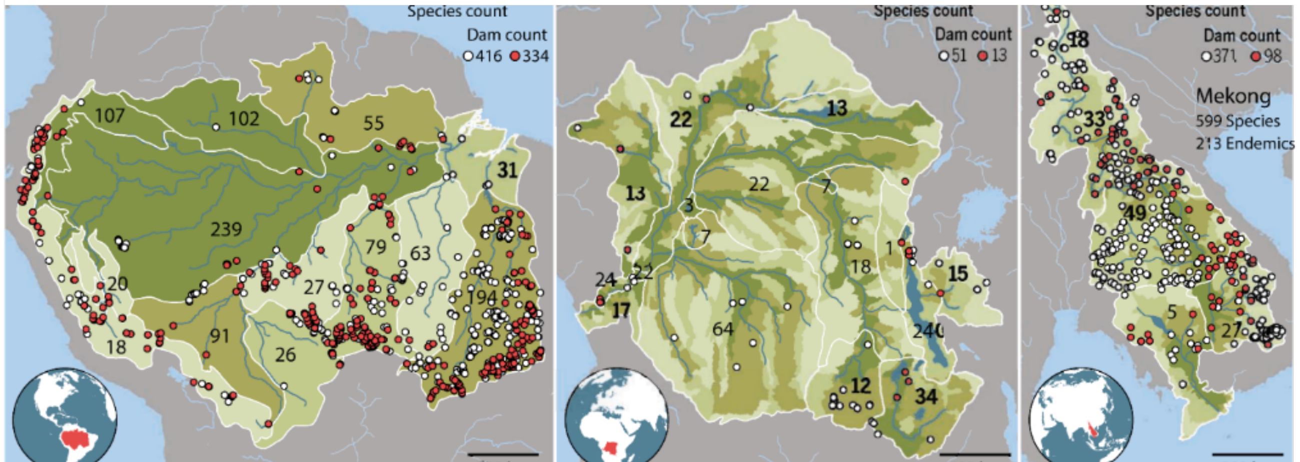
Proposal by US Bureau Reclamation to dredge sand from tributary delta, add to channel below dam

Let’s look at impacts of sediment trapping on infrastructure and river systems at the *river basin scale*

Reservoir sedimentation and storage loss

Impacts on downstream rivers, ecosystem (services), and livelihoods

Amazon *Kongo* *Mekong*



Each dam will have an impact on sediment transport

Avoid trapping sediment by selecting optimal dam sites

Minimize dam sediment trapping by optimal selection of dam portfolios

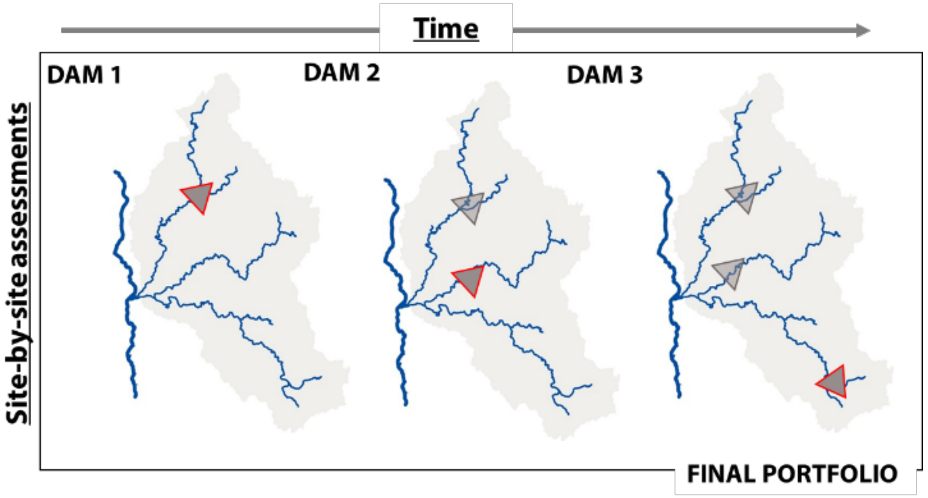
V. Tinocco, ESA, Winemiller et al. 2016

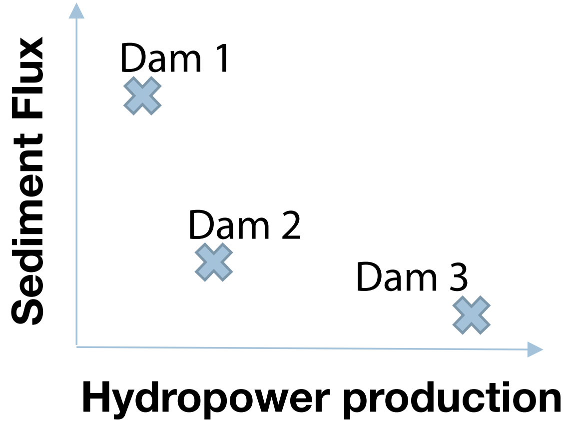
Strategic portfolio perspective to reduce sediment trapping

Site-by-site versus strategic portfolio assessments

Site-by-site planning

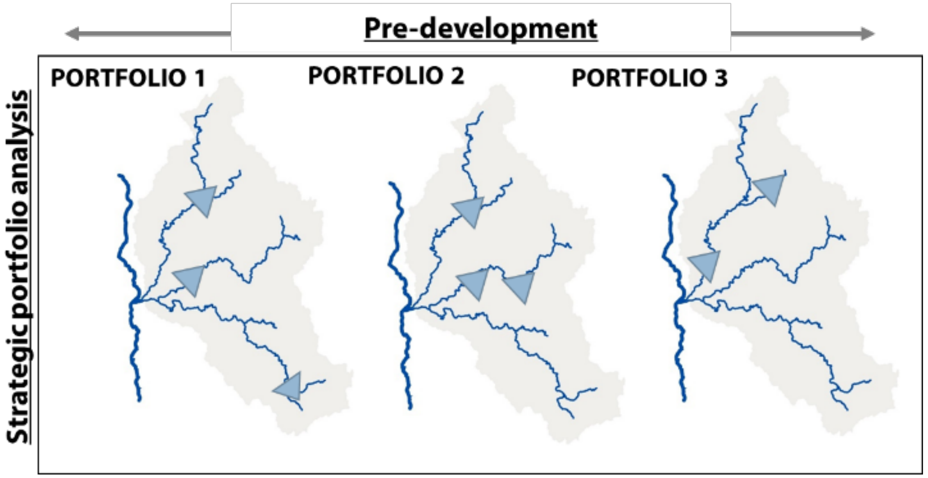
- Plan and develop dams **site-by-site**
- **No strategic vision** on final cumulative impacts and benefits

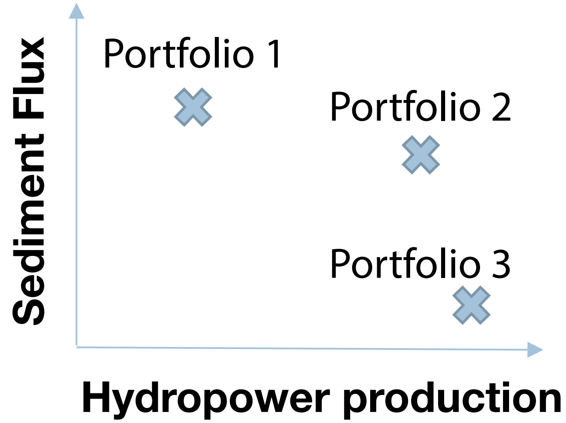




Strategic assessment

- Evaluate impact and benefits of dam portfolios on **network scales**
- Make **informed decisions** and **select optimal trade-offs**





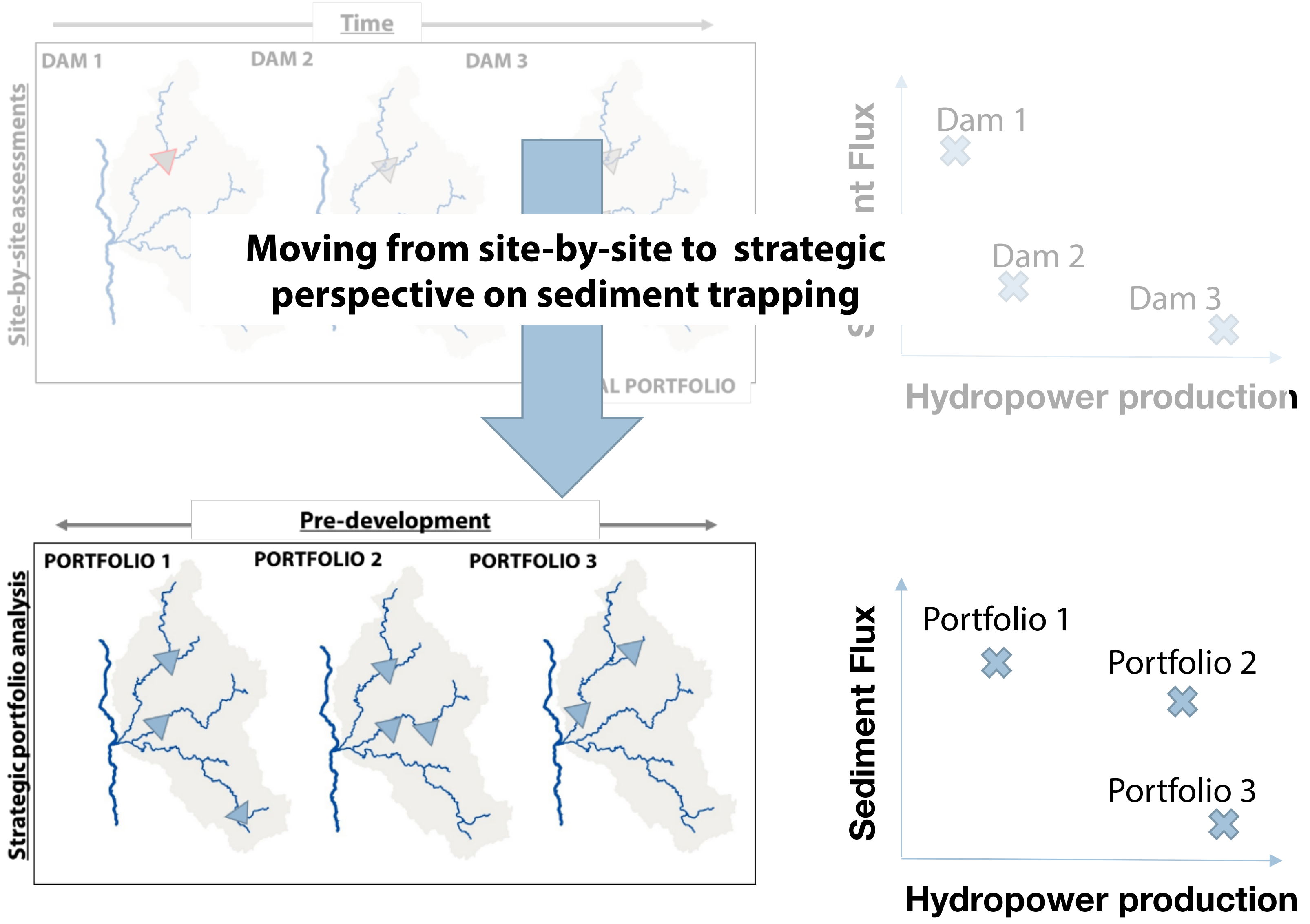
Strategic portfolio perspective to reduce sediment trapping

Challenges for implementation

System reconnaissance
- Spatio-temporal diversity in basin-scale sediment transport

Predictive modelling
- Modeling network-scala cumulative dam impacts

Optimal portfolio selection
- Evaluate a large number of dam portfolios

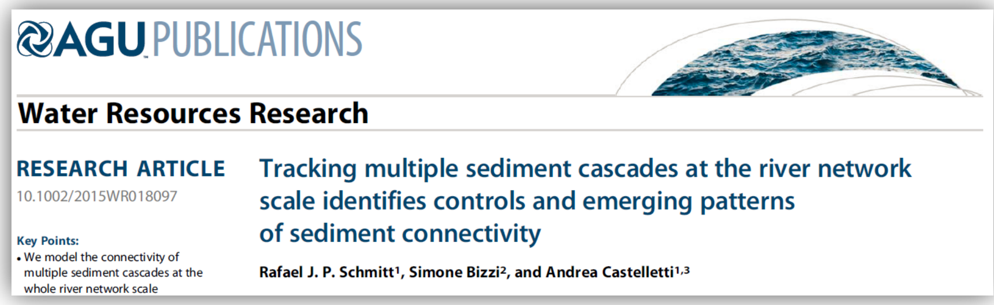


Reconnaissance and modeling

CASCADE (CAtchment **S**ediment **C**onnectivty **A**nd **DE**livery**)** Framework

Network scale sediment connectivity model

Computationally efficient screening tool based on globally available information


AGU PUBLICATIONS

Water Resources Research

RESEARCH ARTICLE

10.1002/2015WR018097

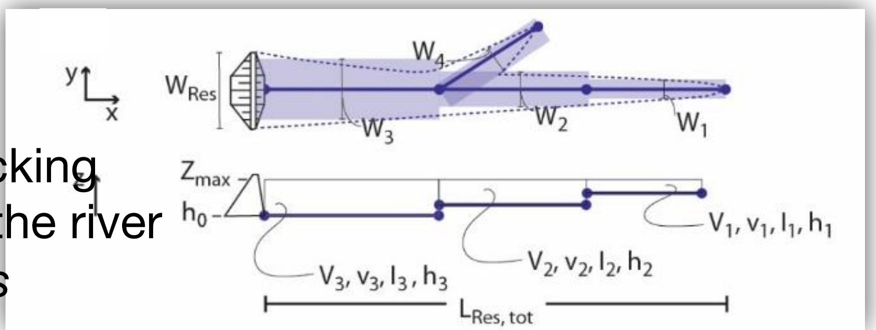
Key Points:

- We model the connectivity of multiple sediment cascades at the whole river network scale

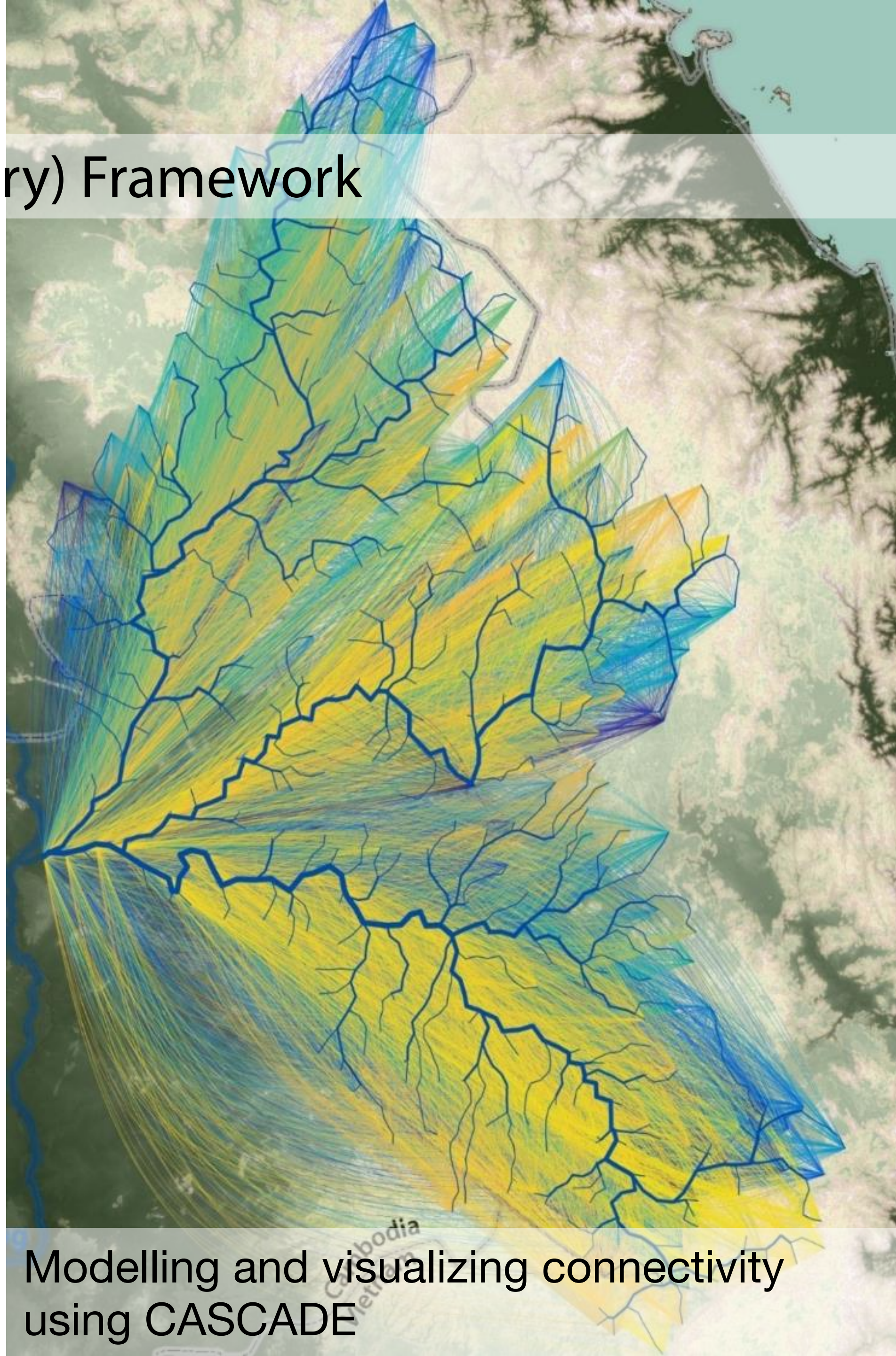
Tracking multiple sediment cascades at the river network scale identifies controls and emerging patterns of sediment connectivity

Rafael J. P. Schmitt[1], Simone Bizzi[2], and Andrea Castelletti[1,3]

Integrates cumulative sediment trapping in dams and complexity in the natural system



Source: Schmitt et al 2016 'Tracking multiple sediment cascades at the river network scale' *Water Resources Research*



Modelling and visualizing connectivity using CASCADE

Case Study

Dam impacts in the Se Kong, Se San, Sre Pok (3S) Rivers

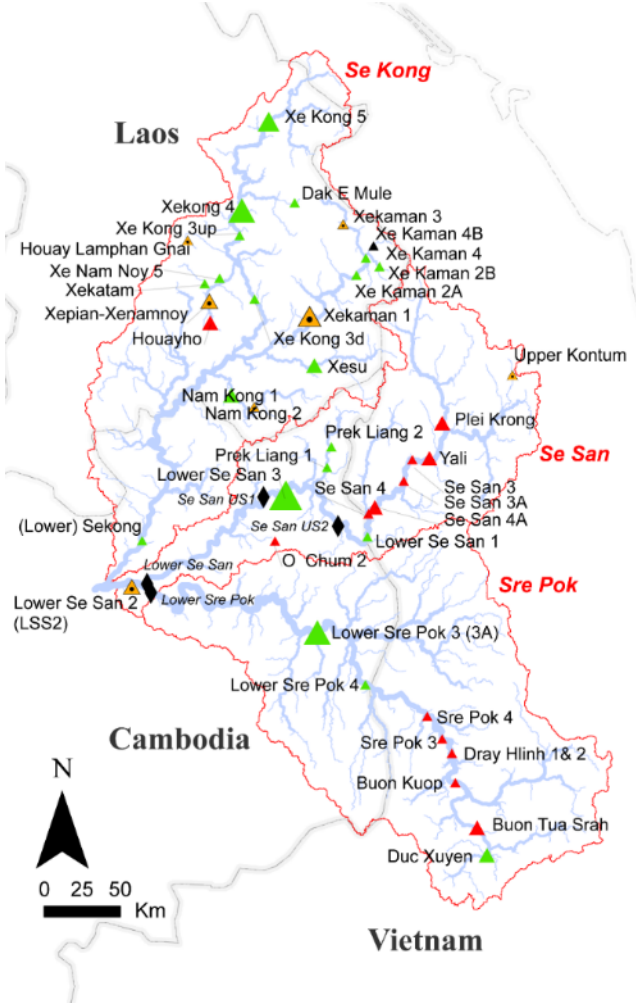
Major tributary of the Mekong

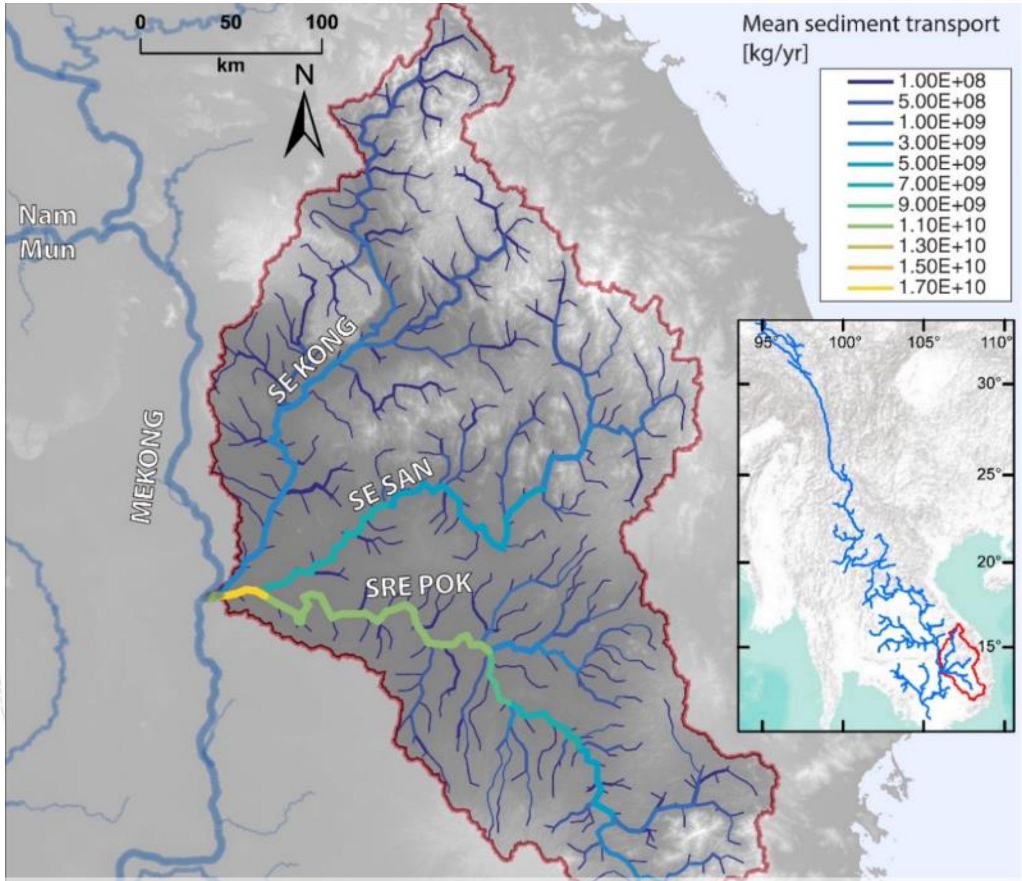
Spatially diverse sediment origin

42 dam sites with 30000 GWh production capacity

Research Questions

1. Optimal trade-offs between sediment trapping and hydropower
2. Performance of the current site-by-site planned hydro-cascade



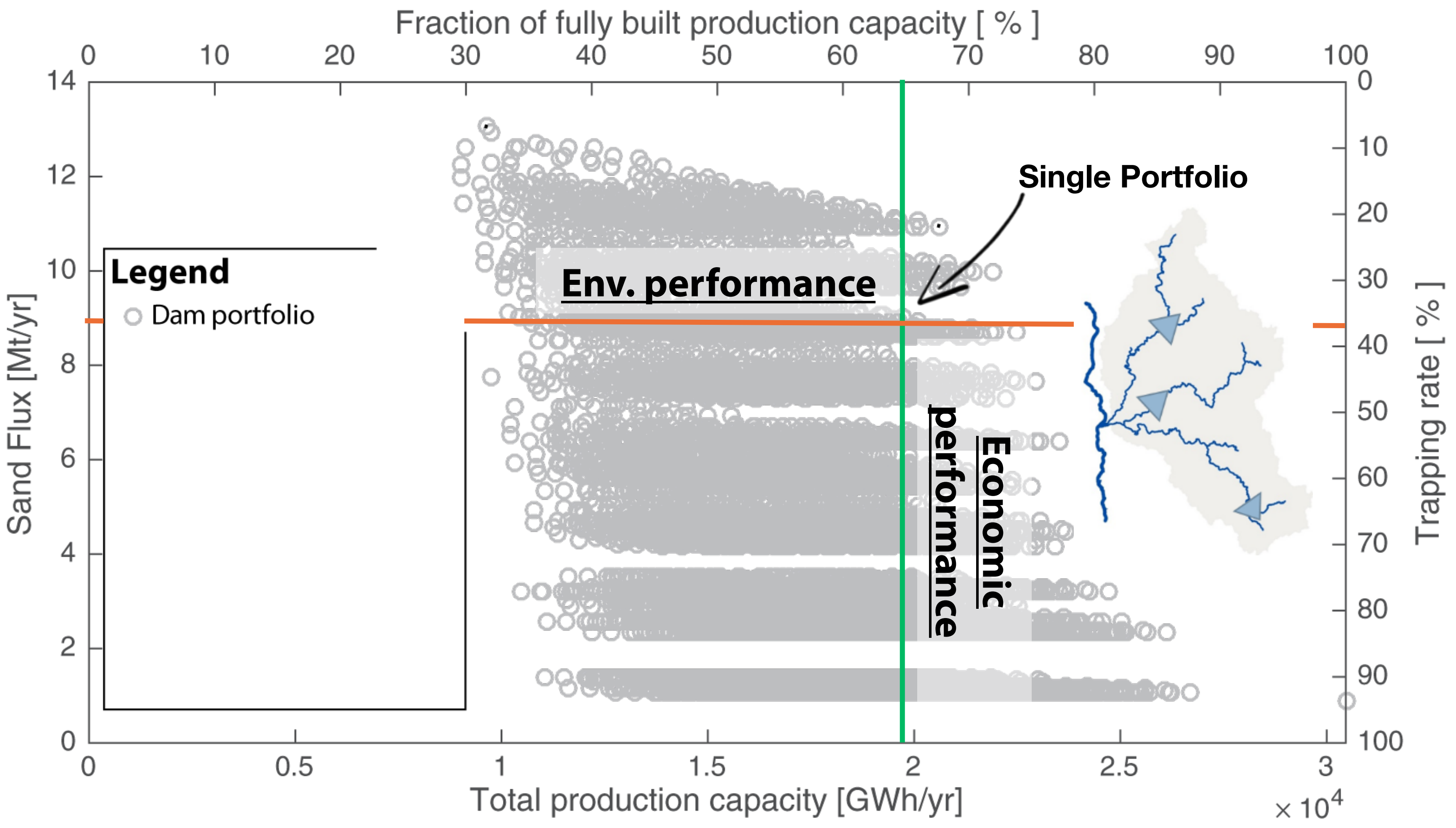


Sediment transport in the 3S basin

Source: Schmitt et al (in review) ‘Inverse modeling of sediment connectivity for reconstructing sediment load origins’

Hydropower in the 3S

Optimal trade-offs between sediment trapping and hydropower

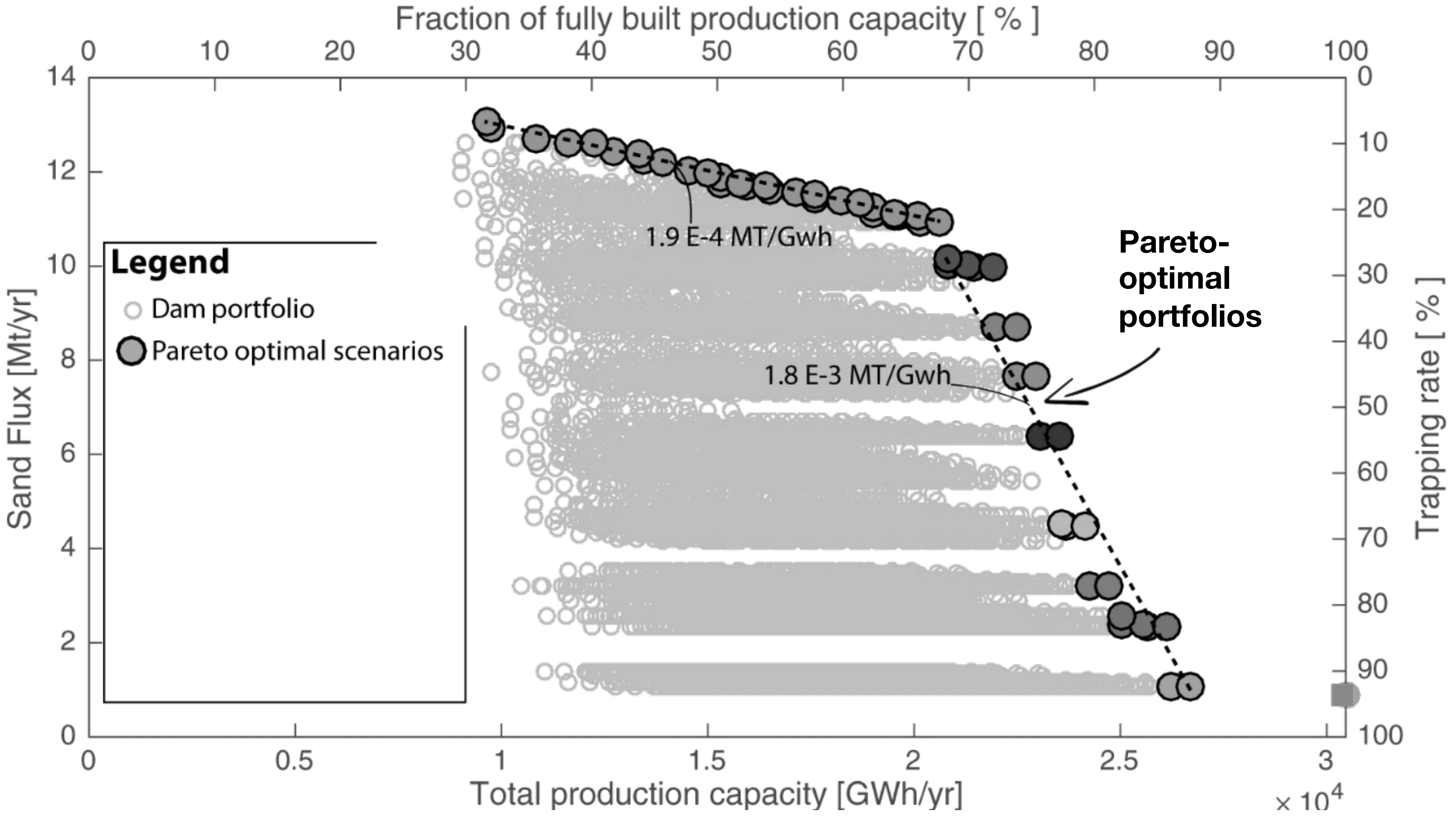


Analysing 17000 dam portfolios using CASCADE

1. Total sediment flux at basin outlet
2. Hydropower production
3. Production costs, fragmentation, hydrologic alteration (not shown)

Hydropower in the 3S

Optimal trade-offs between sediment trapping and hydropower

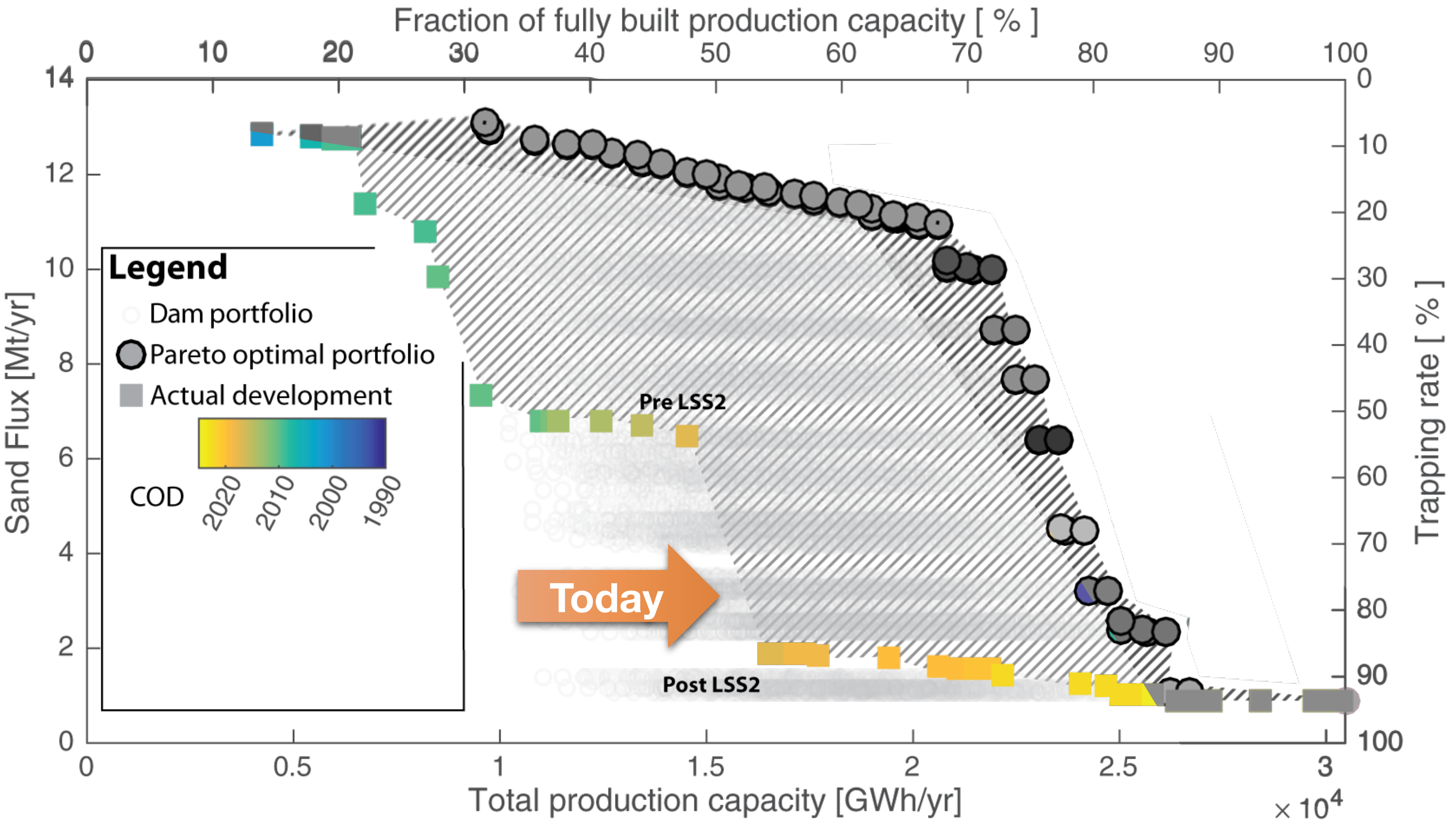


Pareto-optimal portfolios:

- Minimize sediment trapping for a given production capacity
- Quantify trade-offs between sediment trapping and hydropower
- Identify a basin-wide tipping point

Hydropower in the 3S

Lost opportunities through site-by-site planning

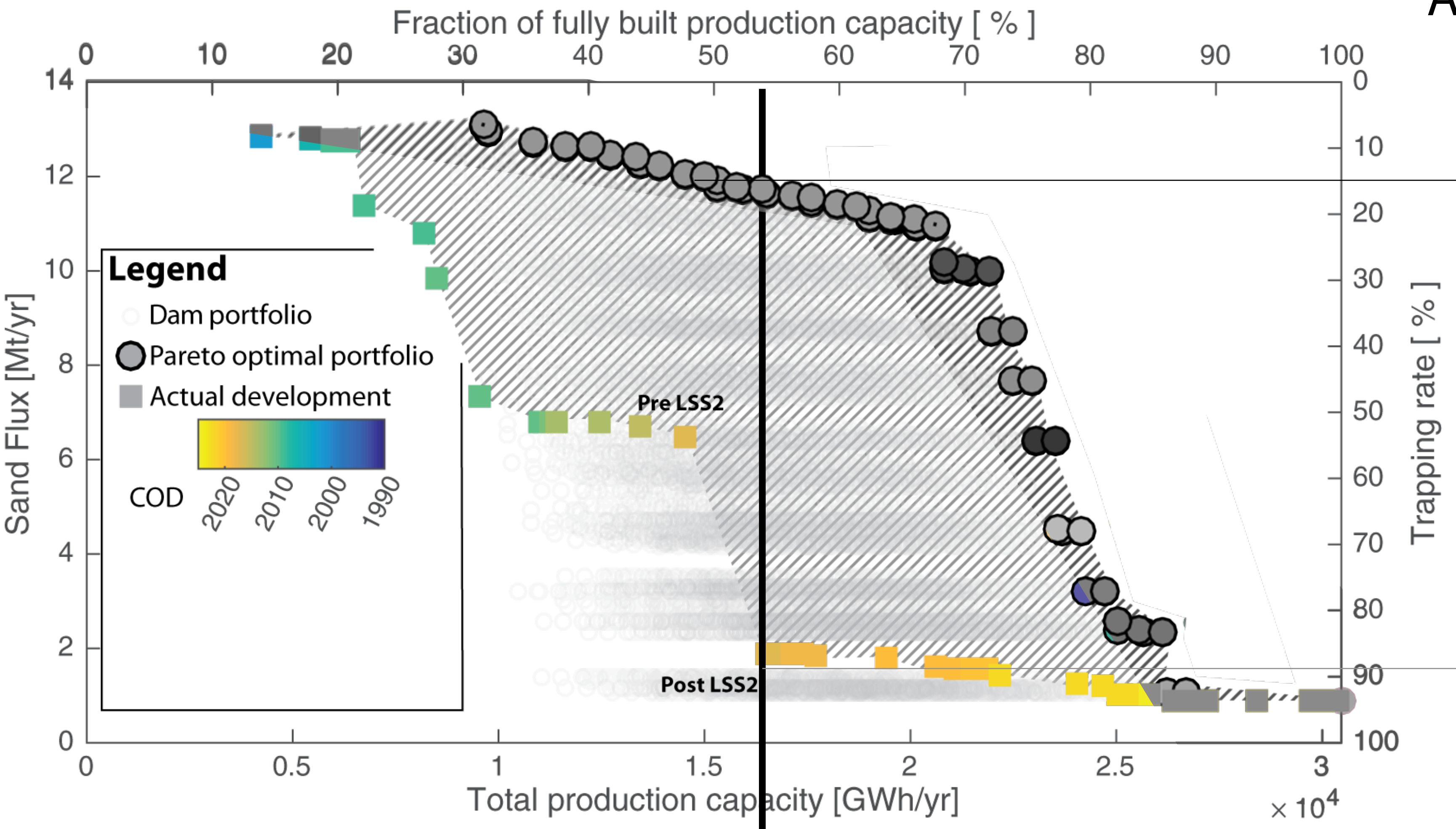


Lower Se San 2 Dam

Hydropower in the 3S

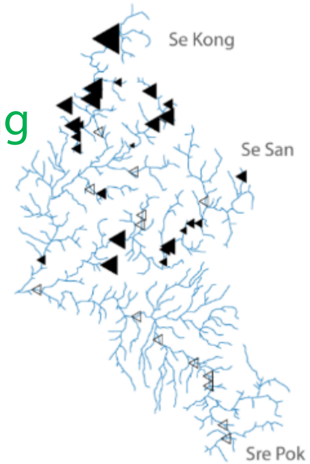
Lost opportunities through site-by-site planning

Actual planning



55 % of total capacity

15 % Trapping



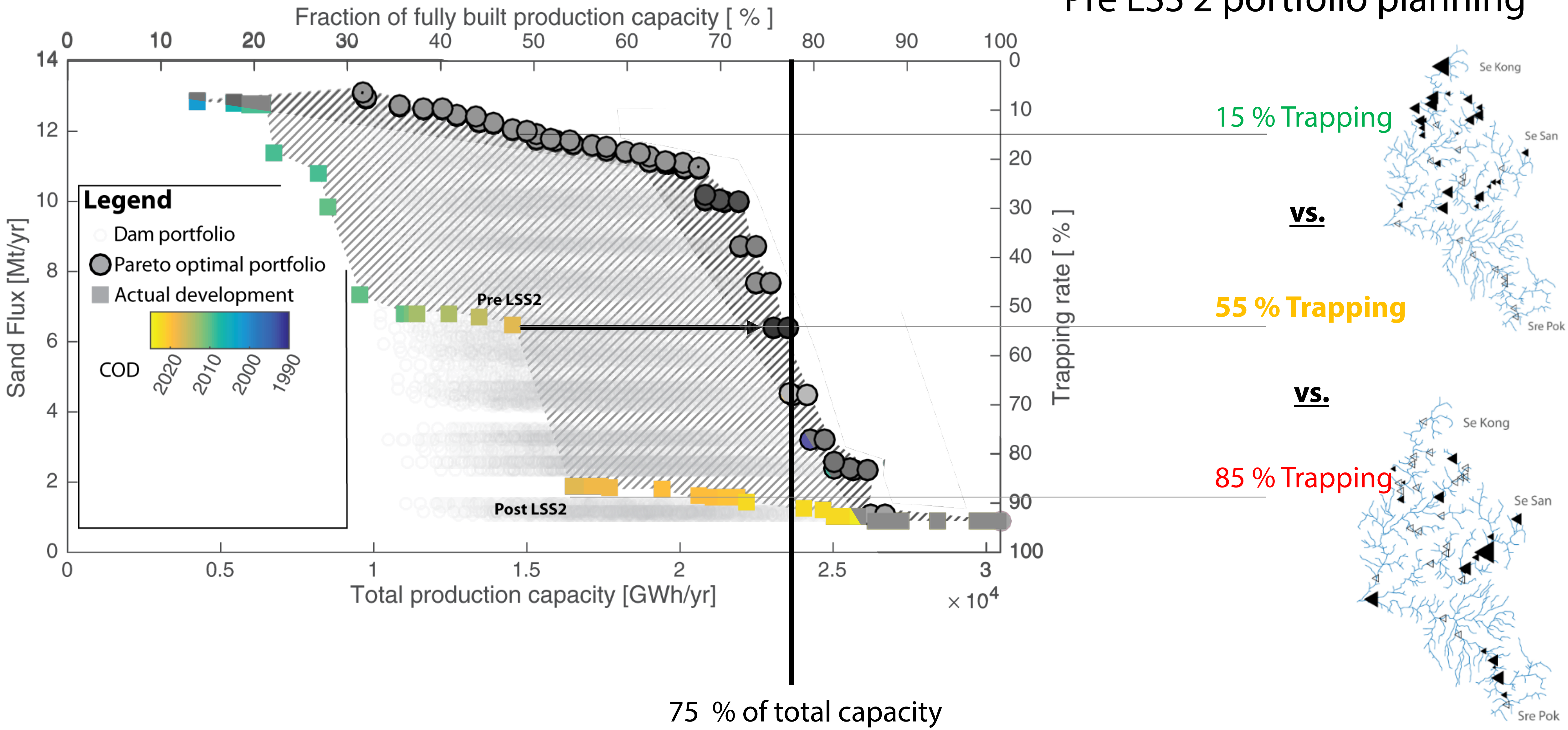
vs.

85 % Trapping

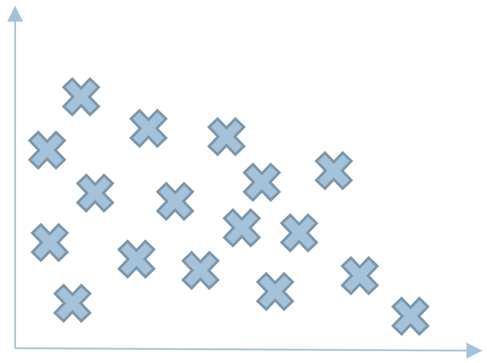
Hydropower in the 3S

Lost opportunities through site-by-site planning

Pre LSS 2 portfolio planning

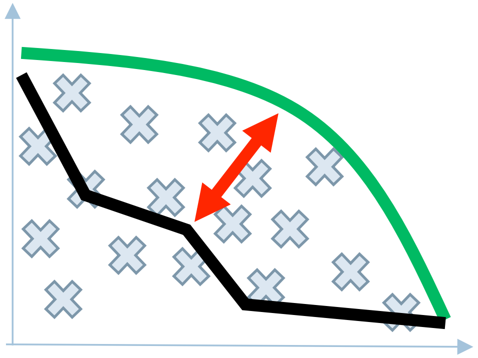


CASCADE - Enabling strategic portfolio optimization of dam sediment trapping

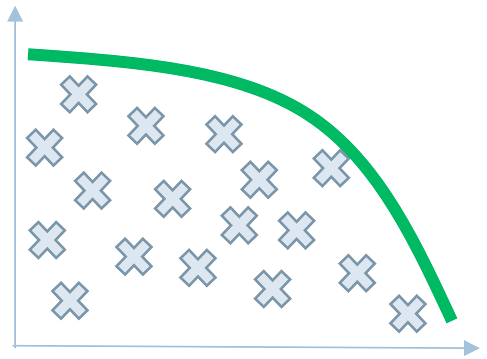


(1) New data and predictive models enable:

- Modeling and understanding sediment connectivity in data-scarce basins
- Evaluating large numbers of dam portfolios



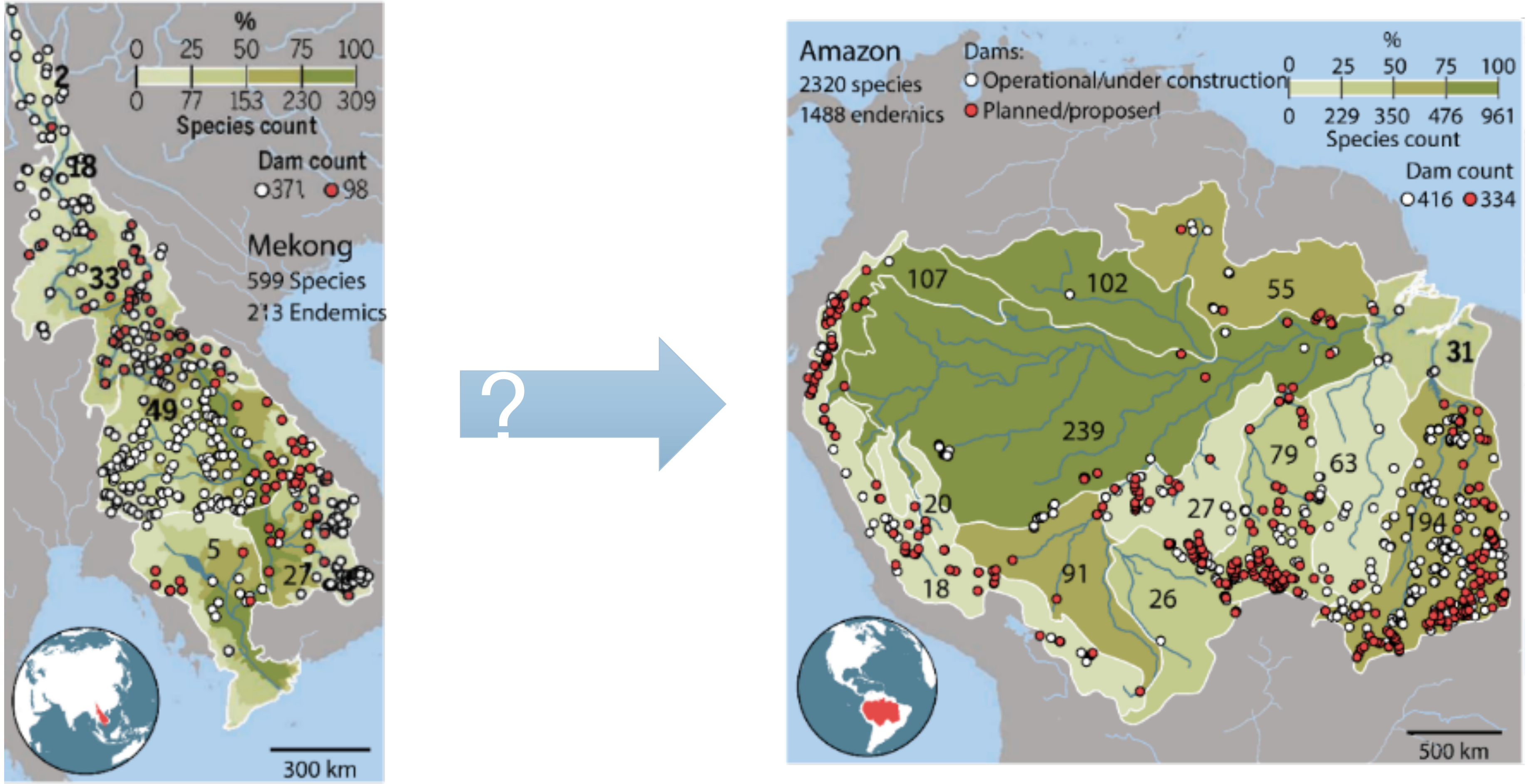
(2) Site-by-site planning is very unlikely to result in optimal trade-offs between sediment trapping and hydropower



(3) A portfolio perspective enables **informed selection** of **optimal trade-offs** between sediment trapping and hydropower production

Need to: 1) assess cumulative effects of multiple dams in a basin,
2) design dams to include sustainable sediment management.
3) plan strategically at the basin scale.

Can we apply insights from Mekong elsewhere?



Thank you!
Questions?

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Additional material

The cost side of optimal portfolios