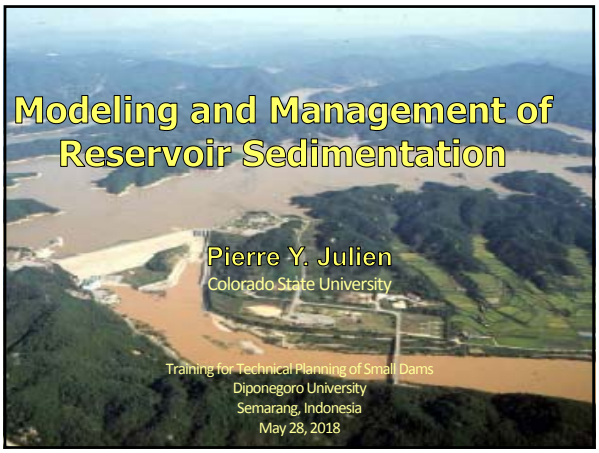
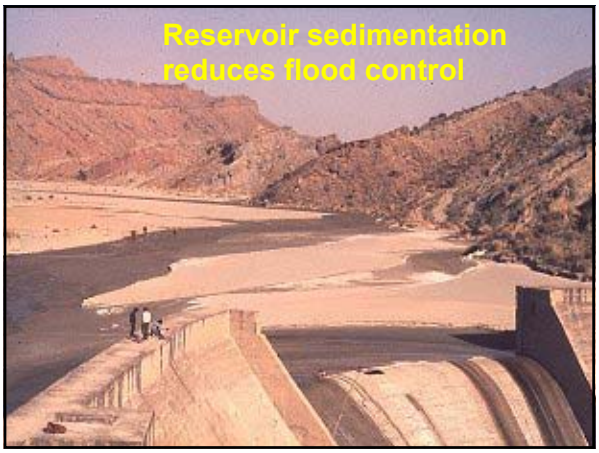


Part I.
Reservoir Sedimentation

Part II.
Sediment Management

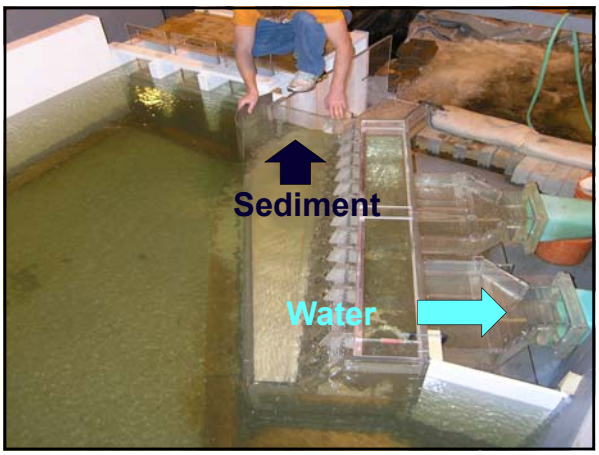
Part II – Sediment Management

1. Sedimentation problems near dams
2. Density currents in reservoirs
3. Dambreak impact
4. Multi-objective dam operations
5. Socio-economic considerations



Locks and Dams

CSU Hydraulics Laboratory


Sediment
Water

Part II – Sediment Management

1. Sedimentation problems near dams
2. Density currents in reservoirs
3. Dambreak impact
4. Multi-objective dam operations
5. Socio-economic considerations

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A general pattern of turbid density currents (Daechung Reservoir, 2004)

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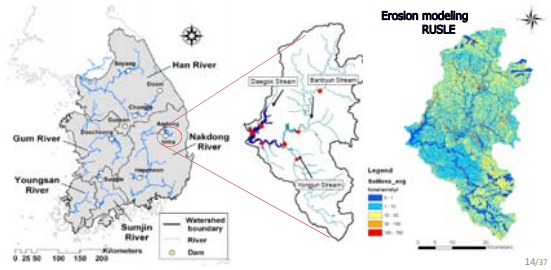
Example

Imha Reservoir has suffered from turbidity problems since 2002.

- Watershed area covers 1,361 km^2
- Three major tributaries



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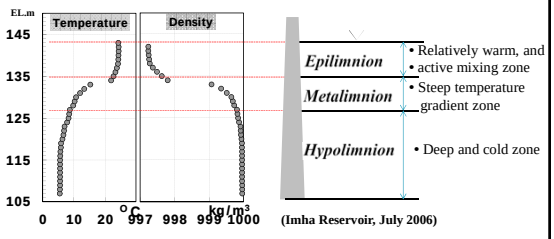
Turbid density currents are developed by thermal stratification

In a deep reservoir, the density is determined by the result of **solar heating** of surface water which produces thermal stratification



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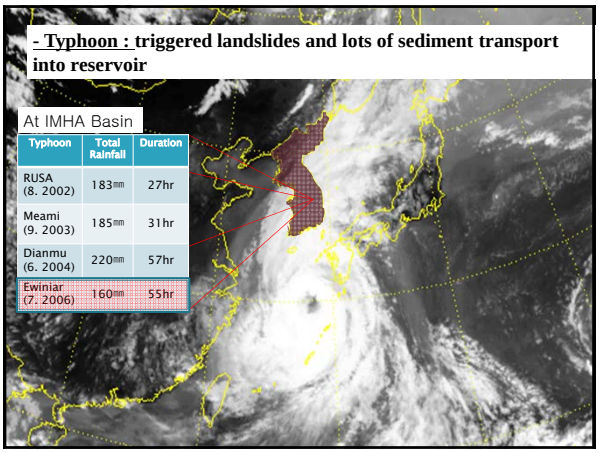
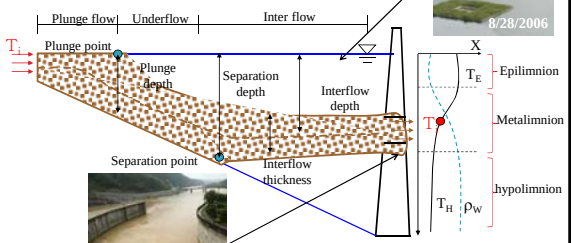
- Typhoon : triggered landslides and lots of sediment transport into reservoir



At IMHA Basin

Typhoon	Total Rainfall	Duration
RUSA (8. 2002)	183㎜	27hr
Meami (9. 2003)	185㎜	31hr
Dianmu (6. 2004)	220㎜	57hr
Ewiniar (7. 2006)	160㎜	55hr

A general type of turbid density currents during summer



Discharge water through intake tower, 8/28/2006

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II. Numerical Model

Governing Equations *based on the Reynolds-averaged Navier–Stokes (RANS) equations combined with a turbulence closure model* (RNG k- ε)

- **Continuity :**

$$\frac{\partial U_1}{\partial x_1}+\frac{\partial U_2}{\partial x_2}+\frac{\partial U_3}{\partial x_3}=0$$

- **Momentum (with Boussinesq approximation, non-hydrostatic) :**

$$\underbrace{\frac{\partial U_i}{\partial t}}_{\text{Local acceleration}}+\underbrace{\sum_{j=1}^{3}U_j\frac{\partial U_i}{\partial x_j}}_{\text{Convective acceleration}}=\underbrace{-g_j}_{\text{Gravity force}}-\underbrace{\frac{1}{\rho_0}\frac{\partial P_{nh}}{\partial x_i}}_{\text{Non-hydrostatic pressure gradient}}-\underbrace{g\frac{\partial \eta}{\partial x_i}}_{\text{Free-surface or 'barotropic' pressure gradient}}-\underbrace{\frac{g}{\rho_0}\frac{\partial}{\partial x_i}\int_z^{\eta}\Delta\rho dx_3}_{\text{Stratification or 'baroclinic' pressure gradient}}+\underbrace{\sum_{j=1}^{3}\frac{\partial}{\partial x_j}\left(\nu\frac{\partial U_i}{\partial x_j}-\overline{u_iu_j}\right)}_{\text{Viscous force and turbulent fluctuations}}$$

$\nu_t\left(\frac{\partial U_i}{\partial x_j}+\frac{\partial U_j}{\partial x_i}\right)$

: i = 1, 2, 3

- **Scalar transport equation :**

$$\frac{\partial \Phi}{\partial t}+\sum_{j=1}^{3}\frac{\partial}{\partial x_j}(U_j\Phi)=\sum_{j=1}^{3}\frac{\partial}{\partial x_j}\left(\Gamma\frac{\partial \Phi}{\partial x_j}+\overline{u_i\phi}\right)$$

$\Gamma_t\frac{\partial \Phi}{\partial x_i}$

$\Gamma_t=\frac{\nu_t}{Pr_t}$

x_i : Cartesian space (i=1,2 are horizontal, i=3 is vertical),
U_i : Mean velocity components,
u_i : Fluctuating velocity components,
η : Free surface elevation,
B : Bottom elevation,
g : Gravitational acceleration,
ν : Kinematic viscosity,
P_{nh} : Non-hydrostatic pressure,
ρ_0 : Reference density,
$\Delta\rho$: Difference between local density and reference density,
Γ : Diffusivity for property Φ ,
Φ : Mean scalar,
ϕ : The corresponding fluctuating scalar,
$\overline{(\cdot)}$: (Overbar) averaging of fluctuating quantities.

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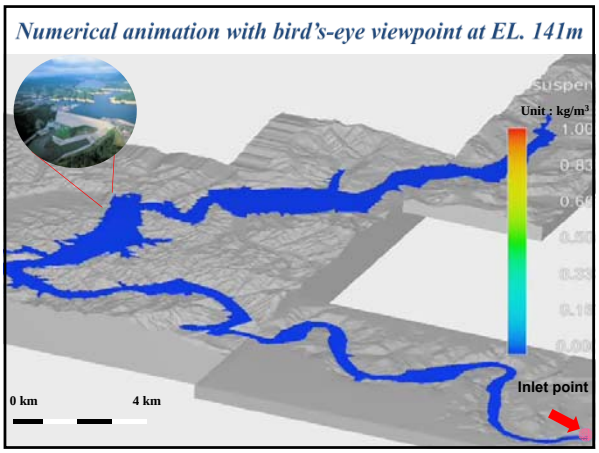

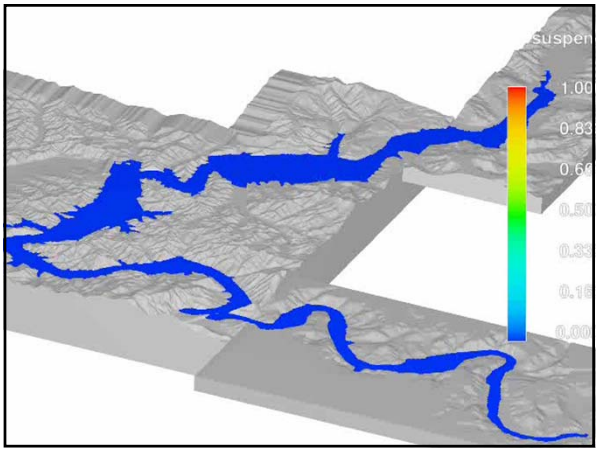

Measuring System

Real-time gaging stations were installed at five stations to monitor turbid density currents propagating from each tributary into to the reservoir

Real-time monitoring system for Imha Reservoir; installed and has been operating by K-water since 2006

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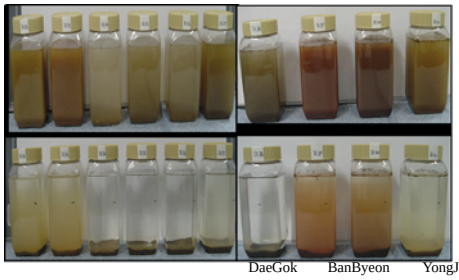
- **Factors inducing turbid density currents**

- Geomorphology and geological features of Imha Reservoir basin : Soil particles not easy to sink

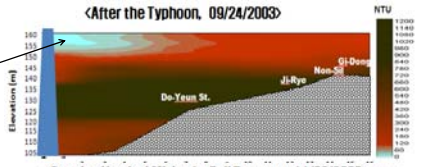
Other Site Imha Dam Basin



DaeGok BanByeon YongJun

<Suspended Particle Sedimentation Test (After 48 hours)>

Turbidity Measurements



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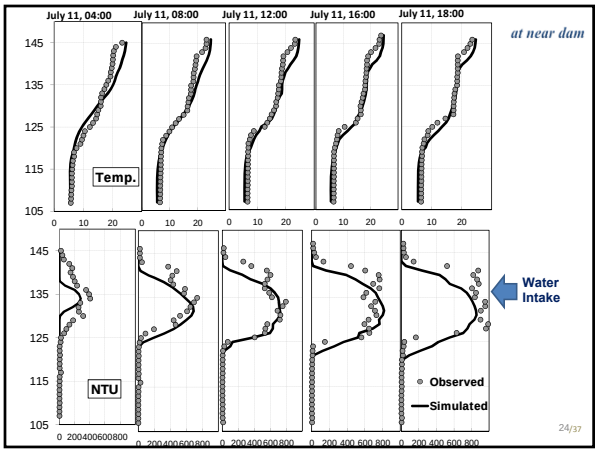

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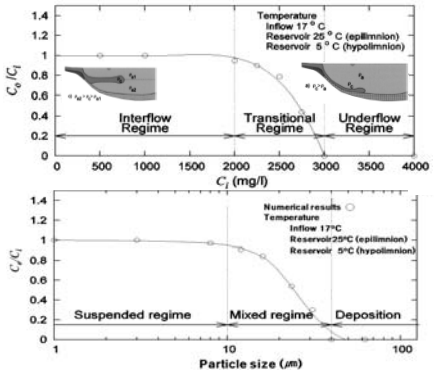
NEW Results on Density Currents!



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Part II – Sediment Management

1. Sedimentation problems near dams
2. Density currents in reservoirs
3. **Dambreak impact**
4. Multi-objective dam operations
5. Socio-economic considerations

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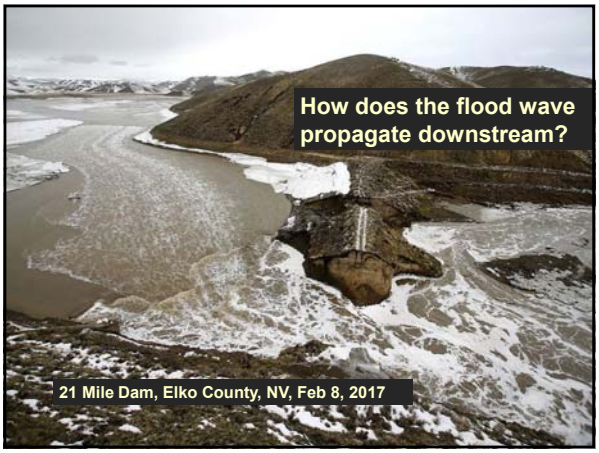
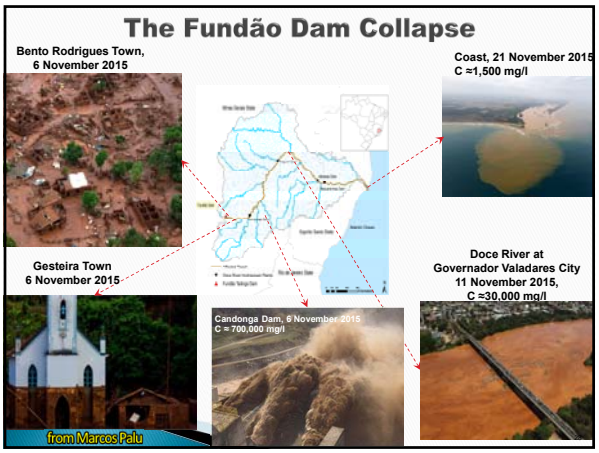
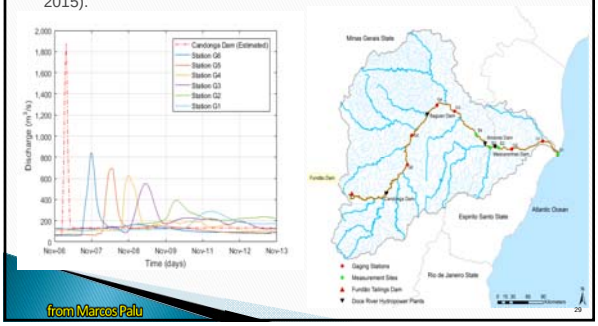


The Fundão Dam Collapse



Hydrographs

Observed hydrographs in Doce River after the Fundão Dam break (ANA, 2015).



Floodwave Propagation

Reach	S (m/m)	L (km)	W (m)	D (m²/s)	Manning n	C_k (m/s)
A	0.0005	204	217	922	0.037	1.20
B	0.0005	133	377	531	0.032	1.04
C	0.0008	34	624	336	0.025	1.40
D	0.0002	108	725	328	0.020	0.60

Space and time steps: $\Delta x = 500\ m,\ \Delta t = 900\ s$

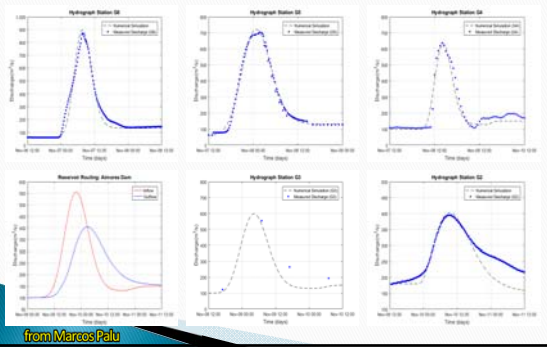
- Reservoir: The reservoir routing can be solved using the Level Pool Routing

$$\frac{dS(t)}{dt} = I(t) - O(t) \rightarrow \frac{2S(t_{i+1})}{\Delta t} + O(t_{i+1}) = [I(t_{i+1}) + I(t_i)] + \left[\frac{2S(t_i)}{\Delta t} - O(t_i)\right]$$

Where:

$S(t)$ = reservoir storage as function of time; $I(t)$ = Inflow; $O(t)$ = Outflow;

Floodwave Propagation Modeling



from Marcos Palu

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Sediment Routing
NEW Development!

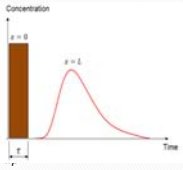
The one-dimensional advection-dispersion equation is applied on the evaluation of transport of suspended load in open channels (Fischer et al., 1979; Julien, 2010).

$$\frac{\partial C}{\partial t} + U\frac{\partial C}{\partial x} = K_d\frac{\partial^2 C}{\partial x^2} - kC$$

C is the concentration;
U is the flow averaged velocity;
κ_d is the longitudinal dispersion coefficient;
k is the settling rate.

Analytical solution for a constant spill in finite time interval is given by (Chapra, 2008):

$$C(x,t) = \frac{C_0}{2}\left\{ e^{\frac{Ux}{2K_d}(1-\Gamma)}\left[erfc\left(\frac{x-Ut\Gamma}{2\sqrt{K_d t}}\right) - erfc\left(\frac{x-U(t-\tau)\Gamma}{2\sqrt{K_d(t-\tau)}}\right)\right] + e^{\frac{Ux}{2K_d}(1+\Gamma)}\left[erfc\left(\frac{x+Ut\Gamma}{2\sqrt{K_d t}}\right) - erfc\left(\frac{x+U(t-\tau)\Gamma}{2\sqrt{K_d(t-\tau)}}\right)\right]\right\}$$



Where: $\Gamma = \sqrt{1+4\eta}$ and $\eta = \frac{kK_d}{U^2}$

The error function complement, *erfc*, is equal to:

$$erfc(b) = 1 - erf(b) = 1 - \frac{2}{\sqrt{\pi}}\int_0^b e^{-\beta}$$

from Marcos Palu

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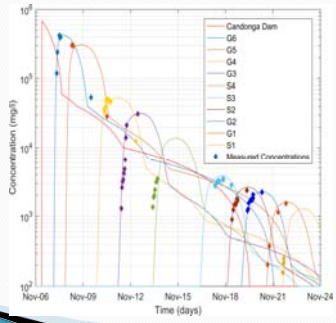
Sediment Concentration Modeling



from Marcos Palu

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Part II – Sediment Management

1. Sedimentation problems near dams
2. Density currents in reservoirs
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4. **Multi-objective dam operations**
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Other Issues besides sedimentation

- It is hard to change reservoir operation rules for sedimentation problems because we have many other issues to deal with.

from H. Kim et al., ASCE, 2017

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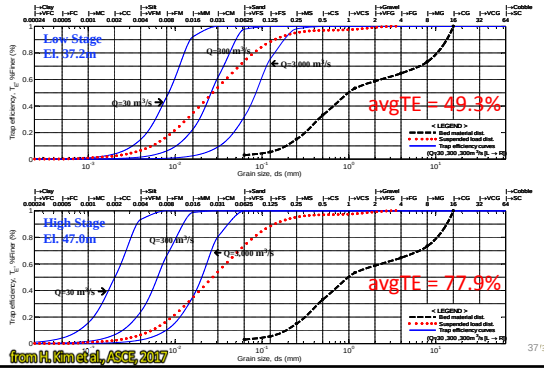
Trap efficiency (T_E)



from H. Kim et al, ASCE, 2017

Sediment Yield & Reservoir Sedimentation

Integrated Reservoir Sedimentation Estimation Procedure (IRSEP)

Conventional FD/SRC method | New approach

@Low stage | FD | SRC | SEMEPP | T_E

Total intervals (%)	Mid-point (%)	delP (%)	Q (cms)	C (mg/l)	Q × delP	Measured load, qs (tons/yr)		qs=qt ratio(%)	Total load, qt (tons/year)		Avg. TE (%)	Res. Sed. (tons/year)	
(1)	(2)	(3)	(4)	(5)	(6)	(7)		(8)	(9)		(10)	(11)=(9)*(10)	
0	0.02	0.01	0.02	1,670	355	0.3	3,743	2%	91%	4,113	2%	37.8	1,555	1%
0.02	0.1	0.06	0.08	1,615	350	1.3	14,257	7%	91%	15,667	7%	38.2	5,991	5%
0.1	0.5	0.3	0.4	1,268	312	5.1	49,896	23%	91%	54,820	23%	41.3	22,654	17%
0.5	1.5	1	1	979	232	6.8	49,576	23%	91%	54,480	23%	49.5	26,992	21%
1.5	5	3.25	3.5	363	148	9.2	42,840	20%	91%	47,077	20%	62.2	29,260	22%
5	15	10	10	194	95	10.4	31,218	15%	91%	34,306	15%	72.1	24,723	19%
15	25	20	10	51	70	5.5	12,058	6%	91%	13,250	6%	76.2	10,103	8%
25	35	30	10	33	55	3.3	5,743	3%	91%	6,311	3%	78.3	4,942	4%
35	45	40	10	21	44	2.1	2,943	1%	91%	3,234	1%	79.4	2,569	2%
45	55	50	10	13	35	1.3	1,435	1%	91%	1,576	1%	80.0	1,261	1%
55	65	60	10	7	27	0.7	640	0%	91%	703	0%	80.4	565	0%
65	75	70	10	3	18	0.3	167	0%	91%	183	0%	81.1	148	0%
75	85	80	10	1	10	0.1	29	0%	91%	32	0%	83.3	27	0%
85	95	90	10	0	3	0	0	0%	91%	0	0%	94.5	0	0%
95	100	97.5	5	0	0	0	0	0%	91%	0	0%	100.0	0	0%
Total						Naesung	214,534	100%	91%	235,752	100%	55.5%	130,790	100%
						Yeong	44,331		82%	54,063		48.4%	26,193	
						Nakdong	128,310		94%	136,501		38.9%	53,042	
						Total	387,175			426,316		49.3%	210,025	

from H. Kim et al, ASCE, 2017

Sediment Yield: 426,000 tons/yr

Excavation Costs

- Nakdong River Estuary Barrage (1990 – 2010)
- V = 13,678,000 m³ (43.2 million dollars)
- Unit cost = 6.31 USD/m³

Nakdong River Estuary Barrage

Photos of excavation

Credit: kwater

from H. Kim et al, ASCE, 2017

Benefit and Cost Analysis
Hydropower Revenues

- Capacity: 1,500 kW * 2 units
- $P = 9.81 \times \eta \times Q_a \times H_a$
- Unit cost of sales = 0.13 USD/kWh

Weir	Production and benefit			Unit cost of sales	
	MWh	Benefit(10^6 KRW)	benefit(10^3USD)	KRW/kWh	USD/kWh
Sangju	8,004	1,179	1,072	147.32	0.13

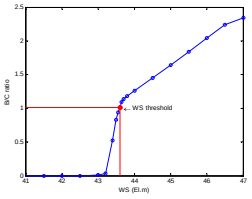
(Data: K-water, 2014, 1 USD = 1,100 KRW)

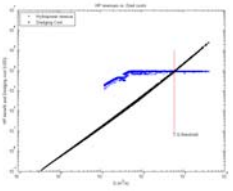
from H. Kim et al., ASCE, 2017

Hydraulic Thresholds

Operate the dam above
H threshold = EL. 43.6 m

Open the gates above
Q threshold = 620 m^3/s





from H. Kim and Julien ASCE, 2018

MCDA Optimization

[MCDA procedure]

STEP 1	• Main-Criteria and Sub-Criteria Identification
STEP 2	• Relative Importance Factors (RIF) Definition
STEP 3	• Constraints Analysis
STEP 4	• Alternatives Development
STEP 5	• Rating method Determination and Modeling

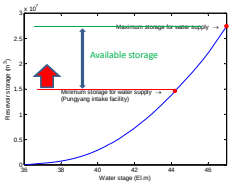
Multi-Criterion Decision Analysis - MCDA
An Approach for Complex Decision Situations

- **Decision making method** to choose the best alternative
- **Systematic process** based on the familiar concept of an **overall score**
- **Provides a way to document and audit decisions**

from H. Kim et al., ASCE, 2017

Water Supply

Max. Reservoir Storage (V)



from H. Kim et al, ASCE, 2017

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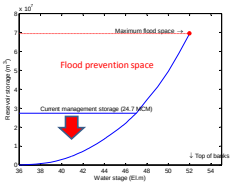
Flood Control

Min. Reservoir storage (V)



from H. Kim et al, ASCE, 2017

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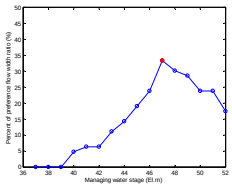
Stream Ecology & Riverside Environment

Max. GVSR

(Good View Station Ratio)



from H. Kim et al, ASCE, 2017

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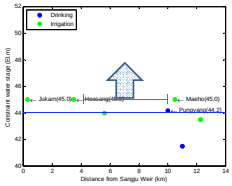
Stage (H) Constraints

Water Supply Constraints

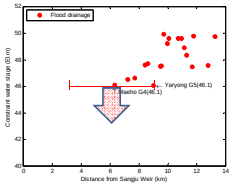
Critical stage (El.45.0m)



* Irrigation duration: May-September

Flood Drainage Constraints

Critical stage (El.46.1m)

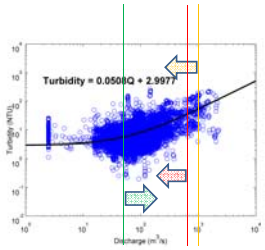


* Flood season: June 21st – Sep. 20th
(Dam management Code, Mar. 1974)

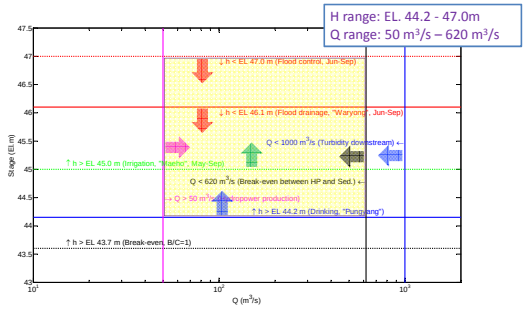
from H. Kim et al, ASCE, 2017

Discharge (Q) Constraints

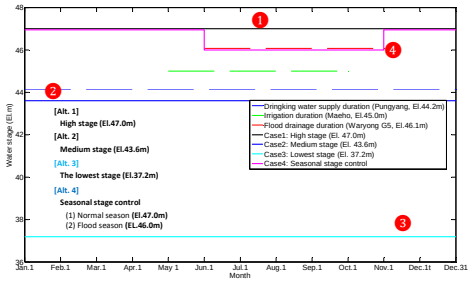
- **Hydropower production**
  Q > 50 m^3/s
- **Break-even discharge**
  Q < 620 m^3/s
- **Turbidity limit Discharge**
  Q < 1,000 m^3/s



H and Q Constraints



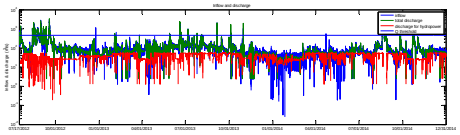
Alternatives development



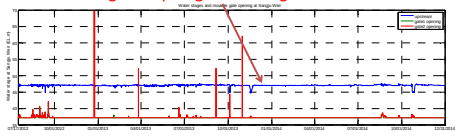
from H. Kim et al., ASCE, 2017

Historical Operational Data

- Sangju Weir, July 2012 – December 2014 (2yrs)



Water Stage is kept high according to the current rule

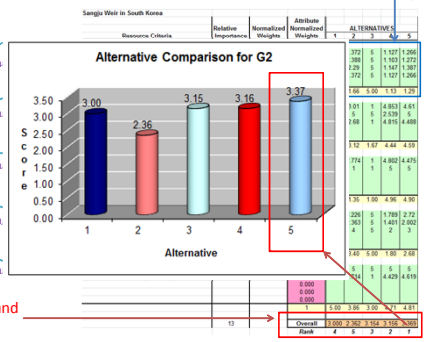


from H. Kim et al., ASCE, 2017

MCDA Rating (WAM)

Rating

Main Criteria (5)



Overall score and Ranking

from H. Kim et al., ASCE, 2017

Part II – Sediment Management

1. Sedimentation problems near dams
2. Density currents in reservoirs
3. Dambreak impact
4. Multi-objective dam operations
5. Socio-economic considerations

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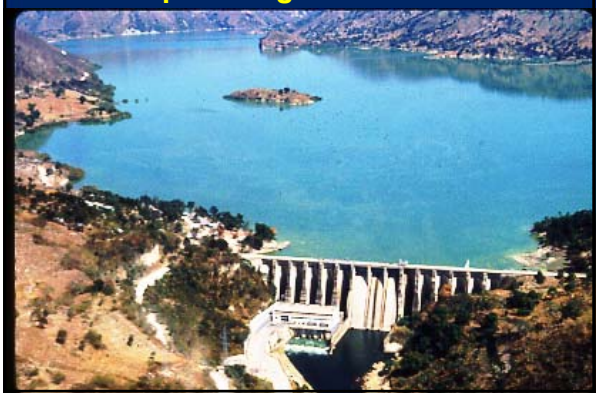
Example: Peligre Dam in Haiti

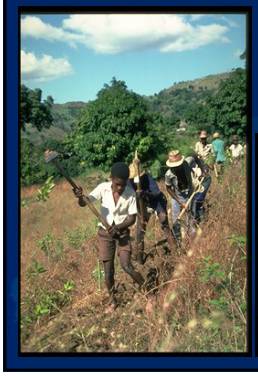


Demographic Expansion

Lowland Slash and Burn

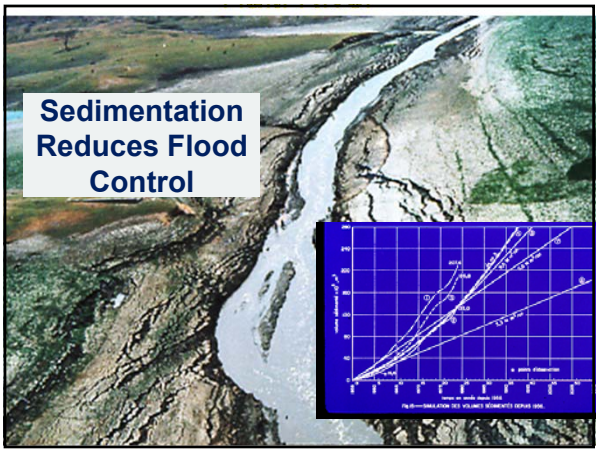
Subsistence Farming

Farming Uphill

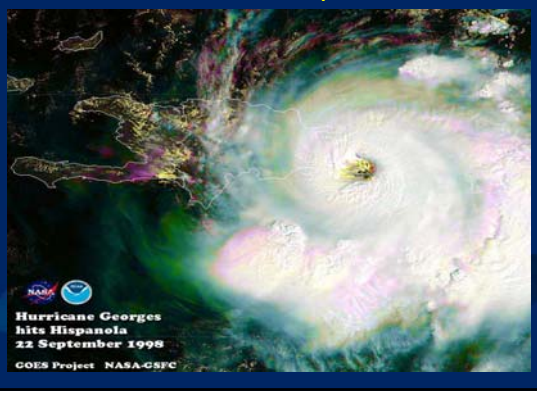


Farming Hilltops?

Upland Degradation Causes Sedimentation



Hurricane Impact



Emergency Spillway Operation

Citizens Blame their Government

Could this be avoided?

Summary and Conclusions

1. Sedimentation Problems near Dams

Flushing and dredging are possible in low-head dams

2. Density Currents in Reservoirs

Turbidity currents can be modeled and predicted

3. Dambreak Impact

Dam breaks impact rivers over long distances

4. Multi-objective Operations

Hydraulic thresholds and MCDA are useful for dam operations

5. Socio-Economic Considerations

Sedimentation can have a large socio-economic impact

Sediment Management References

1. Sedimentation Problems near Dams

Ji, U., P.Y. Julien and S.K. Park, "Case-Study: Sediment Flushing and Dredging near the Nakdong River Estuary Barrage", J. Hydraulic Eng., ASCE, 137(11), 2011, pp. 1522-1535.

2. Density Currents in Reservoirs

An, S.D., and P.Y. Julien, "Case-study: Three-Dimensional Modeling of Turbid Density Currents in Imha Reservoir, South Korea", ASCE J. Hydraulic Eng., 140(5), 2014,

3. Dambreak Impact

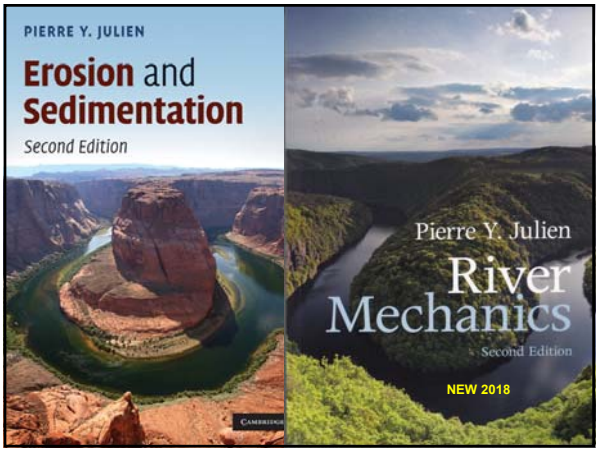
Shin, Y.H. and P.Y. Julien, "Case-Study: Effect of Flow Pulses on Degradation Downstream of Hapcheon Dam, South Korea", J. Hydraulic Eng., ASCE, 137(1), 2011, pp. 100-111.

Sediment Management References

4. Multi-objective Operations

Kim, H.Y., and P.Y. Julien, "Case Study: Hydraulic Thresholds to Mitigate Sedimentation Problems at Sangju Weir", ASCE J. Hydraulic Eng., 144(6), 2018, ISSN 0733-9429, 13p.

Kim, H.Y., D. G. Fontane, P.Y. Julien, and J.H. Lee, "Multi-objective Analysis of the Sedimentation behind Sangju Weir, South Korea", ASCE J. Water Resources Planning and Management, 144(2), 2018, 12p.

5. Socio-Economic Considerations

Luis, J., Sidek, M.L., Desa, M.N.B.M. and P.Y. Julien, "Hydropower Reservoir for Flood Control: A Case Study on Ringlet Reservoir, Cameron Highlands, Malaysia", J. Flood Engineering, 4(1), January-June 2013, pp. 87-102.