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Managing River Sediment in Extreme Conditions: Lessons for California

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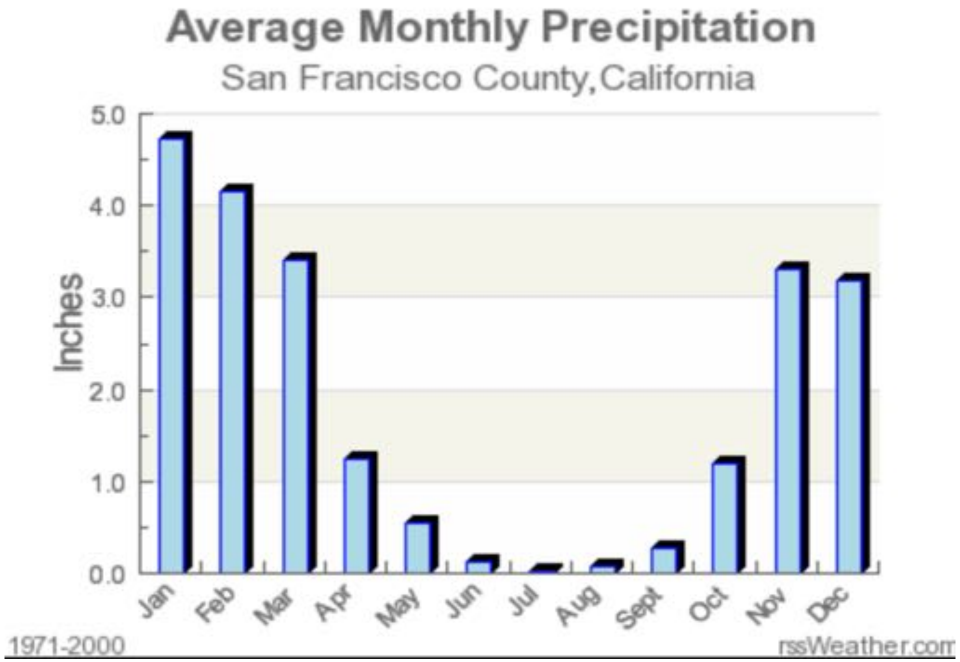
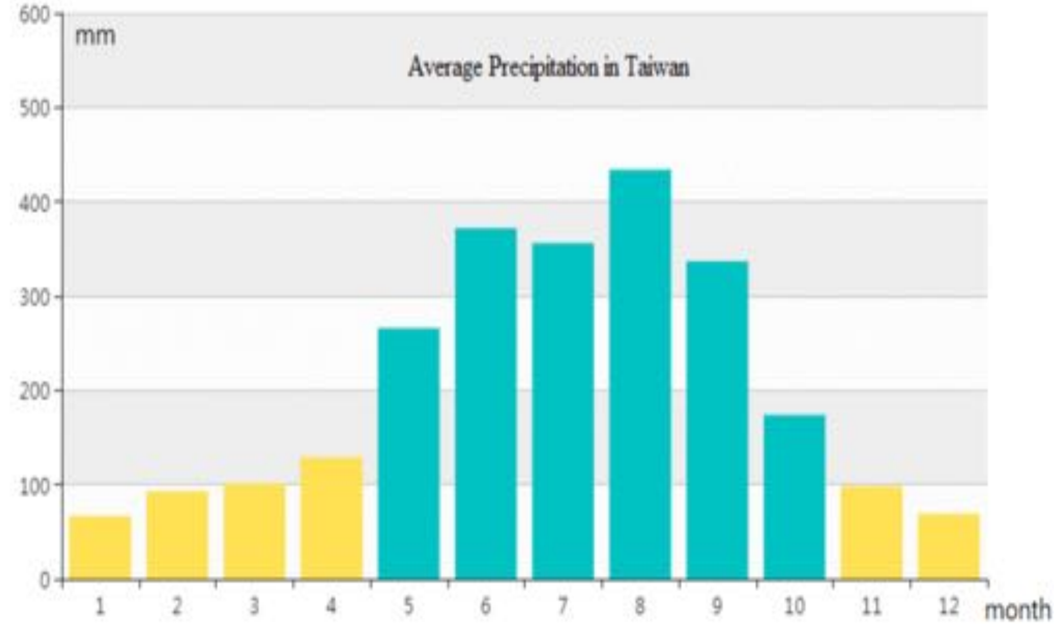
Greenland
Iceland
Finland
Sweden
Norway
Russia
United Kingdom
Poland
Ukraine
Kazakhstan
Mongolia
Canada
United States
California
Spain
Turkey
China
Japan
South Korea
North Atlantic Ocean
Iraq
Iran
Afghanistan
Pakistan
Algeria
Libya
Egypt
Saudi Arabia
Mexico
India
Thailand
Taiwan
Mali
Niger
Sudan
Chad
Nigeria
Ethiopia
Venezuela
Colombia
Kenya
DRC
Indonesia
Papua New Guinea
Tanzania
Brazil
Peru
Angola
Bolivia
Namibia
Botswana
Madagascar
Indian Ocean
South Pacific Ocean
South Atlantic Ocean
Chile

Taiwan and US Comparison





https://www.wrap.gov.tw/en/paper7.aspx

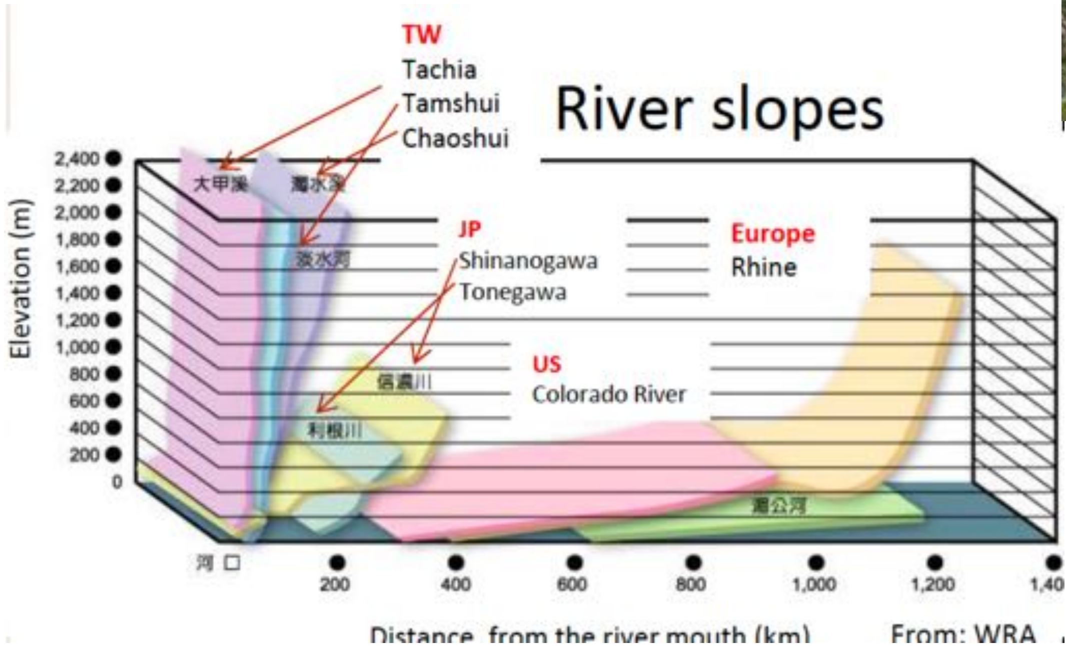
	Taiwan	California
Facts	Hydrology variable, Geologically active, Earthquake, Changing climate…	Hydrology variable, Geologically active, Earthquake, Changing climate…
Annual rainfall (mm/yr)	2509	54.5
Mean length of river (km)	124	584
Population density (people/km^2)	639	93
Per capita distribution of rainfall (m^3/person/yr)	3860	588
No. of Reservoirs	61 major	3190
Owners	Mostly public	Public and private
Total Capacity of Reservoir	2.2 billion m^3	52.5 billion m^3
Reservoir Sedimentation	30% lost for 61 major reservoirs by 2011	7% lost for 43 reservoirs by 2008

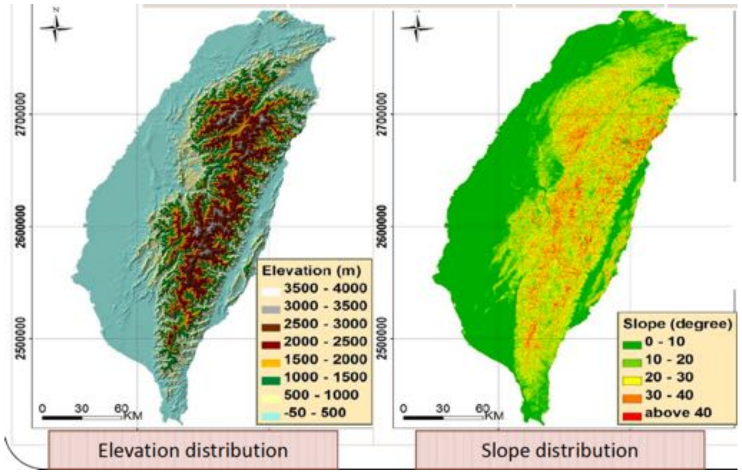
Total area	Mountainous area	Population	Population density
36,000 km^2	66%	23 M	639 per km^2 (10th highest over the world)

California
423,970 km2
~ 39 million people

Taiwan
36,000 km2
~ 23 million people

- Ratio in SIZE = 12
- Ratio in POPULATION: 1.7





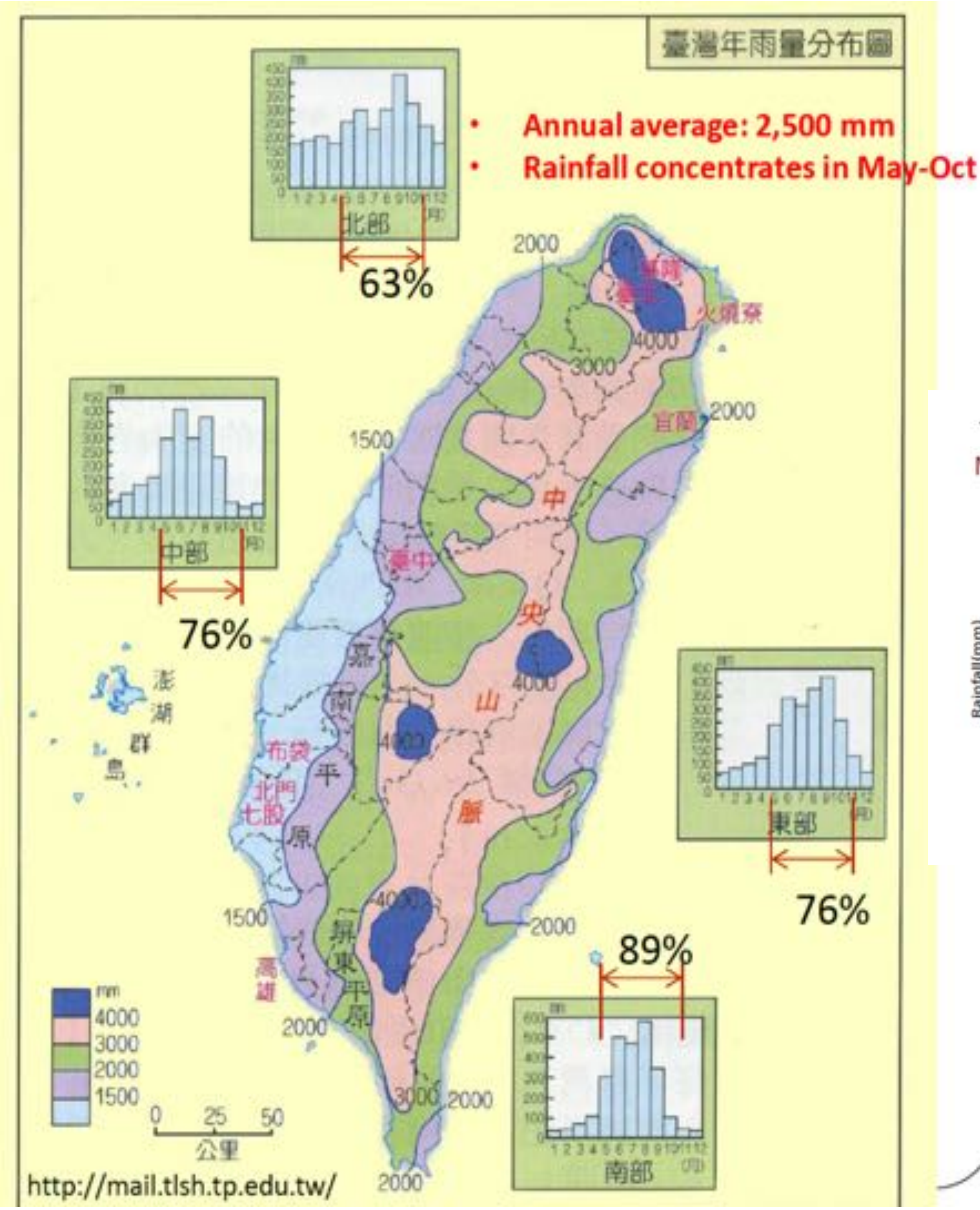

Chishan River
Before and After Typhoon Morakot in 2009
Bedrock exposed

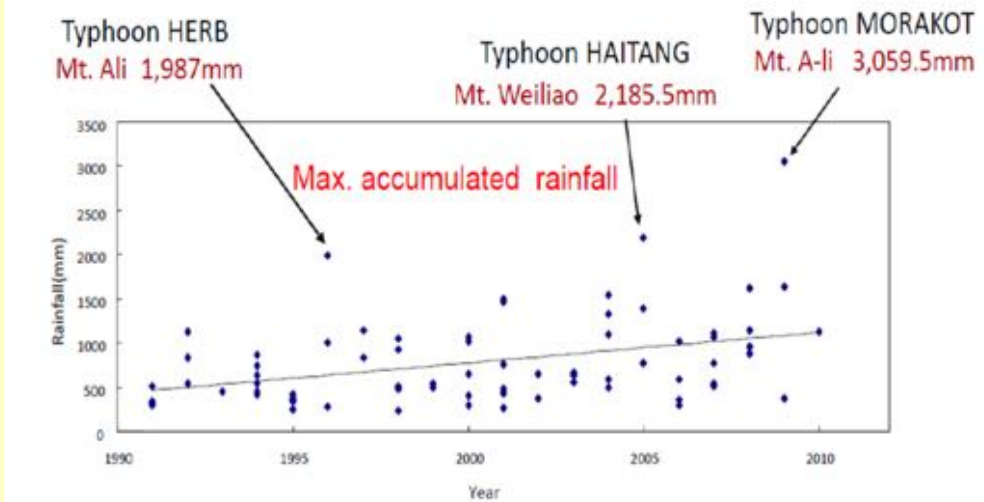

Chishan River
Before and After Typhoon Morakot in 2009
15m deposition


HWM in Tainan

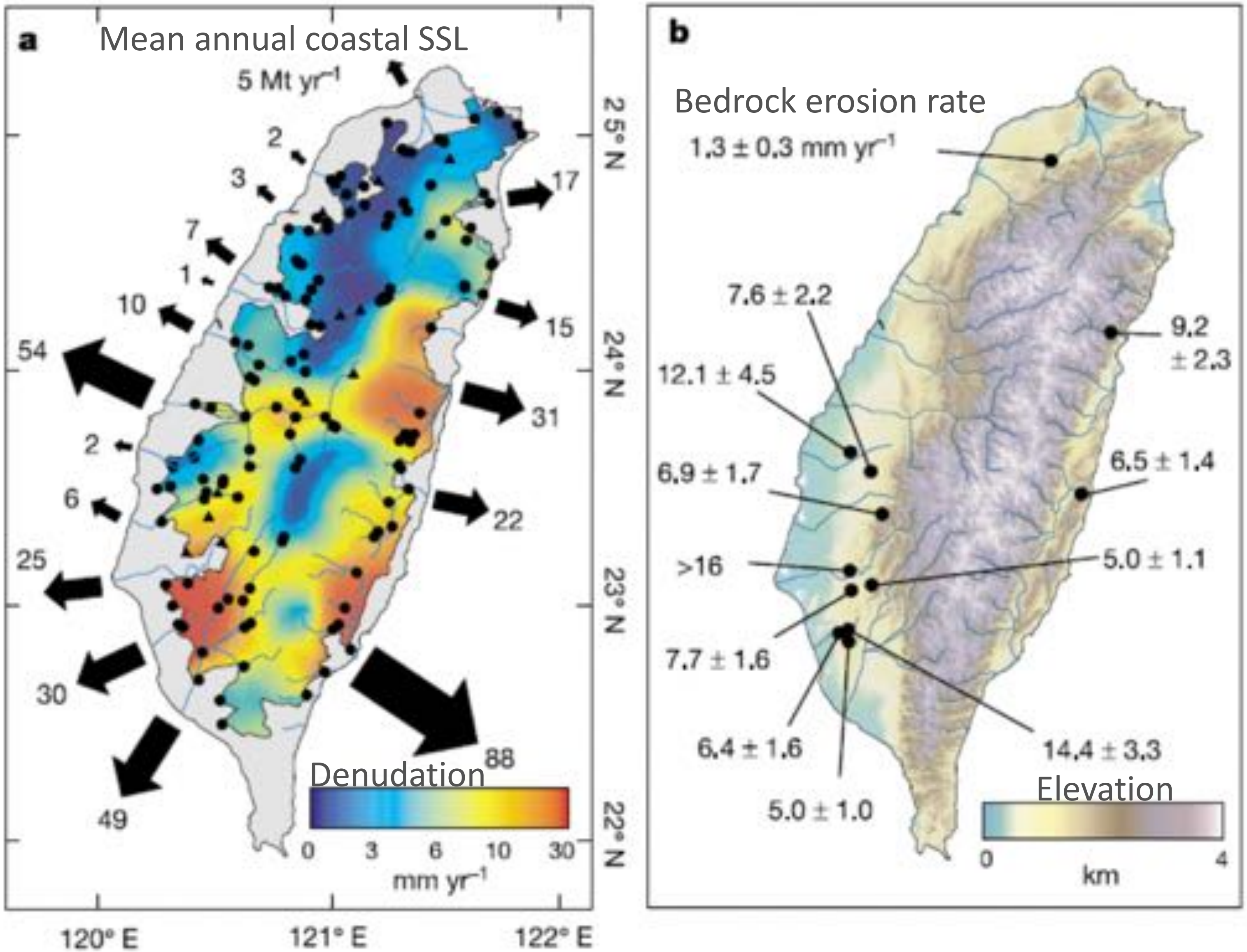
Characteristics of Taiwan

- Northeast monsoon
- Mean annual precipitation of 2.5 m/year
- Annual average of 3~4 typhoons; Frequent earthquakes
- The rainfall ratio of wet to dry season is 1.5 in northern and 9 in south region
- Water demand more in the west
- Denudation rates of 3~6 mm/year
- Sediment yield are high

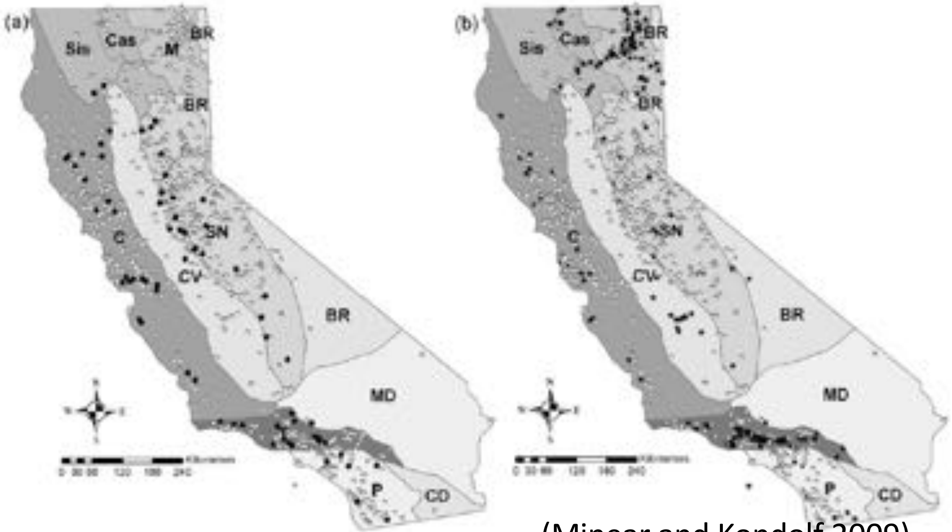

臺灣年雨量分布圖
Annual average: 2,500 mm
Rainfall concentrates in May-Oct
北部
63%
中部
76%
東部
76%
南部
89%
http://mail.tlsh.tp.edu.tw/


Typhoon HERB
Mt. Ali 1,987mm
Typhoon HAITANG
Mt. Weiliao 2,185.5mm
Typhoon MORAKOT
Mt. A-li 3,059.5mm
Max. accumulated rainfall
Rainfall(mm)
Year

Taiwan supplies the oceans with 384 M tonnes of suspended sediment per year, about 1.9% of the world's total, from its 36,000 km2 (only 0.024% of the world's land area).



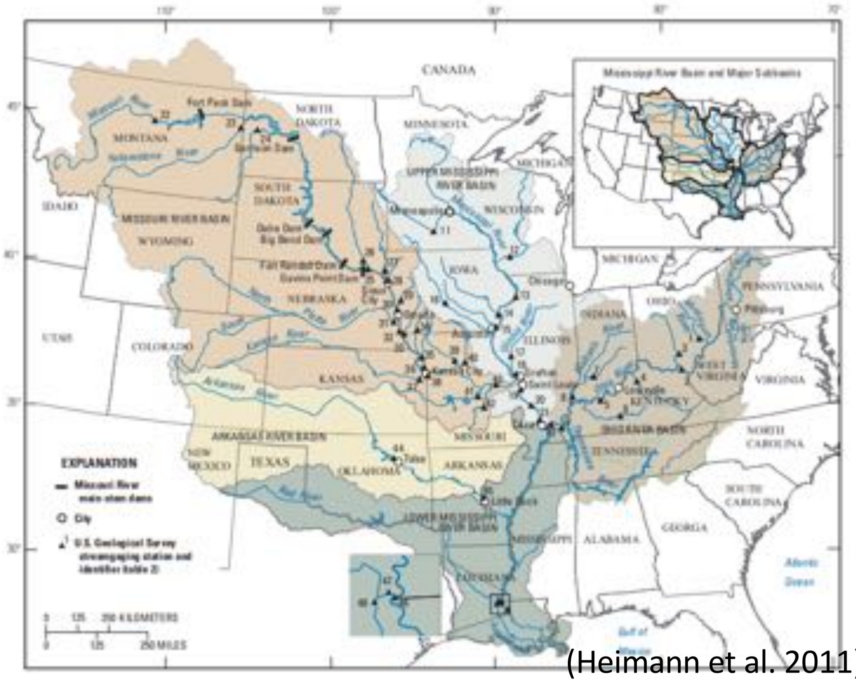
(Dadson et al., 2003)



(Minear and Kondolf 2009)

California

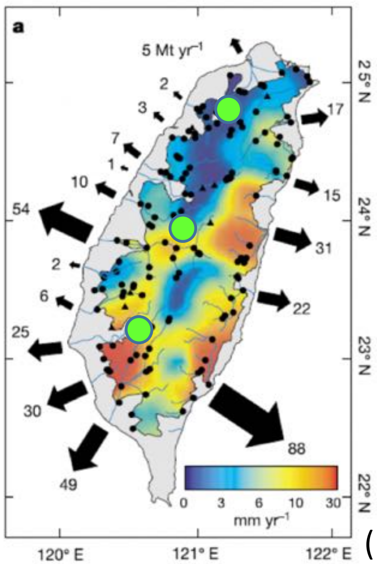
- The median denudation rate is 0.18 mm/yr
- The highest is 0.52 mm/yr in the Transverse Ranges (T)
- The lowest is 0.09 mm/yr in the Central Valley (CV)



(Heimann et al. 2011)

Mississippi River

- The highest is 0.74 mm/yr in the lower Missouri tributaries



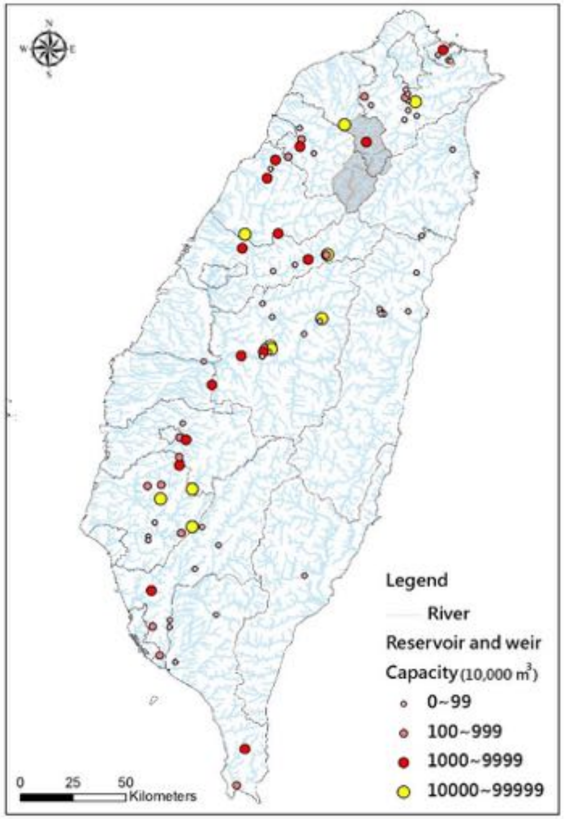
(Dadson et al., 2003)

Taiwan

- Denudation rate (Wang et al., 2018)
- Shihmen reservoir: 2.5 mm/yr
- Wujie reservoir: 0.5 mm/yr
- Zengwen reservoir: 13.7 mm/yr

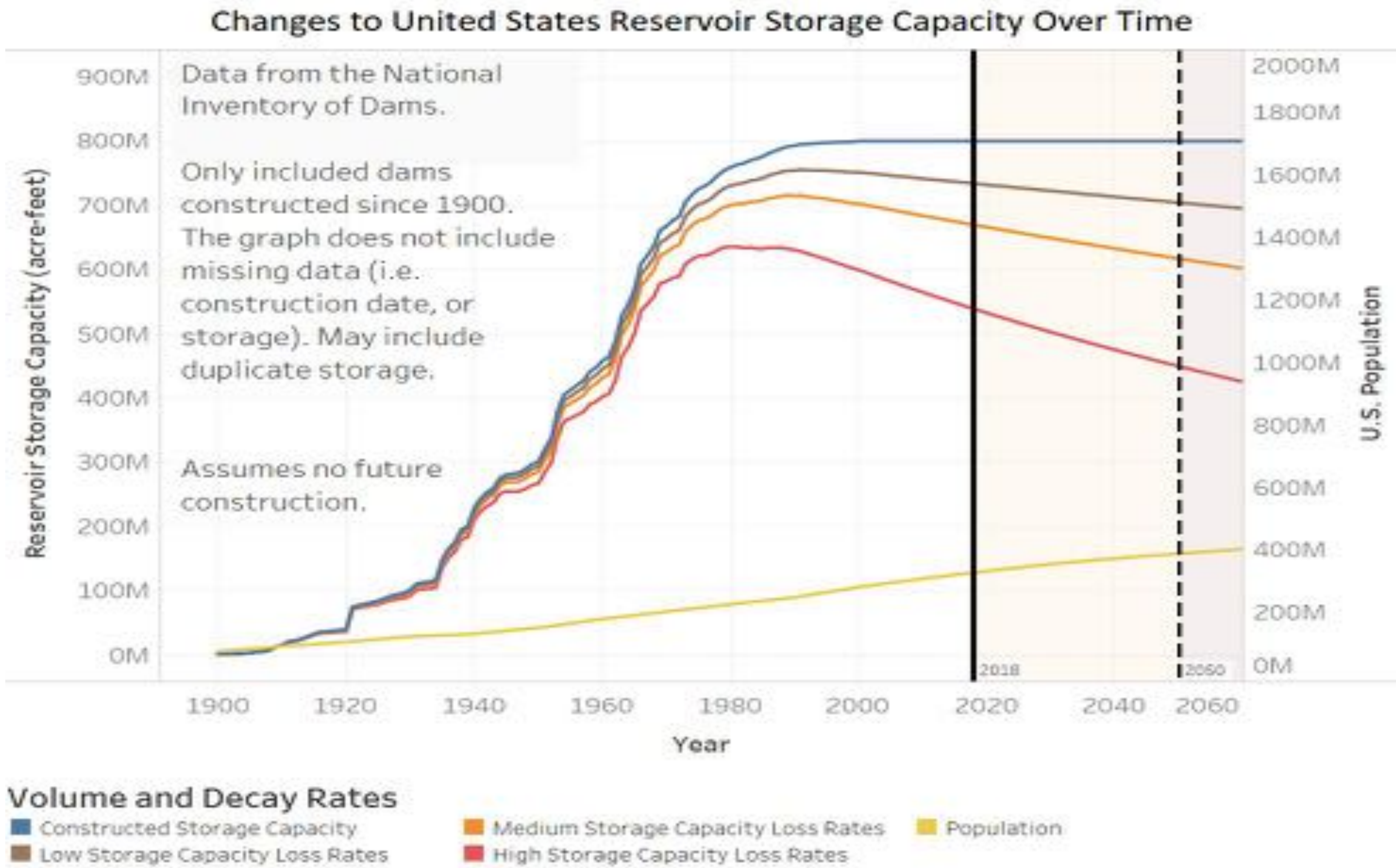
Reservoirs are filling more rapidly!

By 2011, **30 %** of the initial capacities of the major reservoirs lost to sedimentation (WRA, 2011)

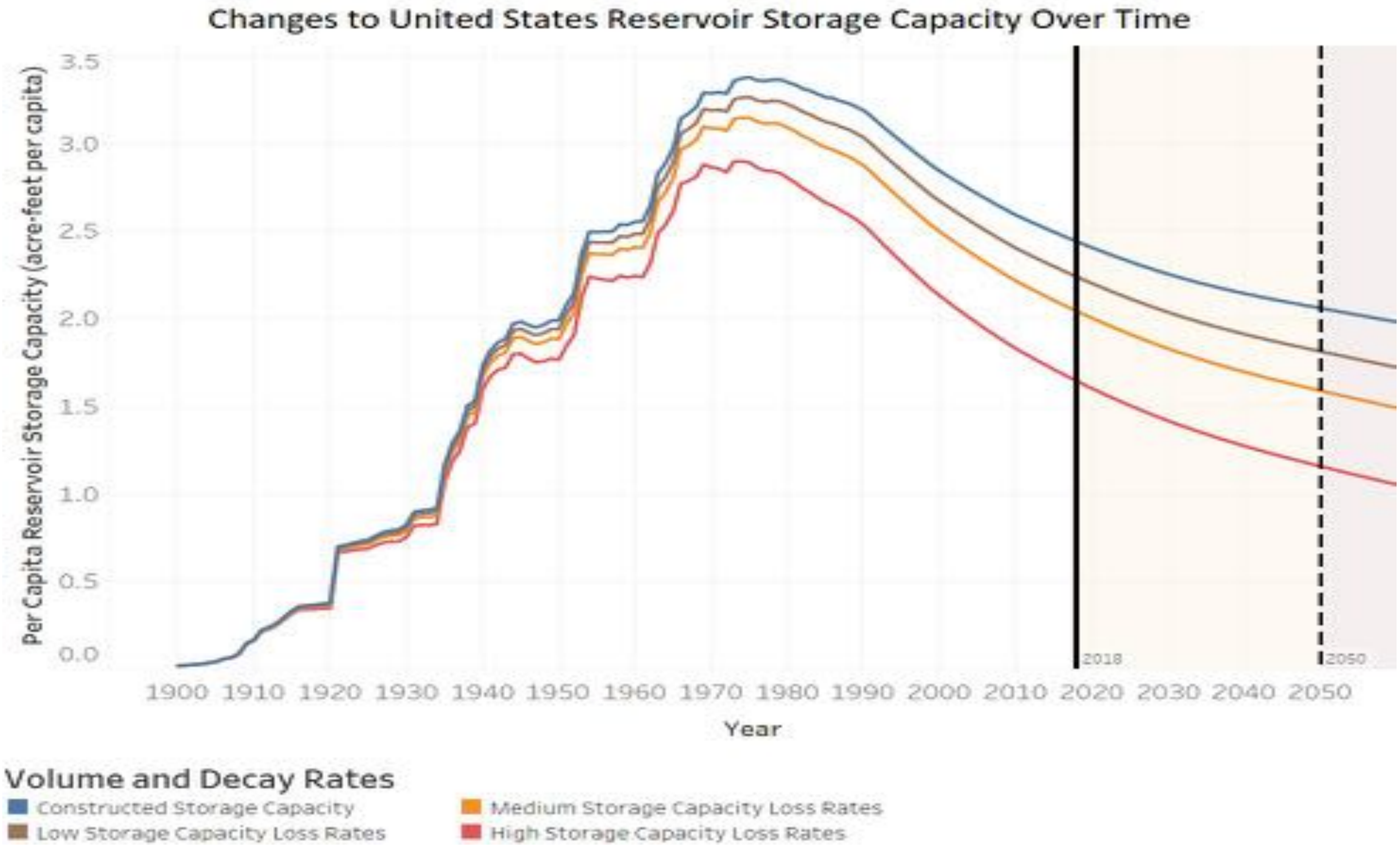


61 major reservoirs in Taiwan impound a total of 2.2 billion m3 for municipal, industrial, and agricultural water supply

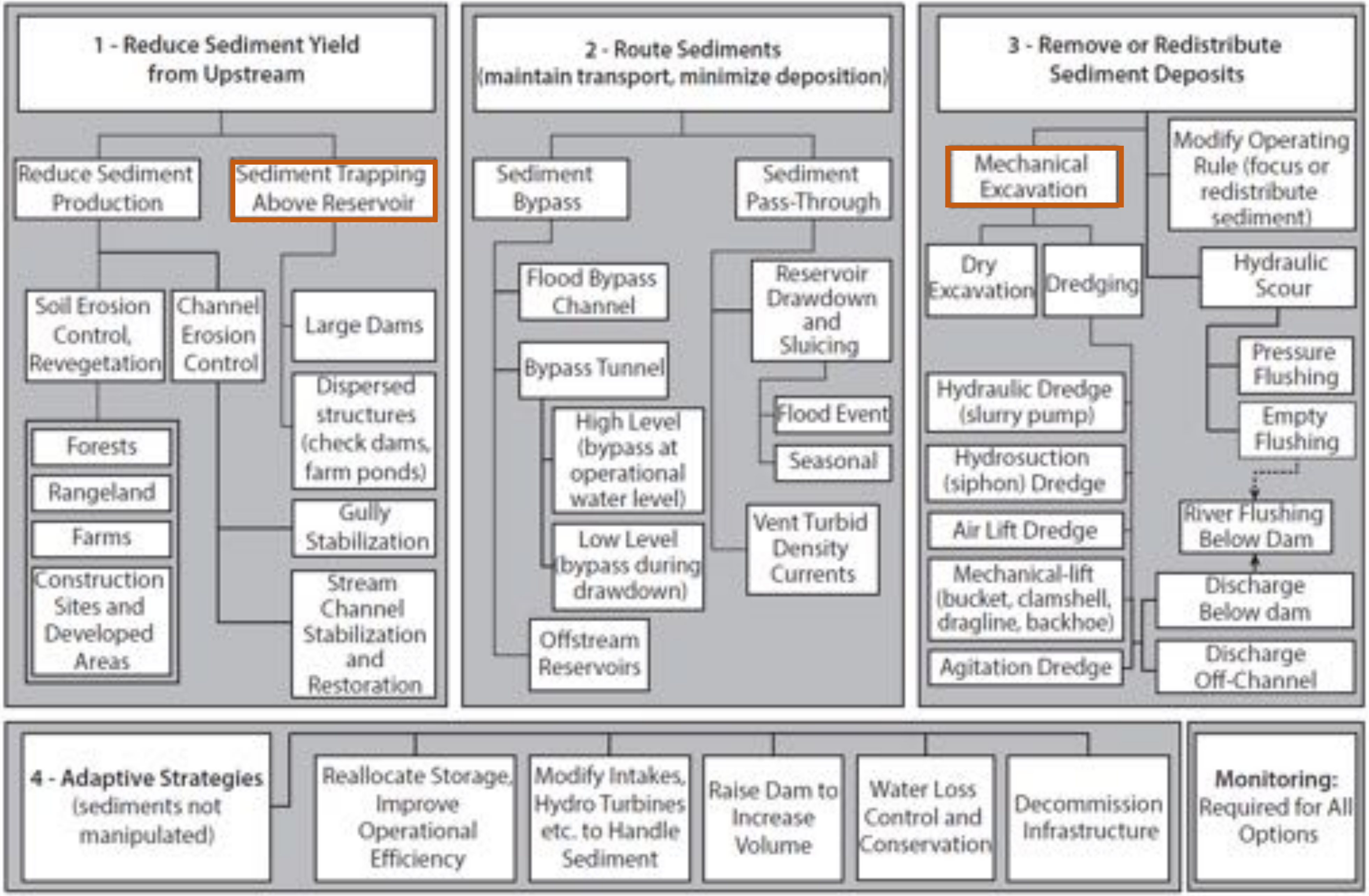
Emerging Worldwide Issues



Emerging Worldwide Issues



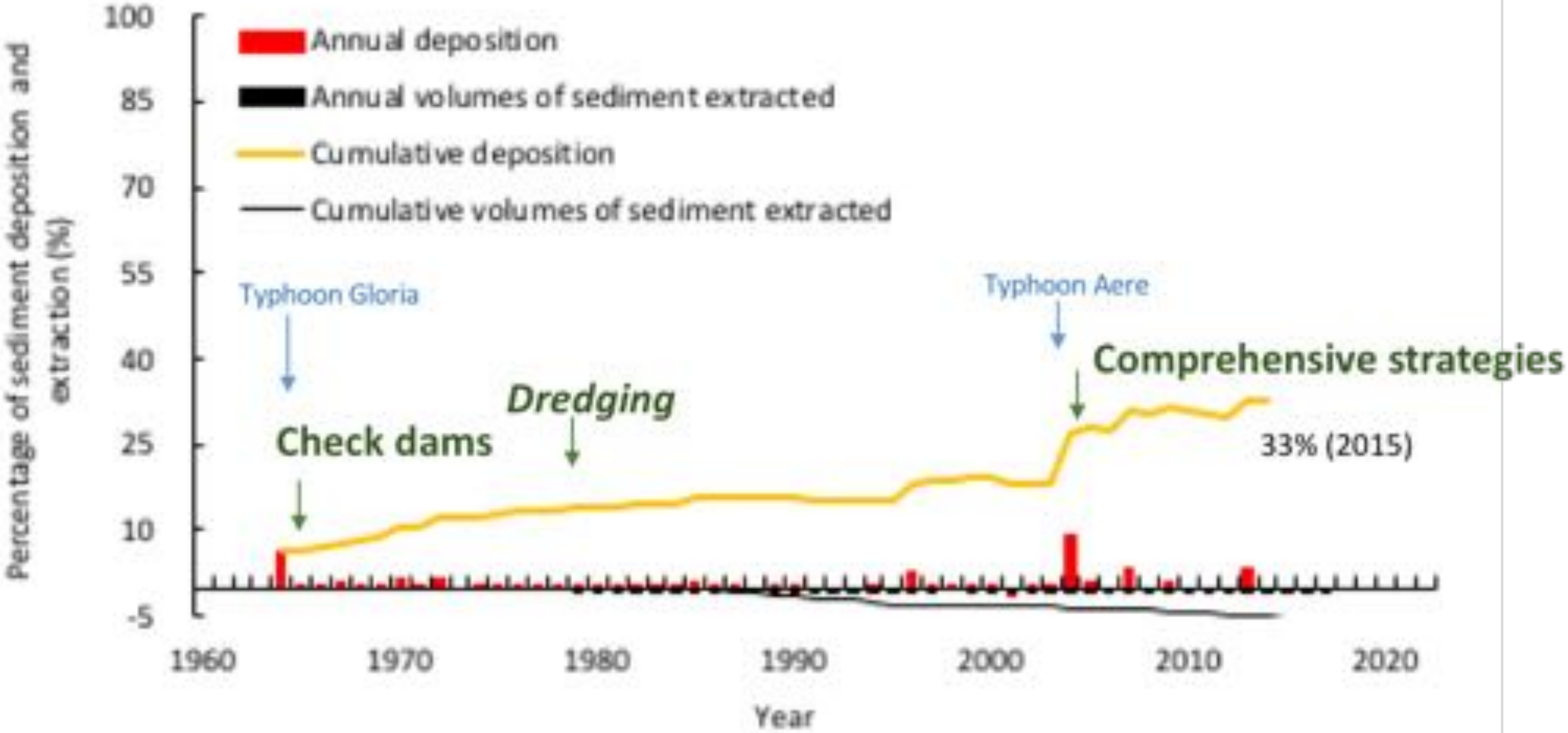
Sediment Management Alternatives



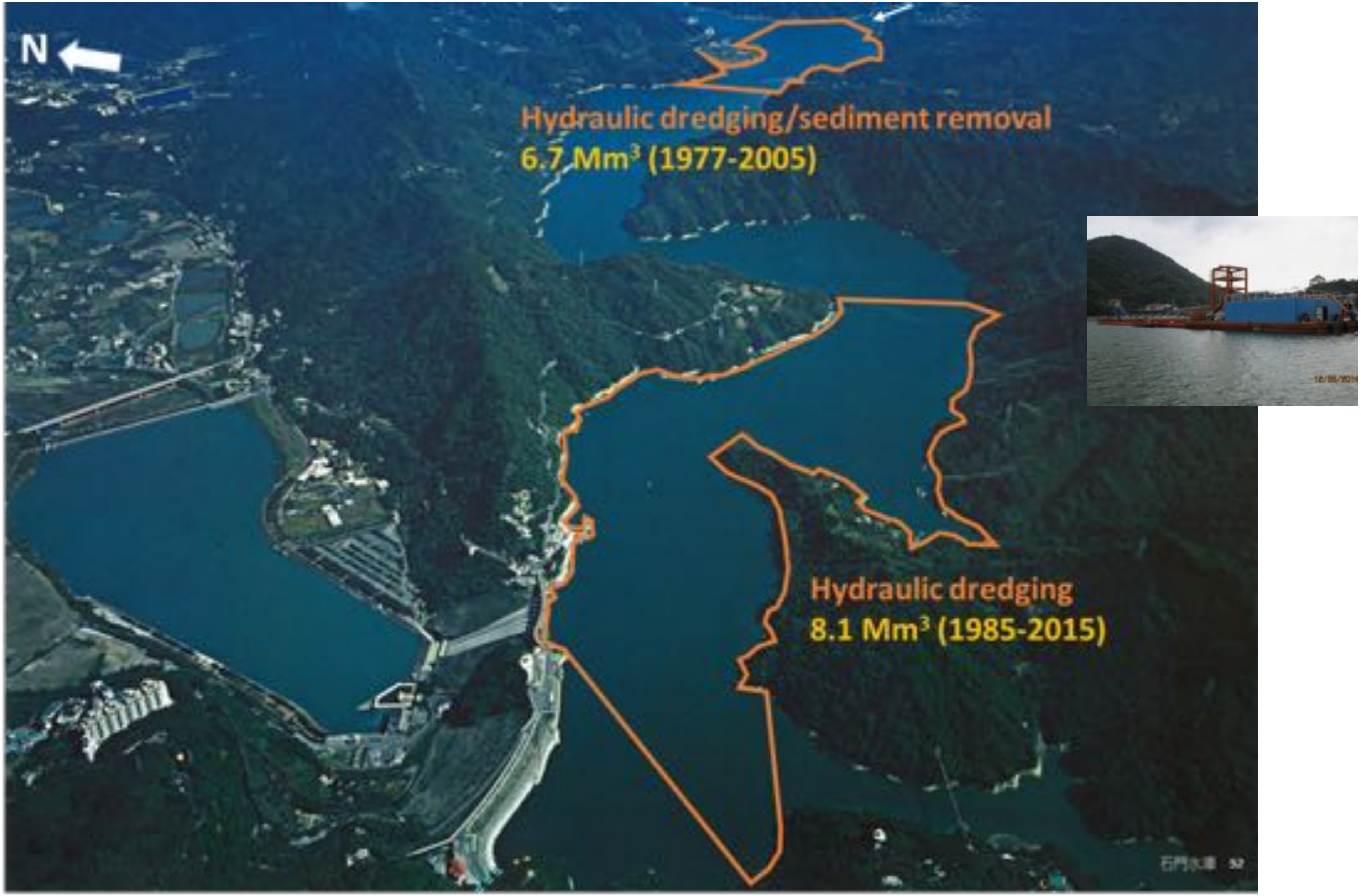
(Morris, 2015)

Shihmen Reservoir

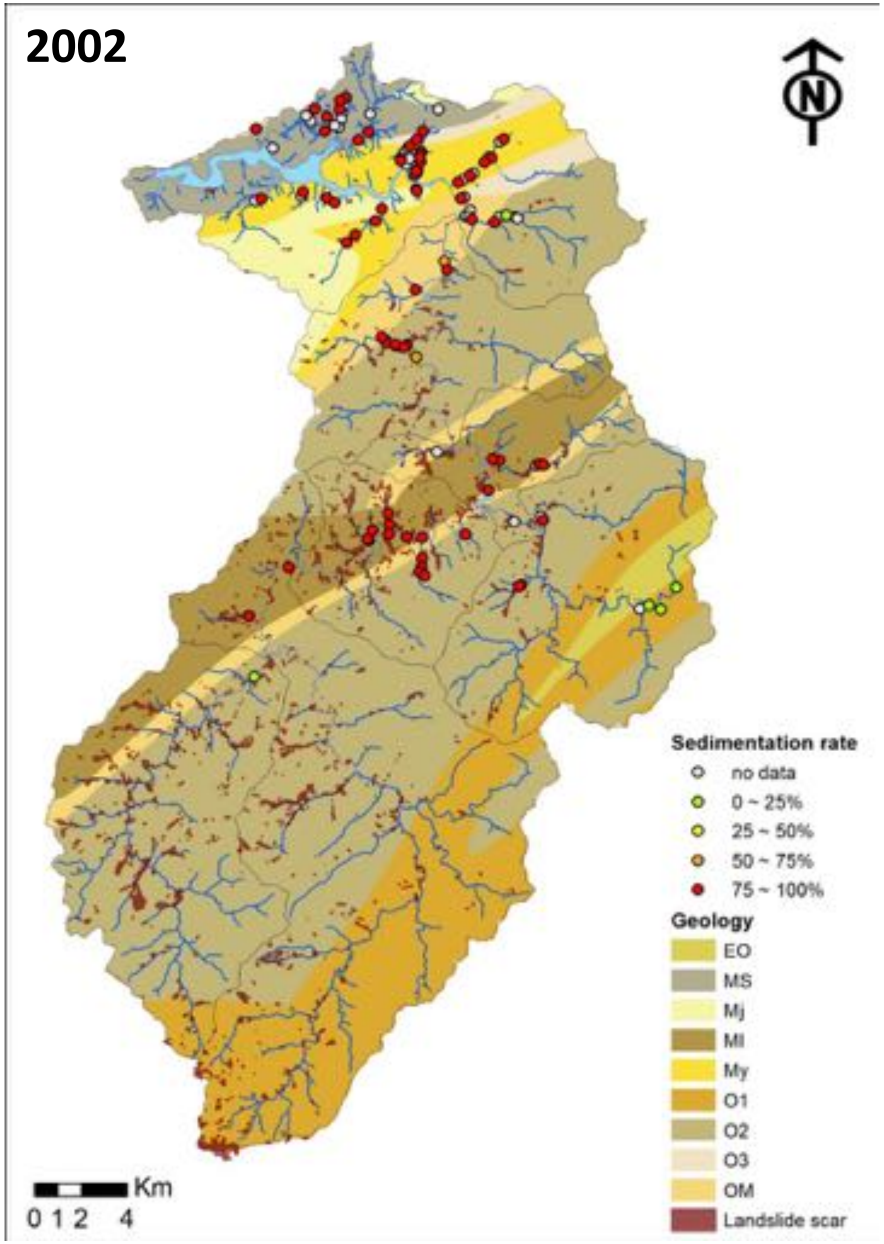
- 1964~
- 133 m high
- Initial total capacity: 309 Mm^3
- Mean annual runoff: 1,468 Mm^3
- Mean annual sediment inflow: 3.42 M m^3
- Flood control, hydropower generation irrigation and municipal supply, recreation



Mechanically dredging

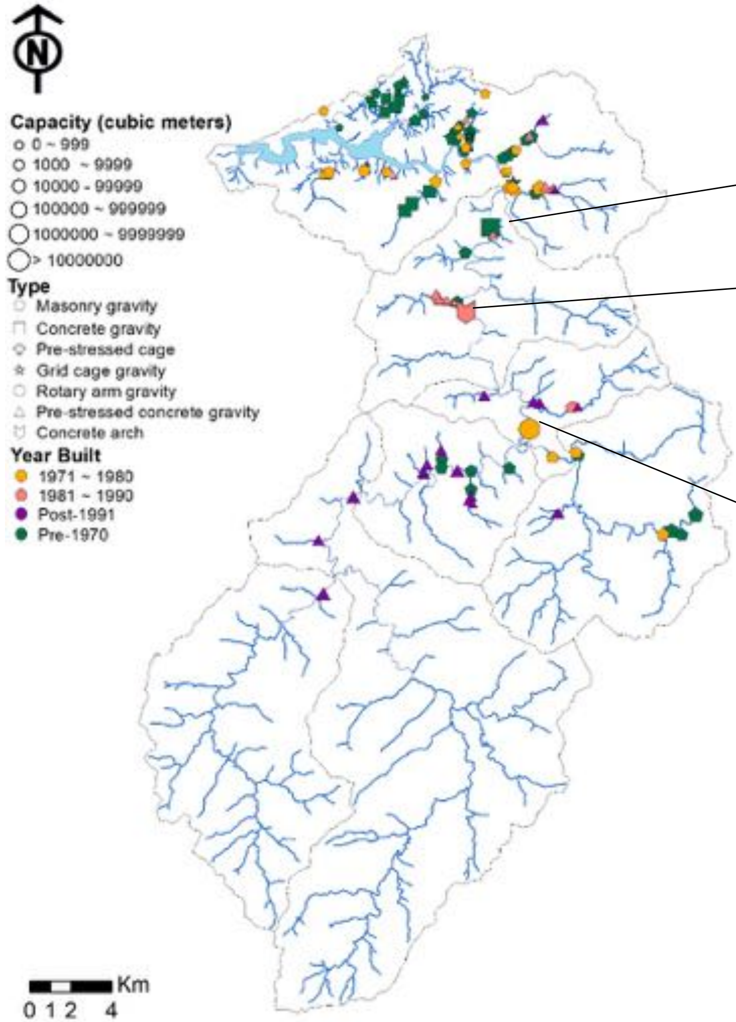


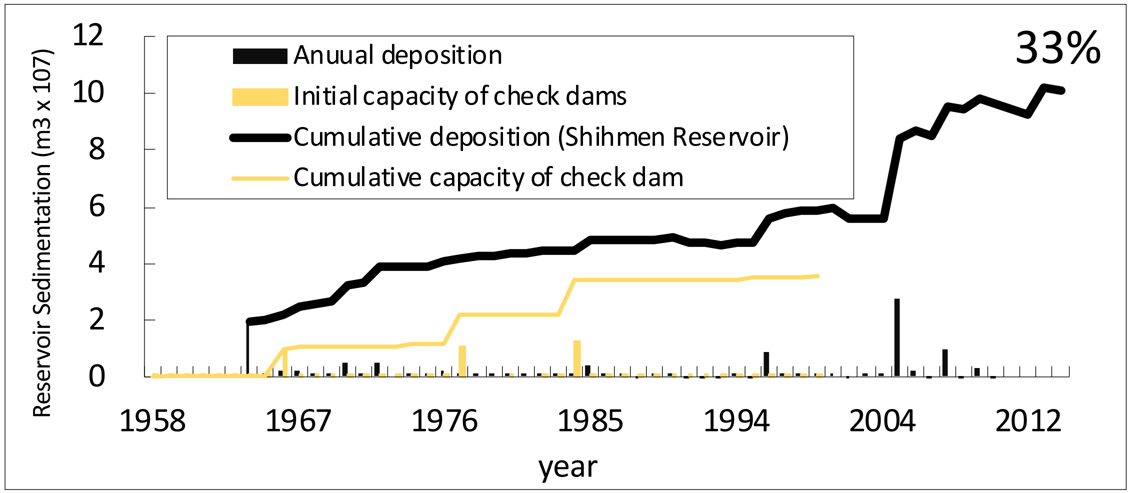
123 check dams upstream of Shihmen Reservoir



(Wang and Kondolf, 2014; Wang et al., 2015)

The three largest check dams

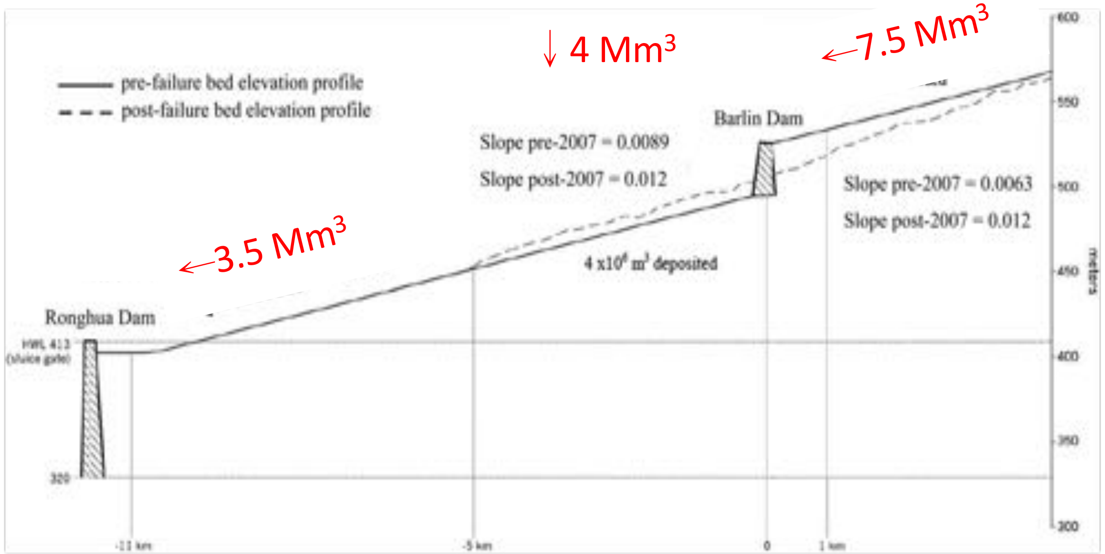




(Wang and Kondolf, 2014; Wang et al., 2015)

Barlin dam failure

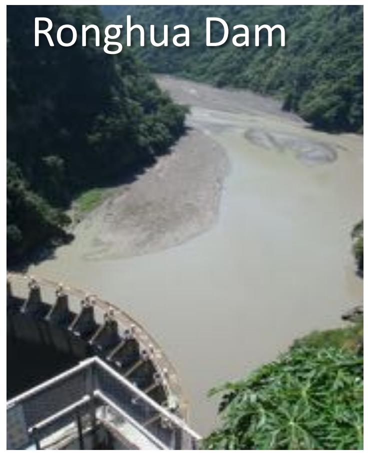
- 1977~2007
- 38-m-high
- 10.47 Mm^3



(Wang and Kondolf, 2014)

Dam structure condition in 2007

Dam (stream)	Initial Capacity (10^3 m^3) (year built)	Apparent Integrity of Dam (from visual inspection)	Filled with Sediment?
Barlin (Dahan)	10,470 (1977)	Failed	Yes (prior to failure)
Ronghua (Dahan)	12,400 (1984)	Main dam condition good (after repairs)	Yes
Yixing (Dahan)	5,800 (1966)	Defense dam failed, dam undercutting possible	Yes



(Wang and Kondolf, 2014)

Shihmen Reservoir during Typhoon Aere in 2004

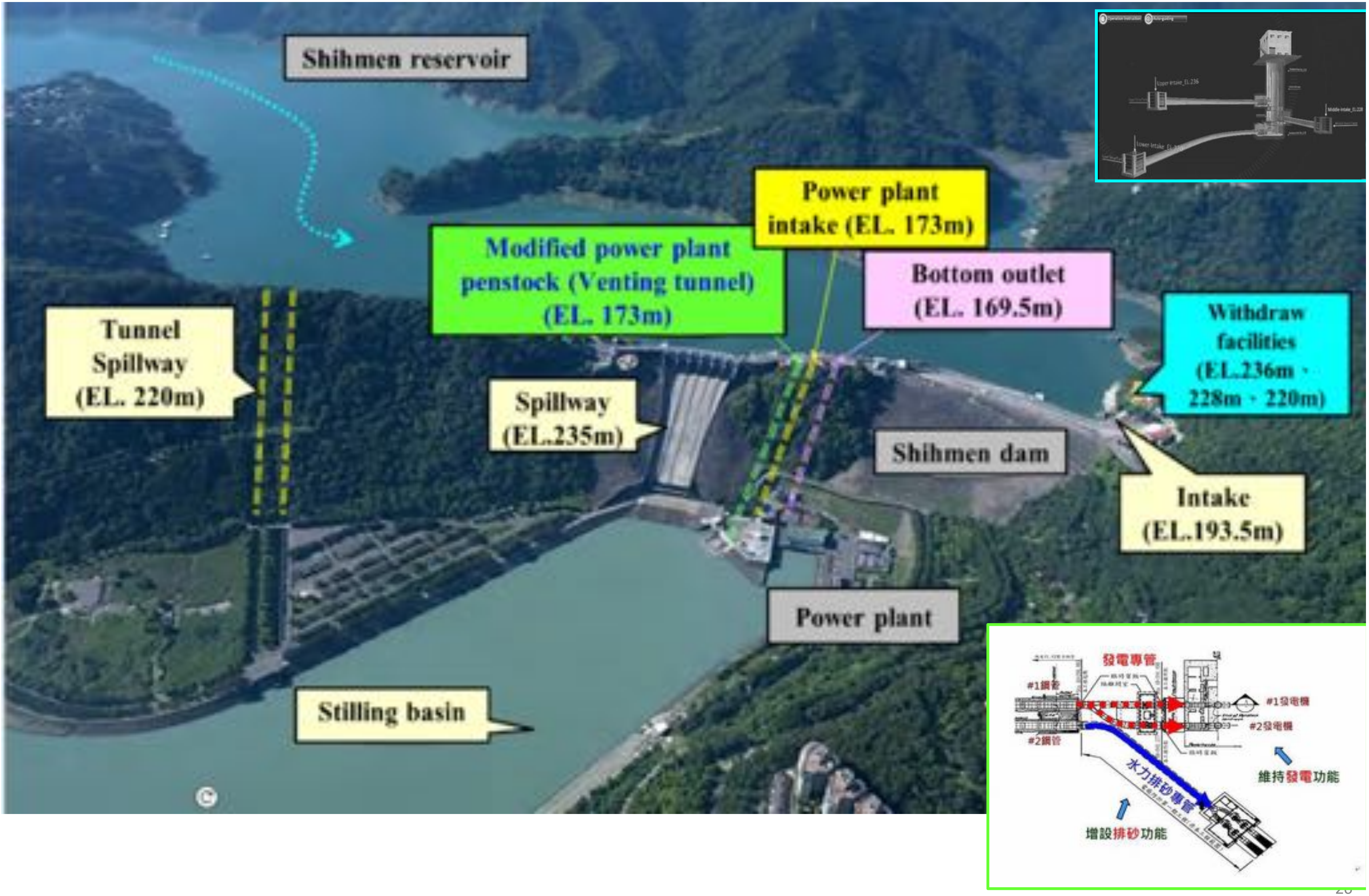

Deposited Muds in Penstocks in Shihmen

Floating Debris after Typhoon Aere at Shihmen



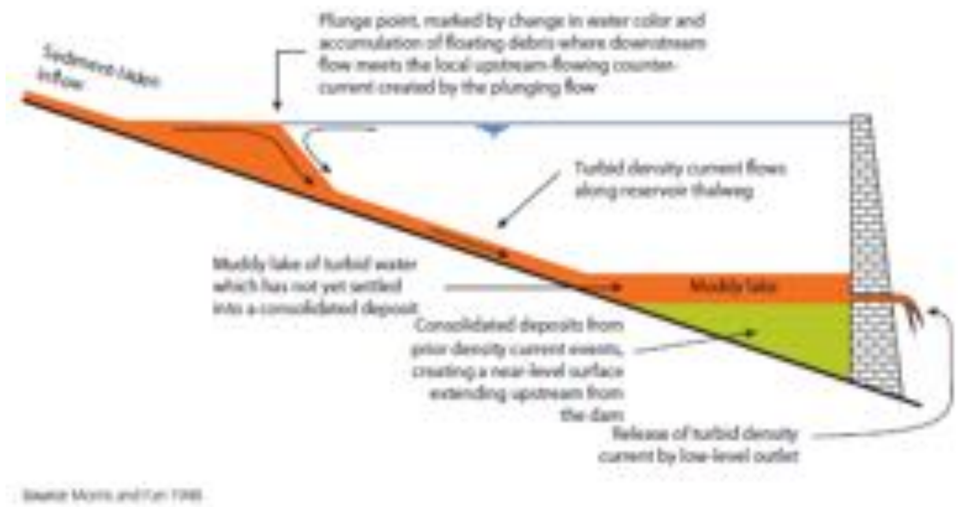

From Water Resources Agency (WRA)

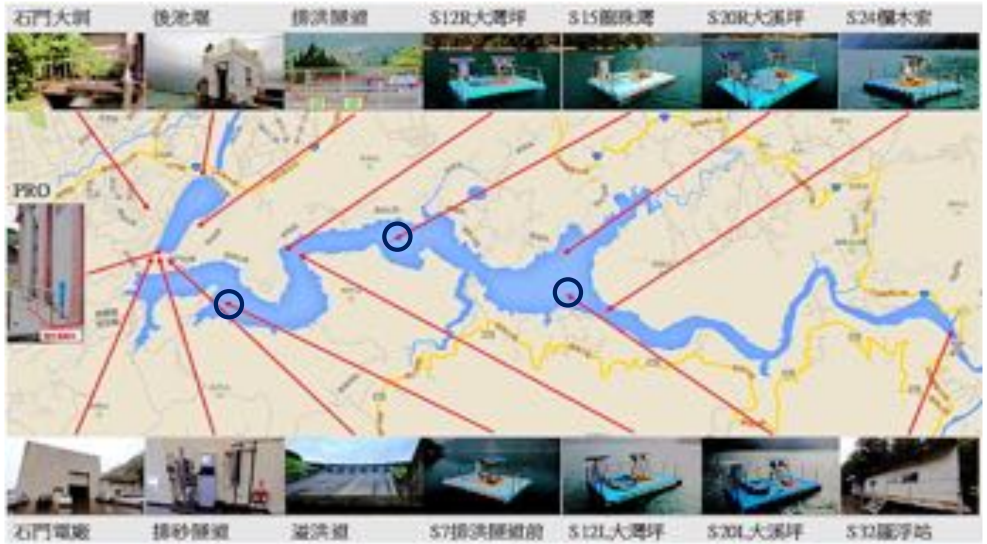
Modifications to Shihmen Reservoir to Manage Sediment



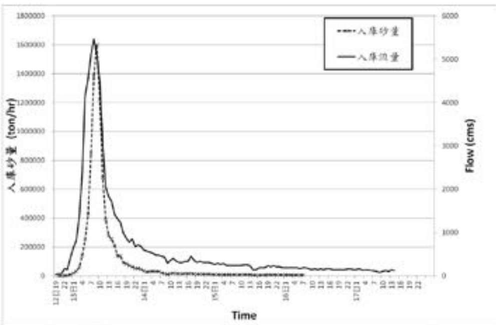
New sediment concentration monitoring technique

- Time Domain Reflectometry, TDR (Chung and Lin, 2011)

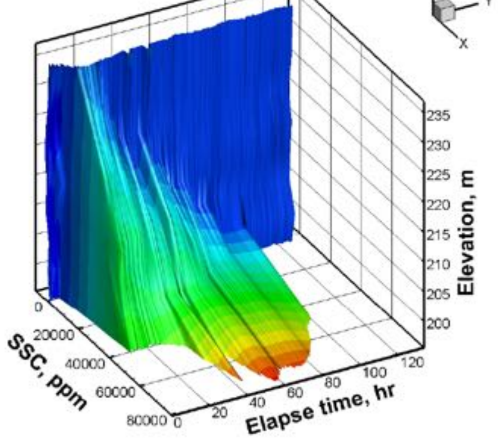




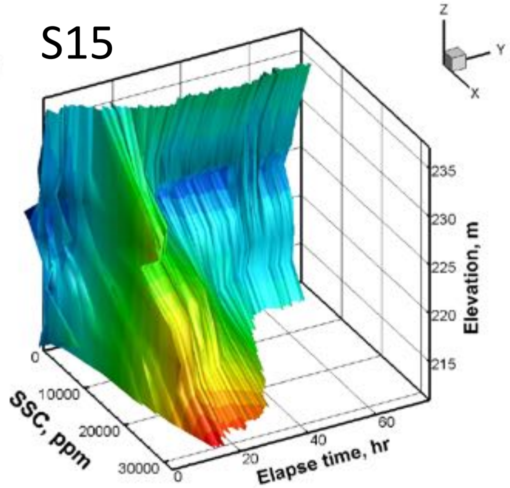
Typhoon Soulik in 2013



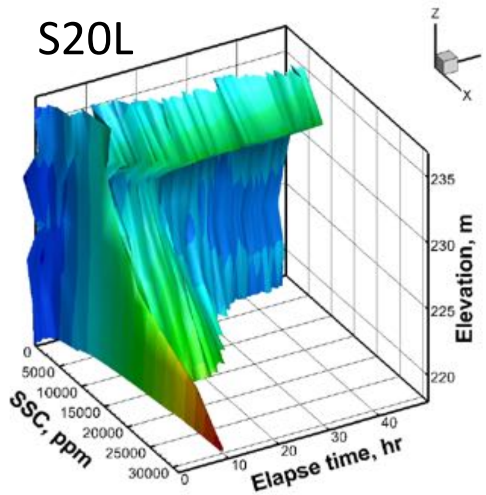
S7

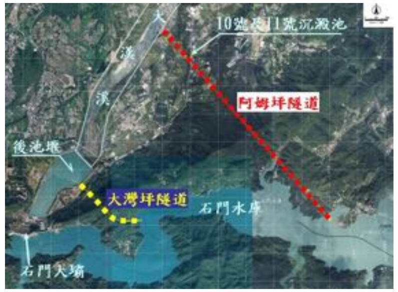


S15



S20L

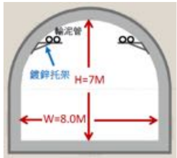


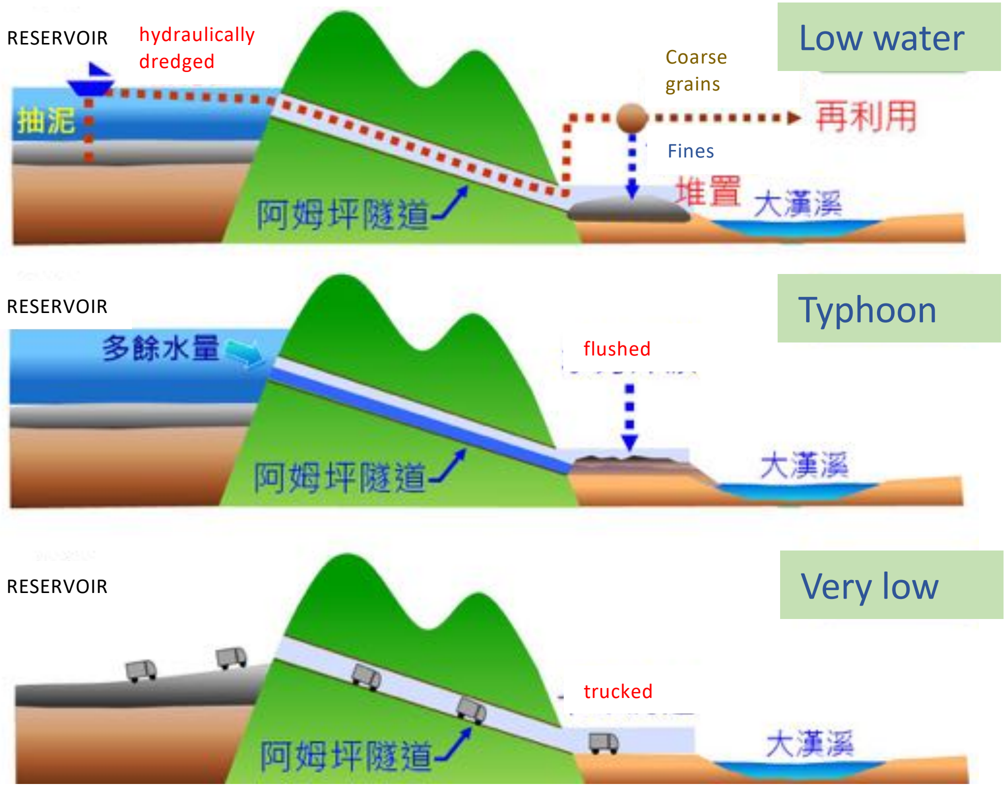


New hydraulic facility

Amuping desilting tunnel (~2021)

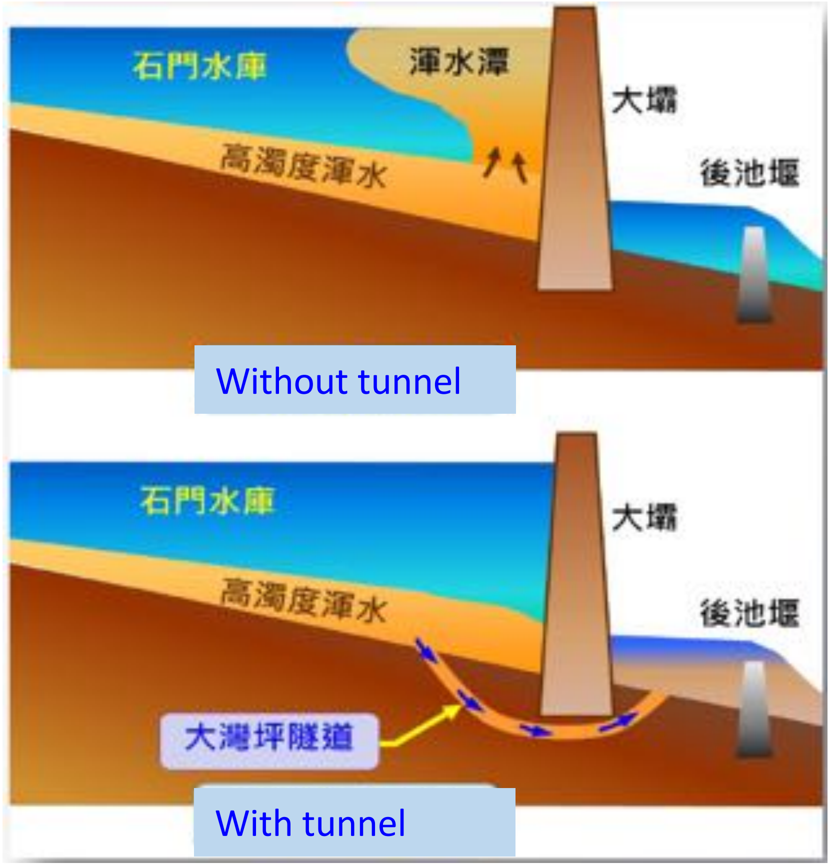
- 3.7-km long; multi-purposes
- $133M USD
- 0.64 Mm^3





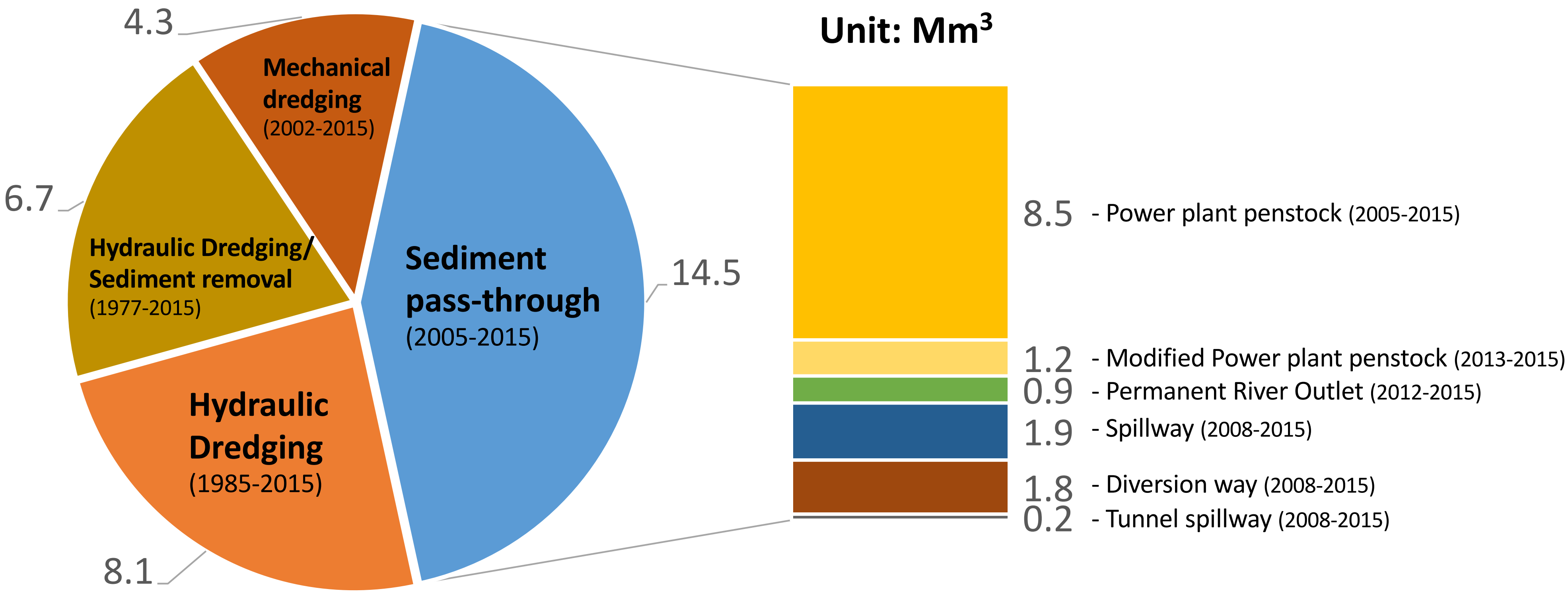
Dawanping desilting tunnel (planning)

- 0.9-km long; turbidity currents
- $160M USD
- 0.71 Mm^3



Sediment Sluicing at Shihmen in 2013

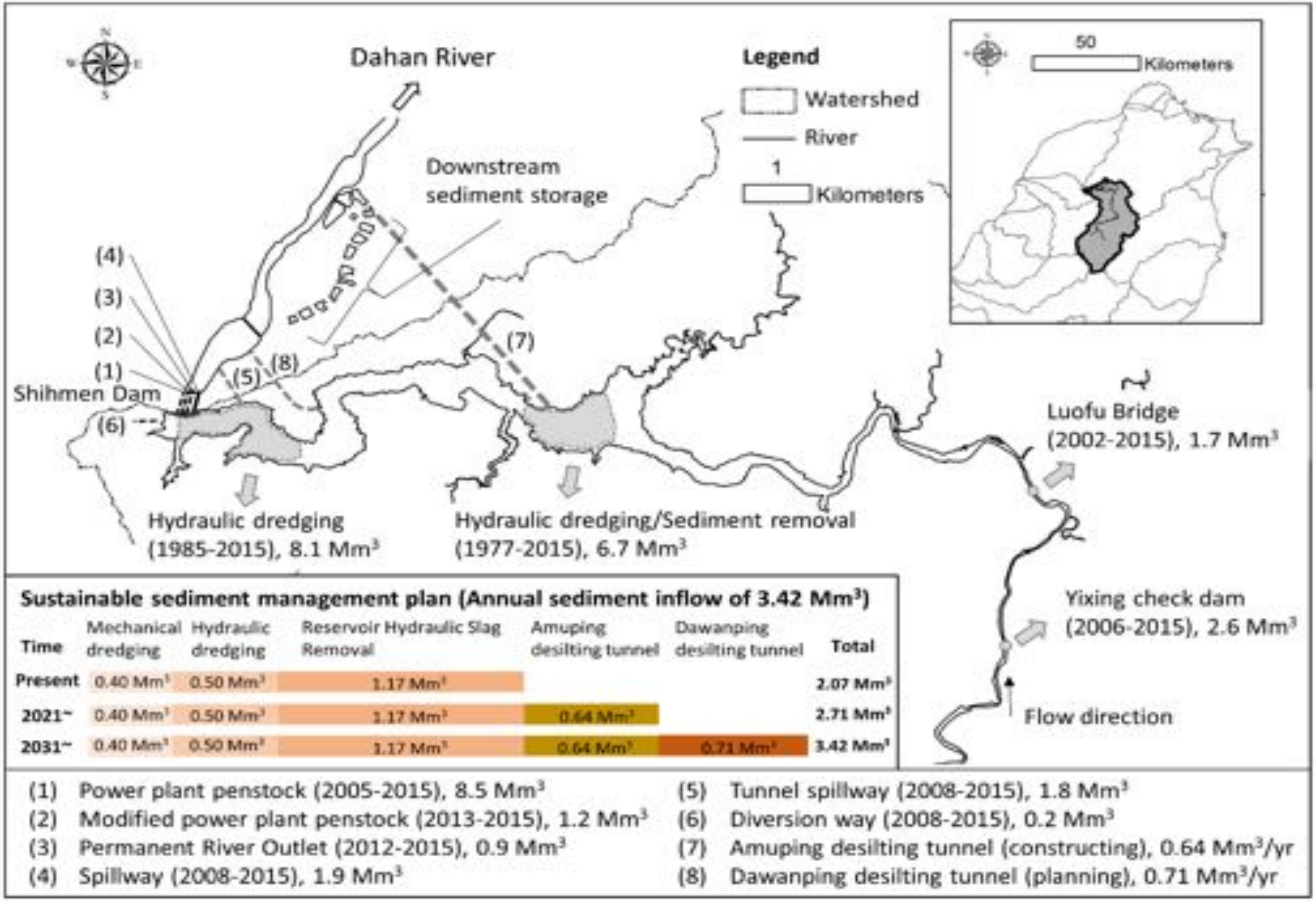
(FROM WRA



Strategy	Years	Cumulative volume of sediment removed	Cost	Unit cost
Hydraulic dredging	31	8.1 Mm^3	\$160 M USD	\$20 USD/m^3
Sediment pass-through	10	12.6 Mm^3	\$67 M USD	\$5 USD/m^3

While the sediment removal innovations have a high initial capital cost, they are more cost effective over the long term than traditional dredging

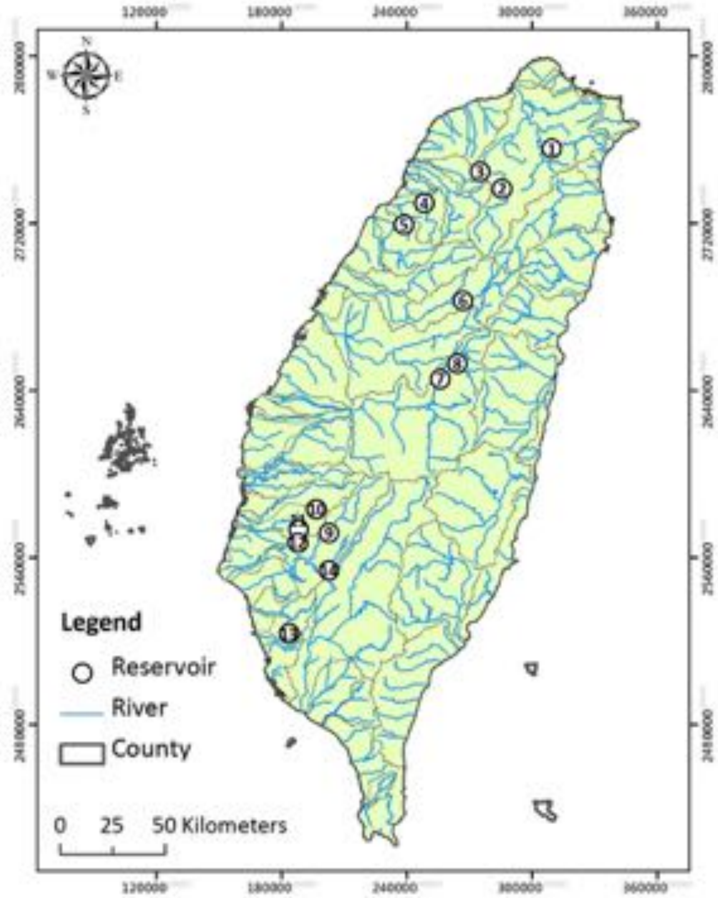
Sustainable sediment management plan at Shihmen



Time	Mechanical dredging	Hydraulic dredging	Reservoir Hydraulic Slag Removal	Amuping desilting tunnel	Dawanping desilting tunnel	Total
Present	0.40 Mm³	0.50 Mm³	1.17 Mm³			2.07 Mm³
2021~	0.40 Mm³	0.50 Mm³	1.17 Mm³	0.64 Mm³		2.71 Mm³
2031~	0.40 Mm³	0.50 Mm³	1.17 Mm³	0.64 Mm³	0.71 Mm³	3.42 Mm³

(Wang et al. 2018)

Sediment management at other reservoirs

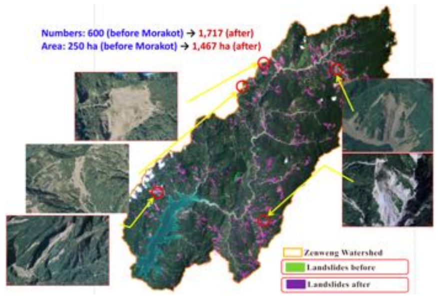


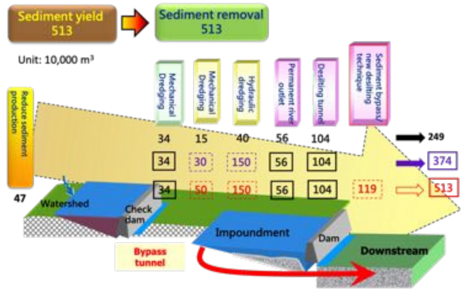
Strategies associated with each reservoirs

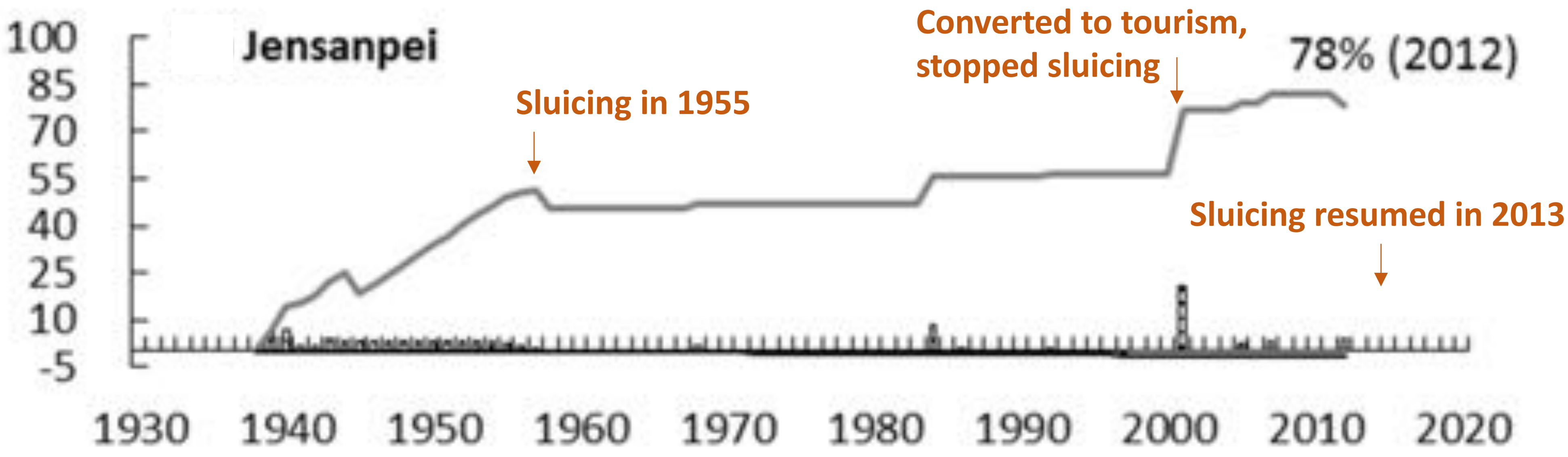
1 Feitsui: AF, ME
2 Ronghua: AF
3 Shihmen: AF, HD, ME, SL, VT, DT
4 Tapu: AF, EF, HD
5 Minte: AF, HD
6 Techi: AF, ME
7 Wujie: AF, DF
8 Wusheh: AF, ME
9 Zengwen: AF, HD, ME, OS, SL, (SB), VT
10 Paiho: AF, HD, ME, (SL), (SB)
11 Jensanpei: AF, EF, ME
12 Wusantou: AF, HD
13 Agongdian: AF, EF, ME
14 Nanhua: AF, ME, HD, VT

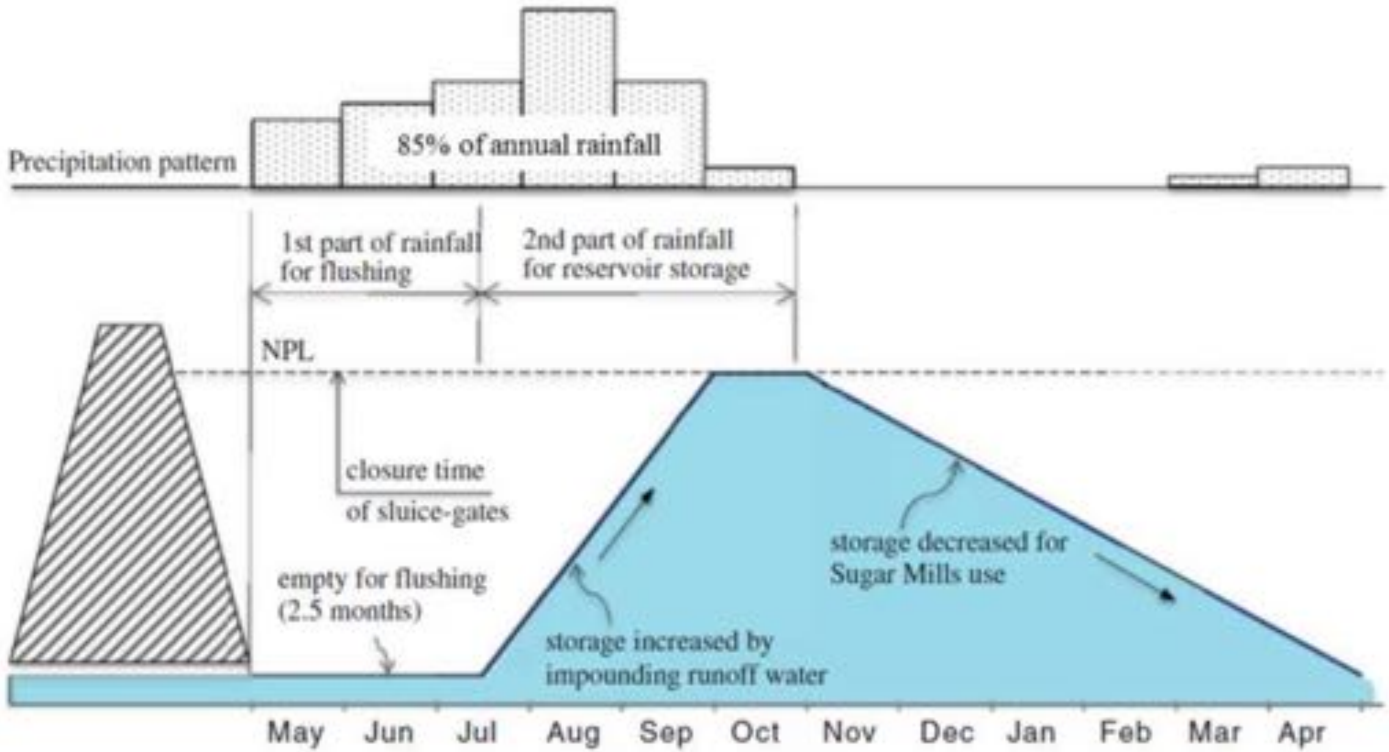
Description

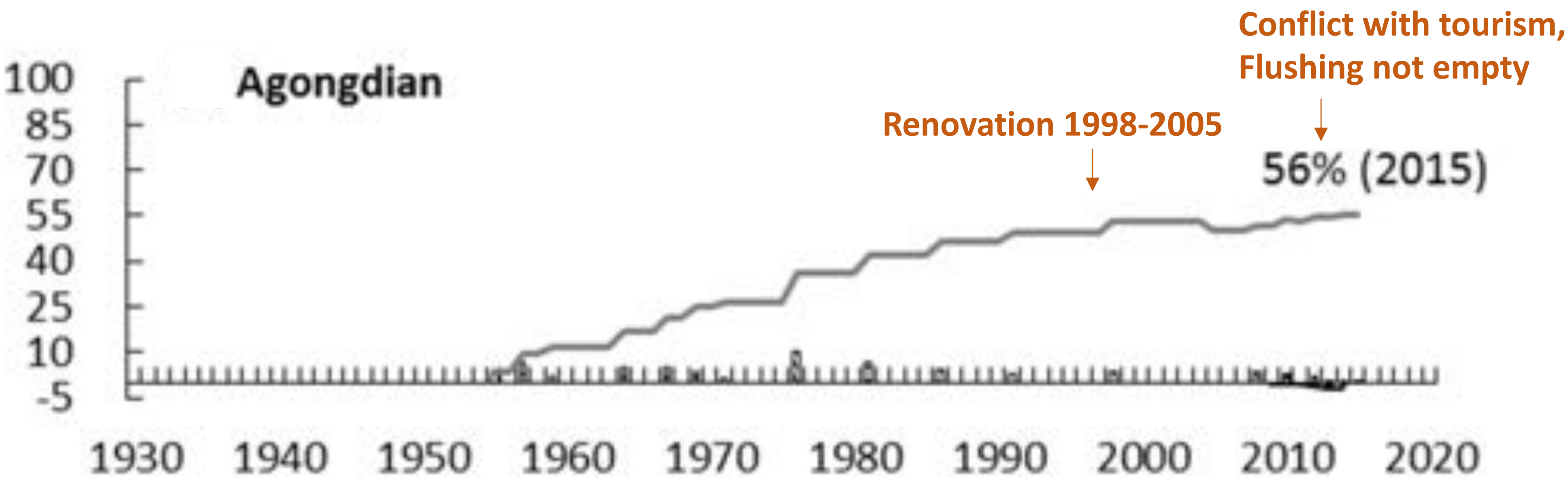
AF: AFforestation
DF: Drawdown Flushing
DT: Desilting Tunnel
EF: Empty Flushing
HD: Hydraulic Dredging
ME: Mechanical Excavation
OS: routing Off-Stream reservoir
SL: SLuicing
SB: Sediment Bypass
VT: routing Venting Turbidity currents

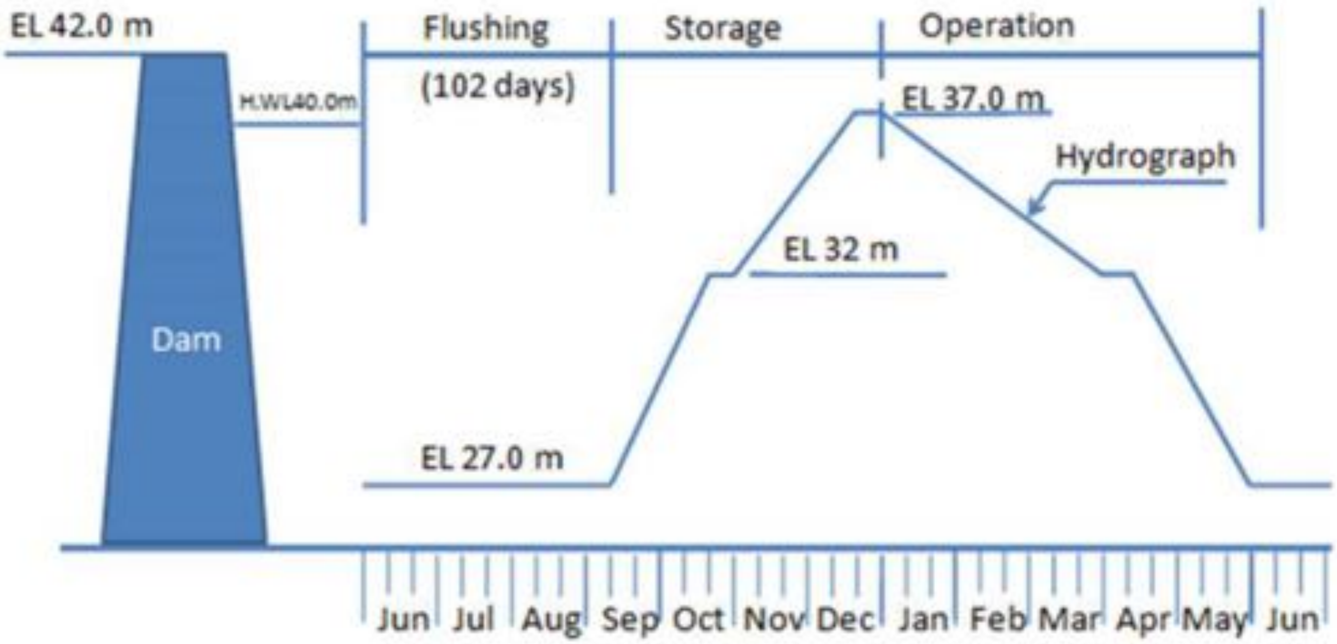


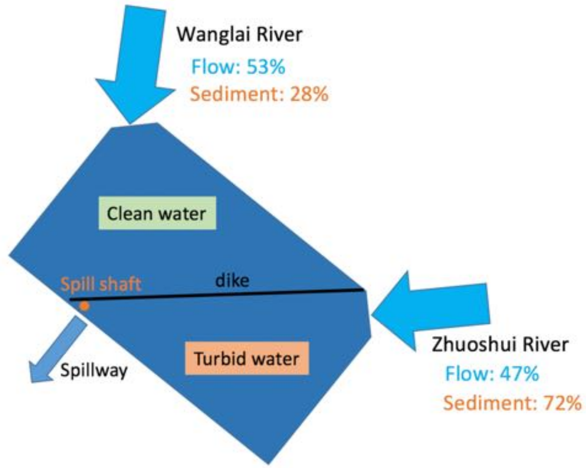



Jensanpei
Converted to tourism,
stopped sluicing
78% (2012)
Sluicing in 1955
Sluicing resumed in 2013
100
85
70
55
40
25
10
-5
1930
1940
1950
1960
1970
1980
1990
2000
2010
2020

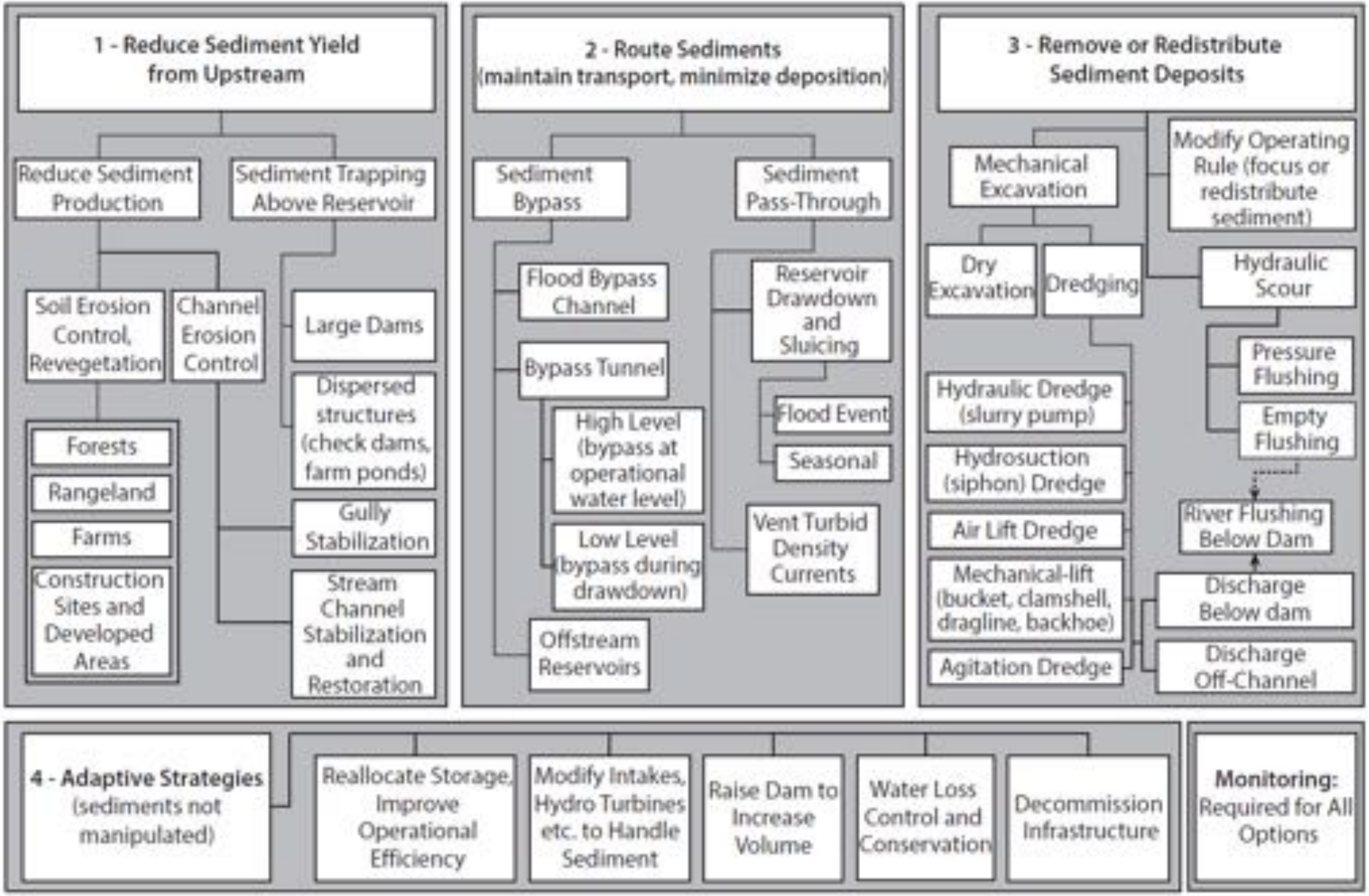

Precipitation pattern
85% of annual rainfall
1st part of rainfall for flushing
2nd part of rainfall for reservoir storage
NPL
closure time of sluice-gates
empty for flushing (2.5 months)
storage increased by impounding runoff water
storage decreased for Sugar Mills use
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan
Feb
Mar
Apr


Conflict with tourism,
Flushing not empty
Renovation 1998-2005
56% (2015)
Agongdian
100
85
70
55
40
25
10
-5
1930
1940
1950
1960
1970
1980
1990
2000
2010
2020

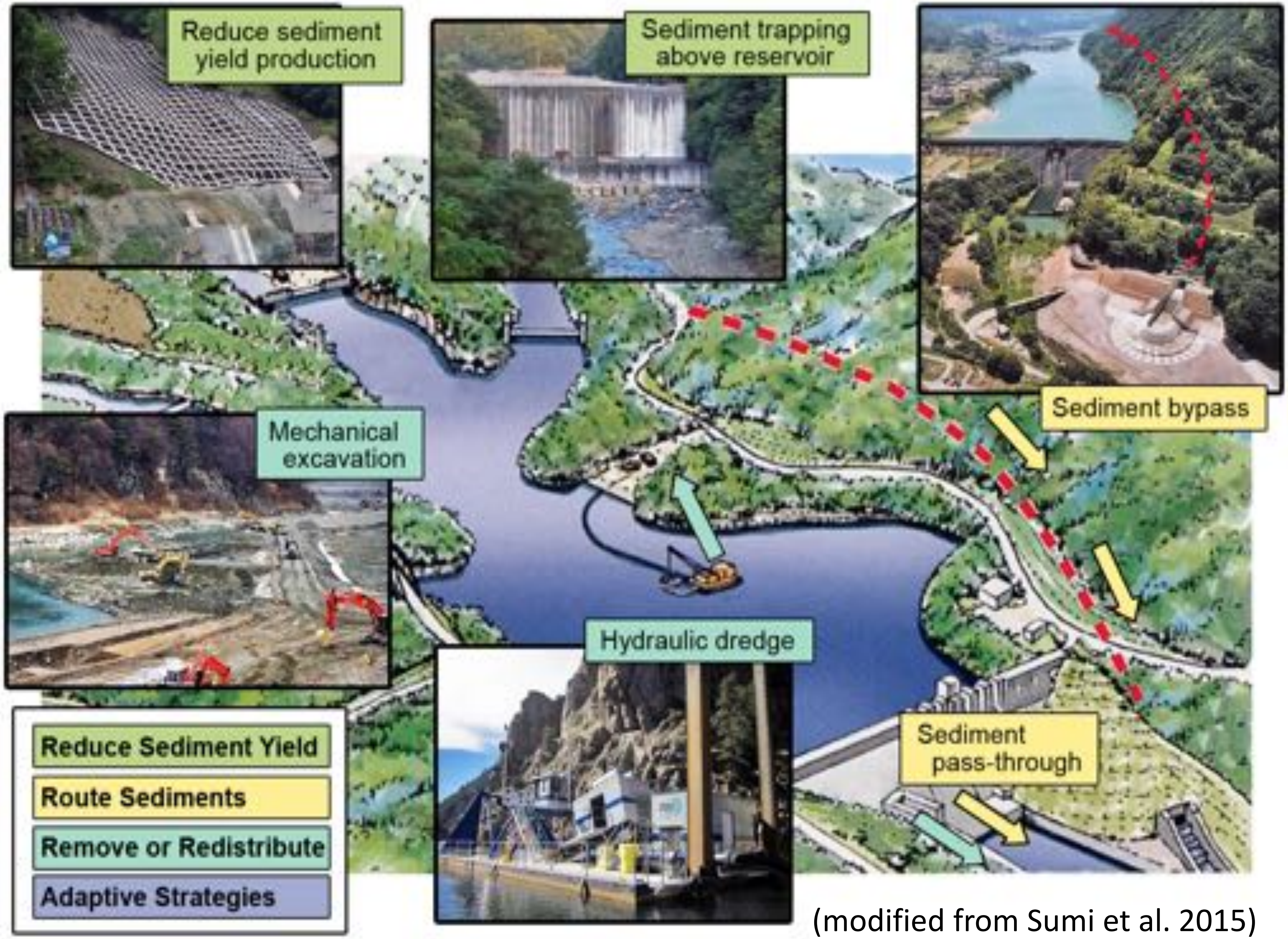

EL 42.0 m
H.WL40.0m
Flushing
(102 days)
Storage
Operation
EL 37.0 m
Hydrograph
EL 32 m
EL 27.0 m
Dam
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun


Wanglai River
Flow: 53%
Sediment: 28%
Clean water
Spill shaft
dike
Spillway
Turbid water
Zhuoshui River
Flow: 47%
Sediment: 72%

Sediment Management Alternatives



(Morris, 2015)



(modified from Sumi et al. 2015)

Pros and Cons of Sediment Management Strategies

For example:

- Dredging- low initial capital capacity, high long-term operational cost, low effectiveness
- Sediment Bypass Tunnel- high initial capital capacity, high effectiveness

Table 1. Characteristics and limitations of sediment management strategies. Fo
the strategy contributes to the characteristic (Annandale et al. [8]; Morris and

Sediment Management Strategy	Requires Low Level Outlets	Requires Drawdown	Maintenance of Reservoir Capacity [1]	Appropriate Reservoir Size	Ability to Remove Deposited Sediments
Doing nothing [2]	no	no	no	none	no
Sediment yield reduction [3]	no	no	medium	all	no
Dredging [4]	no	no	low	all	yes
Hydrosuction and wet/hydraulic dredging [5]	no	no	low	all	yes

water

MDPI

Article

Sediment Management in Taiwan's Reservoirs and Barriers to Implementation

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Abstract: Reservoirs play a critically important role in supplying water for human uses. However, sedimentation limits storage capabilities and increases risk for aging infrastructure. The objectives of this paper are to synthesize both general sediment management strategies and past sediment management efforts in Taiwan in order to identify the barriers to more effective sediment management

			Shih-men	Rong-hua	Wu-jie	Jen-san-pei	A-gong-dian	Zeng-wen
Have the sediment management alternatives been considered/implemented?	Reduce sediment yield from upstream	Reduce sediment production	●	●	●	●	●	●
		Sediment trapping above reservoir	●	●	●	x	●	●
	Route sediments	Sediment bypass	●	◎	x	x	●	◎
		Sediment pass-through	●	◎	x	x	●	●
	Remove or redistribute sediment deposits	Mechanical excavation	●	x	x	●	●	●
		Modify operating rule	●	●	●	●	●	●
		Hydraulic scour	x	●	●	●	●	x
	Adaptive strategies	Reallocate storage	x	x	x	◎	x	x
		Modify facility to handle sediment	●	◎	x	x	●	●
		Raise dam to increase volume	x	x	x	●	x	●
		Water loss control and conservation	●	x	x	x	x	x
		Decommission infrastructure	x	x	x	x	x	x
Has a sustainable sediment management plan been developed to identify the management [illegible] sedimentation?			●	x	x	x	x	●
Have or Will measures be implemented to enhance sustainability with implementation schedule?			●	x	x	x	x	◎
Are the dam, intakes, and other hydraulic structures designed to facilitate implementation of future sediment control measures?			●	◎	x	●	●	●
Has the need for a real-time sediment monitoring system and sediment-guided operation been evaluated, and if needed has it been incorporated into the project?			●	x	x	x	x	●
Is there a viable end-of-project scenario?			x	x	x	x	x	x
Has a reservoir monitoring program been developed that includes a standardized bathymetric protocol starting with the first bathymetric survey soon after initial filling?			●	x	x	x	●	●
Has a monitoring program for impacts downstream of the dam been designed?			●	x	x	x	◎	●

- ***A real-time sediment monitoring system and sediment-guided operation is needed, but has only been incorporated into the projects of the two principal reservoirs.***
- ***There is not a viable end-of-project scenario.***

●: Considered and implemented; ◎:Only considered; x: Not considered

(Wang et al. 2018)

There in no ‘end-of –project’ scenario…

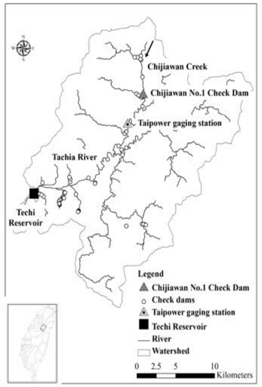
These costs are substantial, as has been demonstrated at over 1200 dam removals

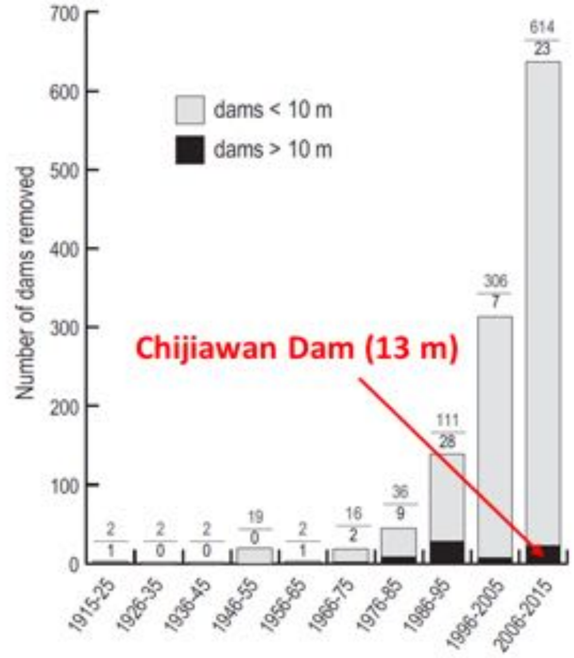
Name	Height (m)	Year removed	Cost (millions of USD)	Comments
Chiloquin (Oregon, US)	7	2008	18	Privately owned irrigation diversion, removed due to aging structure and fish passage; replaced by new pumping station
Savage Rapids (Oregon, US)	12	2009	39	Privately owned irrigation diversion, removed due to aging structure and fish passage; replaced by new pumping station
Marmot (Oregon, US)	15	2008	17	Privately owned hydropower (22 MW) dam, removed due to cost of fish passage and upkeep
Elwha and Glines Canyon (Washington, US)	32, 64	2012	325	2 dams; both publicly owned; water supply and hydropower (15 MW) dams, alternate water supply constructed
Milltown (Montana, US)	7	2008	120	Privately owned hydropower dam (1.4 MW), Largest Superfund site in US, 6 million tons of contaminated (arsenic, lead, zinc, copper, and other metals from mining and smelting) sediments removed
4 Klamath River Dams (Copco I & II, Iron Gate, and JC Boyle) (Oregon, US)	41, 10, 58, 21	2020	Est. 291	4 privately owned hydropower (163 MW) dams

(Wang et al. 2018)

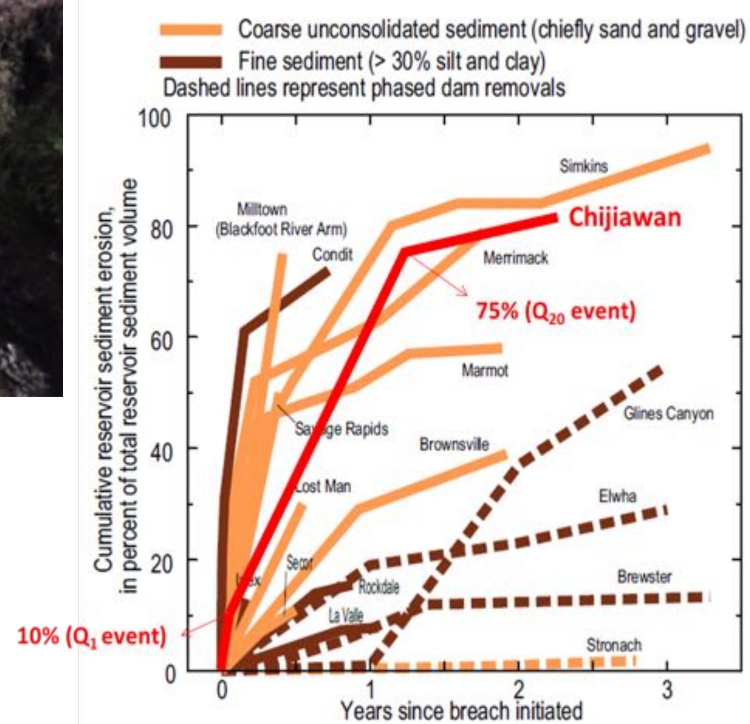
Chijiawan dam removal

- 13-m high, 1972~2011
- 200,000 m^3
- Coarse bed sediment
- Safety concern and Habitat restoration



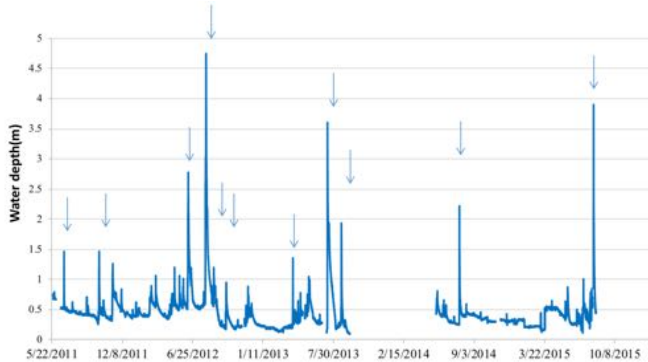


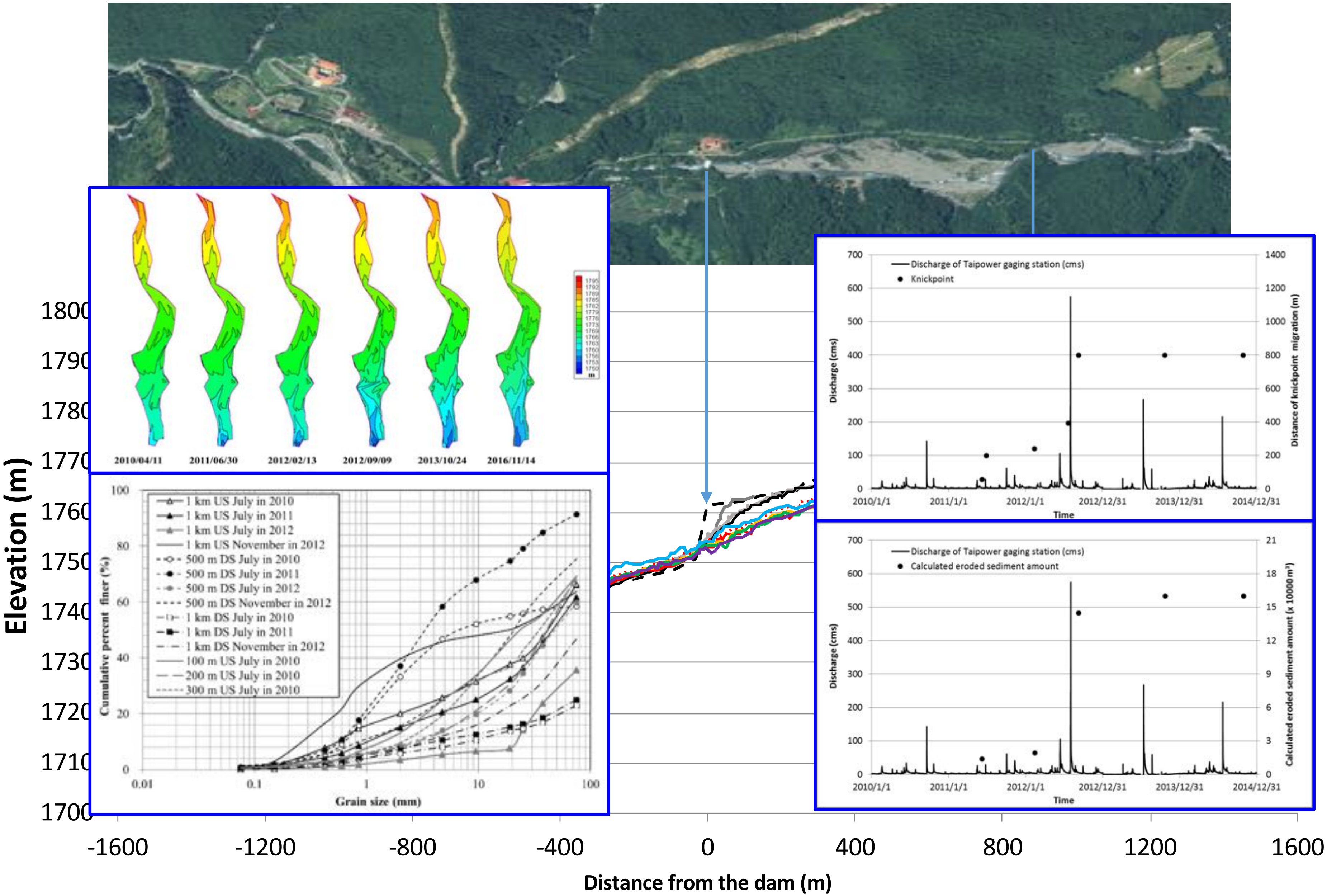
Formosan Landlocked Salmon



- 2013/7/12~7/15

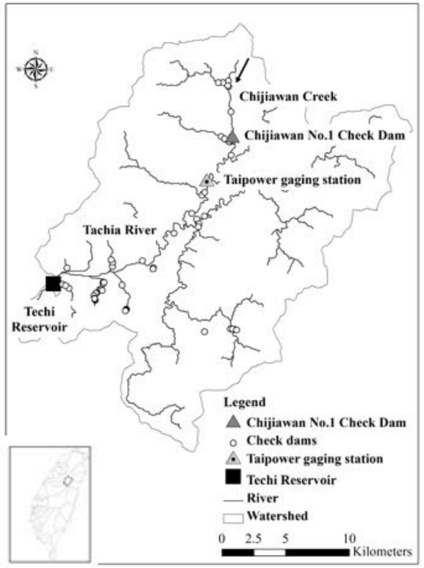
Event	Date	Highest water depth (m)	Discharge (cms)	Return period (Year)
Typhoon Meari	2011/6/23~25	1.46	28.8	1
Northeast monsoon	2011/10/3	1.42	28.8	1
Plum rain	2012/6/12	2.79	76.2	< 2
Typhoon Talim	2012/6/19~21	1.19	29.2	1
Typhoon Saola	2012/7/30~8/3	4.75	573.5	< 20
Typhoon Tembin	2012/8/21~25	1.20	25.9	1
Plum rain	2013/4/6	1.36	28.9	1
Typhoon Soulik	2013/7/11~13	3.59	225.8	< 5
Typhoon Trami	2013/8/20~22	1.94	62.2	< 2
Typhoon Matmo	2014/7/23~25	2.21	91.06	< 2
Typhoon Soudelor	2015/8/7～8/9	3.90	327	5

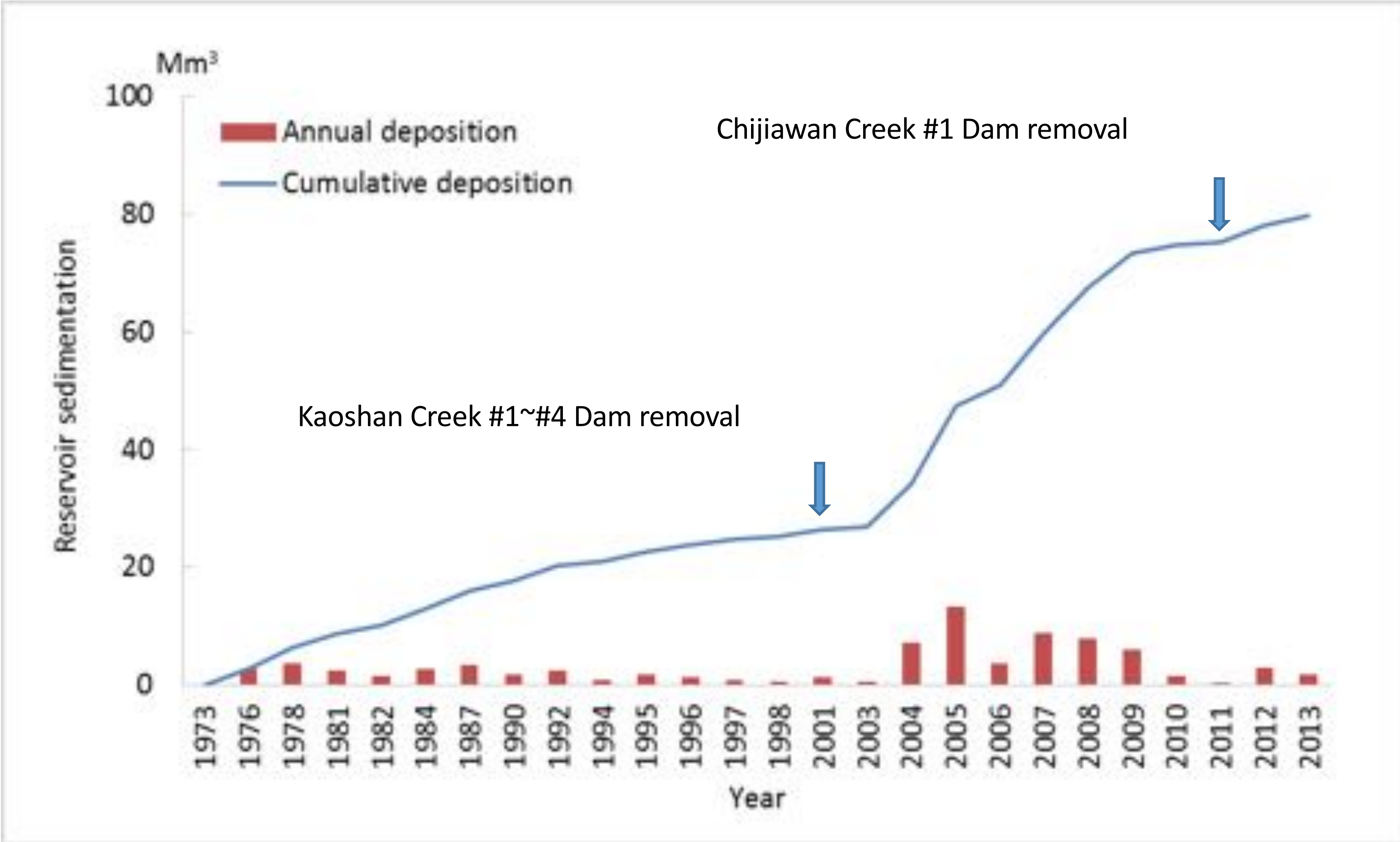




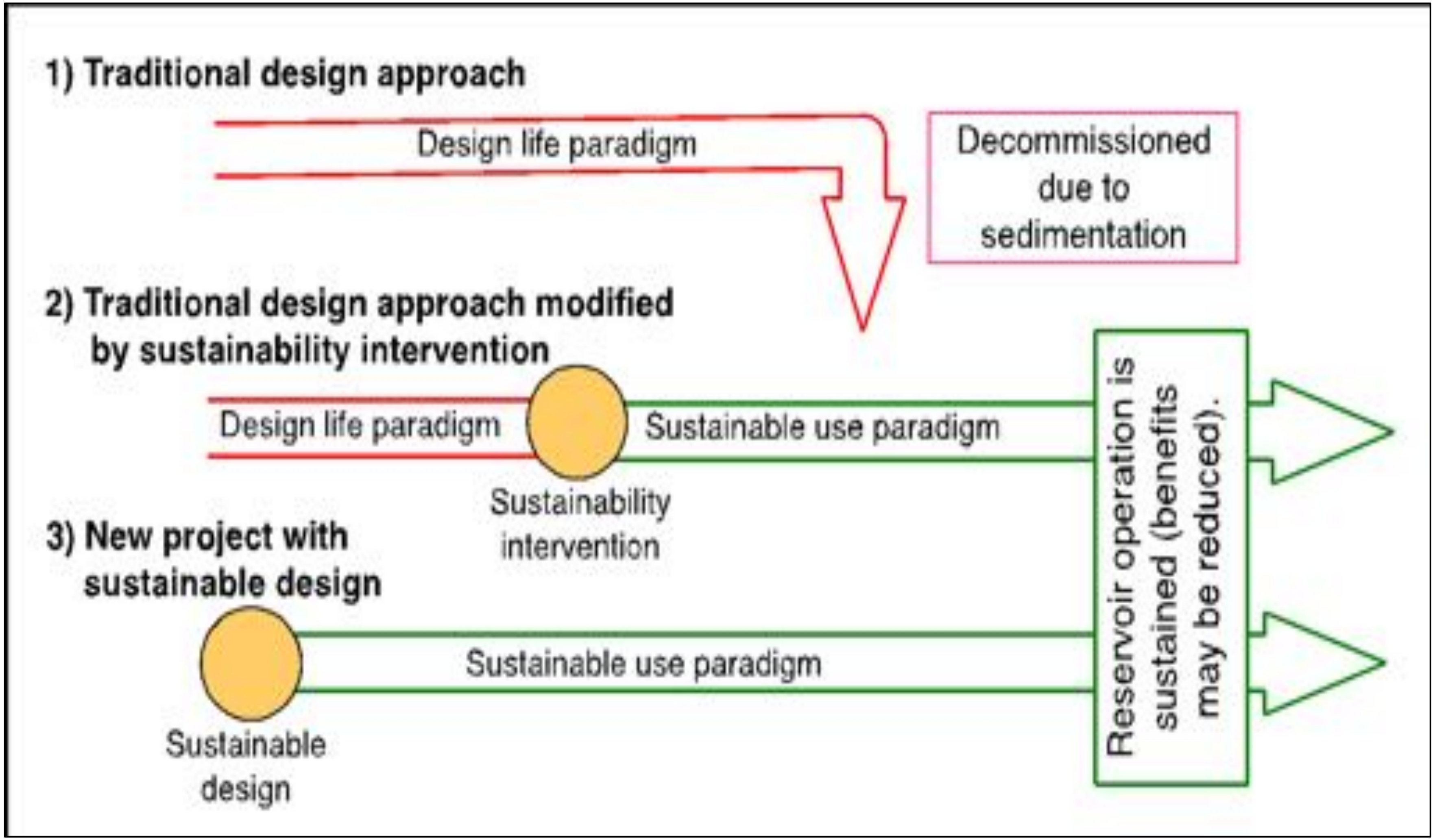
(Wang and Kuo, 2016)

Dam removal V.S. Reservoir sedimentation



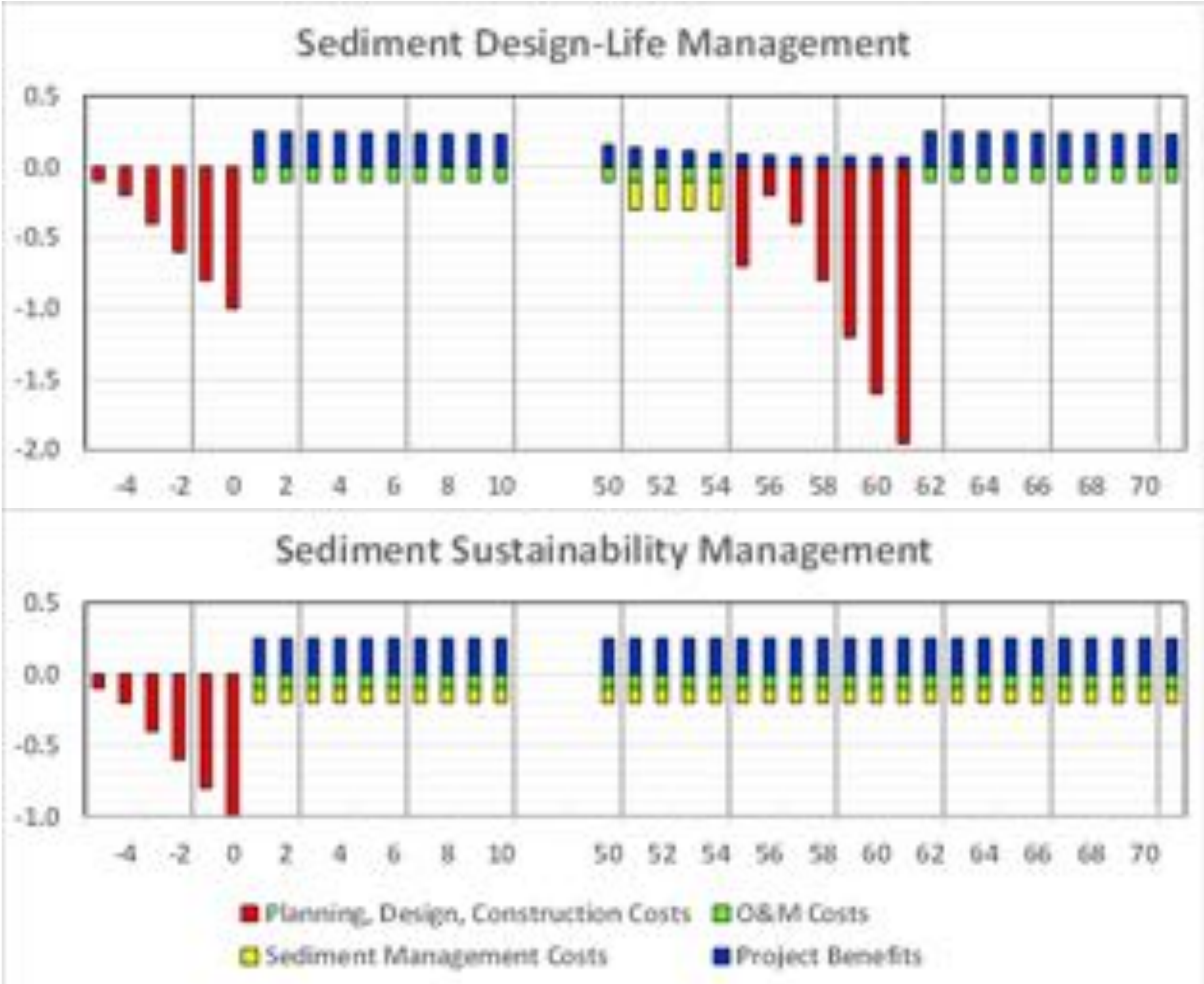


Implications?



Today's reservoirs were originally designed under a "design-life" paradigm in which the designer provided sufficient storage capacity to accommodate 50 or 100 years of sedimentation. Little to no attention was given to long-term sustainable sediment management. Most reservoirs are even more valuable today than when they were originally built because the levels of population and economic activity that depend on them has increased over the decades.

Under the typical sediment design-life management scenario, there are no sediment management costs, but the project benefits gradually decrease over time with reductions in reservoir storage capacity.



Lessons Learned in Taiwan

- Implementation of sediment management in Taiwan’s reservoirs has been relatively slow and sometimes ineffective for a variety of social, technical, environmental and economic reasons.
- The commonly used strategies (e.g., dredging) are relatively easy to implement, have low capital investment requirements, and offer potential value added from selling coarse aggregate for construction (at least when the material can be sold). However, the effectiveness of dredging even to maintain reservoir capacity relative to annual sediment inflow is very low.
- The barriers to reservoir sustainability include the crisis-response approach to addressing sedimentation and the low priority for sediment management relative to competing objectives for reservoirs. Technical and economic barriers are driven primarily by the engineering challenges and costs of retrofitting existing dams with new infrastructure to flush or bypass sediment.
- The most commonly identified conflicts (e.g., design-life, capital costs, monitoring, impacts to water supply) tended to be addressed by more short-term strategies (e.g., mechanical dredging, check dams) over the long-term solutions (e.g., infrastructure retrofits).

In California, sediment problems evident already in some reservoirs in high sediment yield areas…

San Clemente Dam on the Carmel River. Filled with sediment, seismically unsafe, removed in 2014 at cost of over $85M

Matilija Dam, Ventura River, California

Filled with sediment, safety hazard, blocks fish migration

To be gradually removed (cost> $110M)

Biggest concern: sediment impacts on downstream channel, possible aggradation/flooding

One of 4 dams in the Coast Ranges of California filled with sediment and posing safety risks.
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

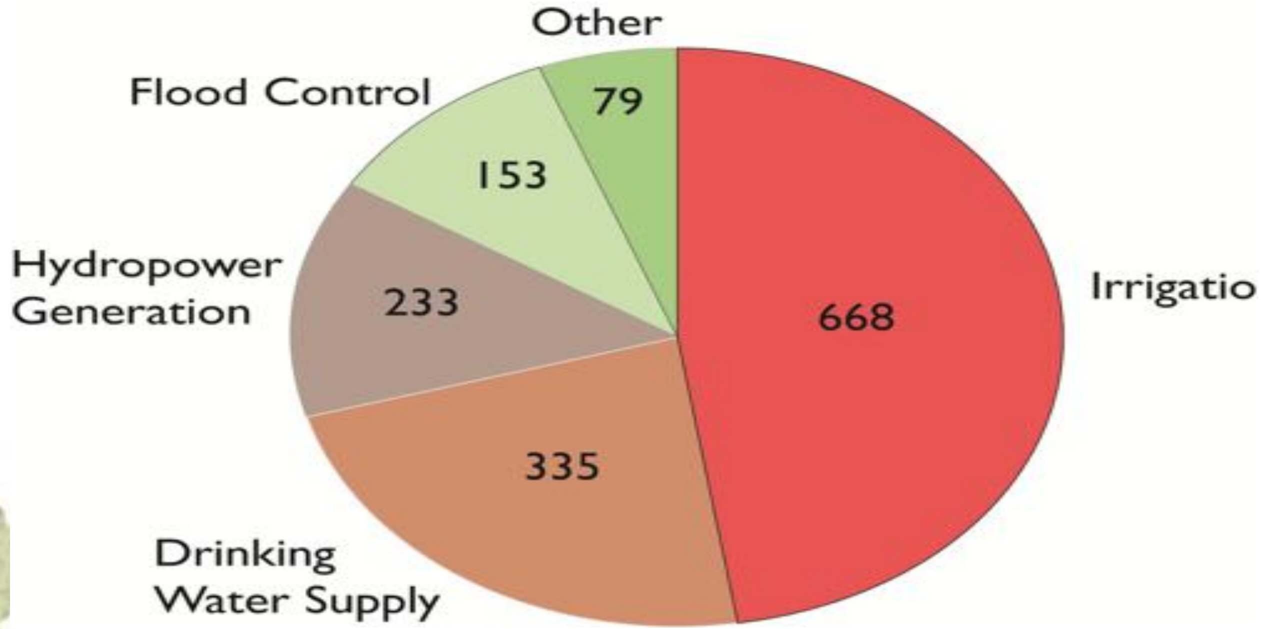
Rindge

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

WATER RESOURCES RESEARCH, VOL. 45, W12502, doi:10.1029/2007WR006703, 2009

Click Here for Full Article

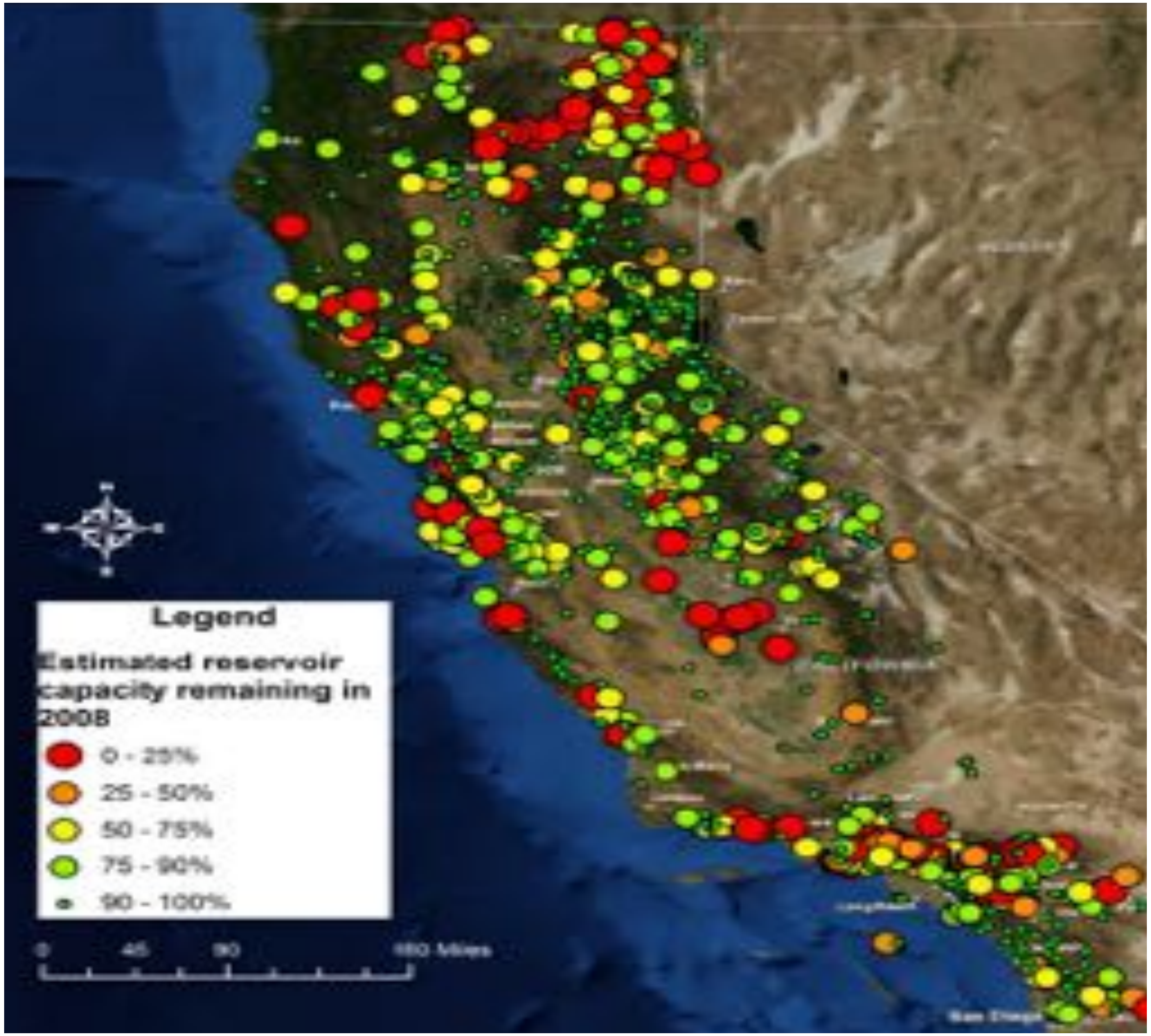
Estimating reservoir sedimentation rates at large spatial and temporal scales: A case study of California

J. Toby Minear[1] and G. Matt Kondolf[1]

Received 27 November 2007; revised 8 June 2009; accepted 27 July 2009; published 25 December 2009.

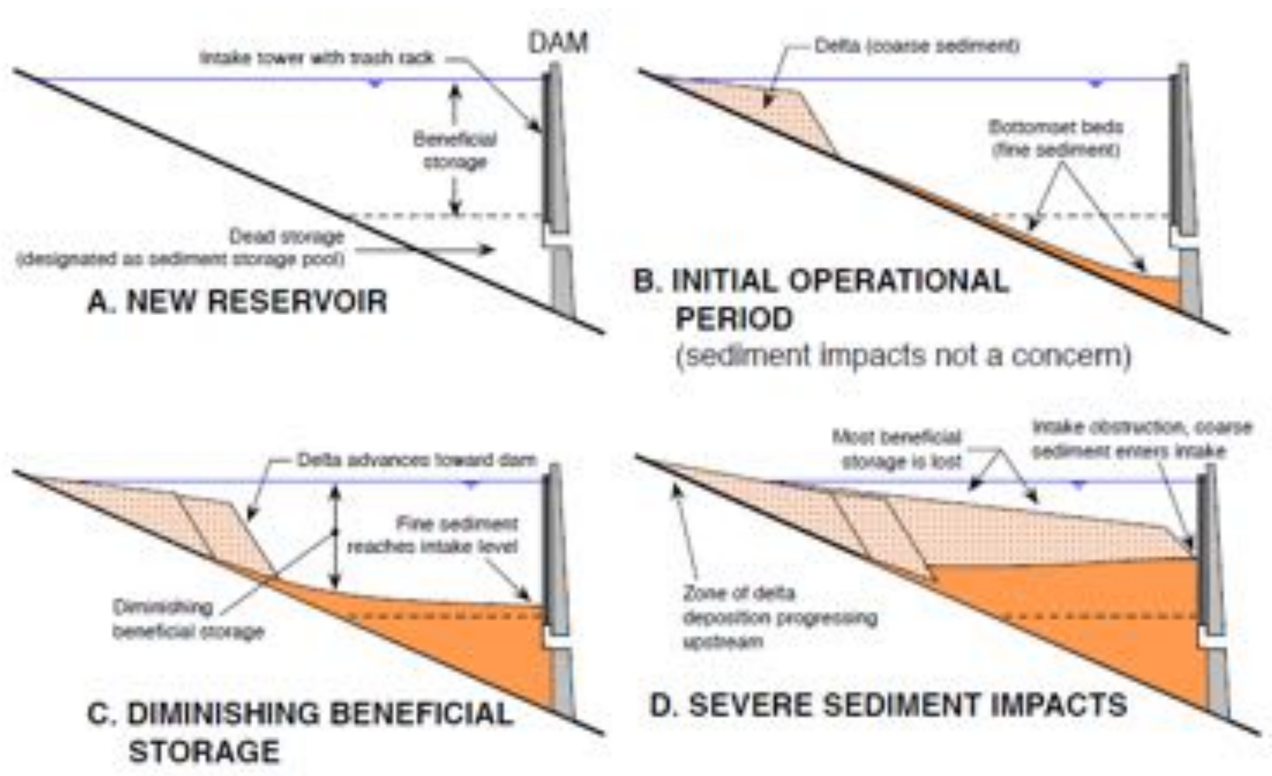
[1] Previous reservoir sedimentation models have ignored two key factors for large spatial and temporal modeling of multiple reservoirs: trapping by upstream dams and

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



So in California the problem is beginning to manifest….

- The severity of the sedimentation problem varies from one site to another. Some have looming near-term sedimentation problems, while others may not have significant problems until the next century. Thus, sustainability planning for reservoirs occurs on two levels: (1) ***monitoring and screening*** to identify the most critical reservoirs, and (2) ***problem diagnosis*** and ***design of sustainability interventions*** at the critical sites.



TAKE-HOME MESSAGES FOR CALIFORNIA

- The risk of dams filling with sediment, failing, and releasing decades of accumulated sediment is not unique to Taiwan.
- The best reservoir sites have already been built – thus existing storage capacity is valuable to maintain.
- Sustainable sediment management strategies are rarely implemented before a reservoir evinces negative effects of sediment accumulation – but then it may be too late to implement some strategies.
- Needed: A systematic approach to evaluate social, economic, ecological, and engineering tradeoffs of sediment management.
- For many high-sediment yield areas, a suite of sediment management practices may be necessary.


Questions?
Comments?