Estimation of External Costs Associated with Hydroelectric Projects Having Reservoirs

Ghulam Rasul Athar

Applied Systems Analysis Group,

Pakistan Atomic Energy Commission,

P.O. Box 1114, Islamabad, Pakistan

asag@comsats.net.pk

IAEA Workshop on the 'Use of the SimPacts Model for Estimating Human Health and Environmental Damages from Electricity Generation'

Trieste, Italy, May 12-23, 2003.

Scope of HydroPacts

Estimation of external costs due to:

- Displacement and Resettlement
- Atmosphere Emissions (i.e GHG, SO_x) during Construction and Operation
- Accidental Dam Breach
- Loss of Land, Agriculture Products, Livestock

Displacement and Resettlement

First Attempt to Correlate Displaced Population with Simple Parameters

$Area_{Inundated}$ [km^2] = 0.57 * Capacity [MW]	$Coeffic_{Correlation}$: 0.523
$Population_{Resettled}$ [persons] = 3.1 * Capacity [MW]	$Coeffic_{Correlation}$: 0.160
$Population_{Resettled}$ [persons] = f ($Area_{Inundated}$)	$Coeffic_{Correlation}$: 0.041
Resettlement $Cost_{per\ Person}$ [$/capita] = 1.33 * GDP_{pc1999}	$Coeffic_{Correlation}$: 0.843

- Approach found that most relationships had low correlations
- Does not take into account basic dam and reservoir characteristics
- Does not account for different terrains
- Does not consider population distribution

Physical and Economic Impact Estimation of Displacement

- **Estimation of displacement follows similar routine than air impacts and is based on regional population density**

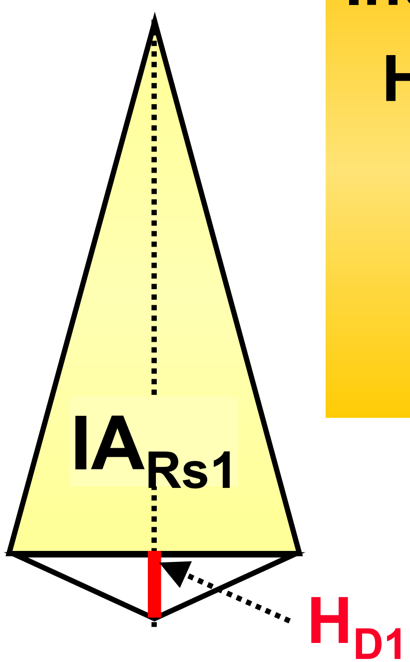
$$POP_{DIS} = IA_{RS}\left[km^{2}\right] x \; POP_{Density}\left[\frac{persons}{km^{2}}\right]$$

If you know the inundated area, you can enter it.

Alternatively

you can use the model to estimate the inundated area

Area Inundated by the Reservoir is a Function of the Dam Height (at Constant Terrain)



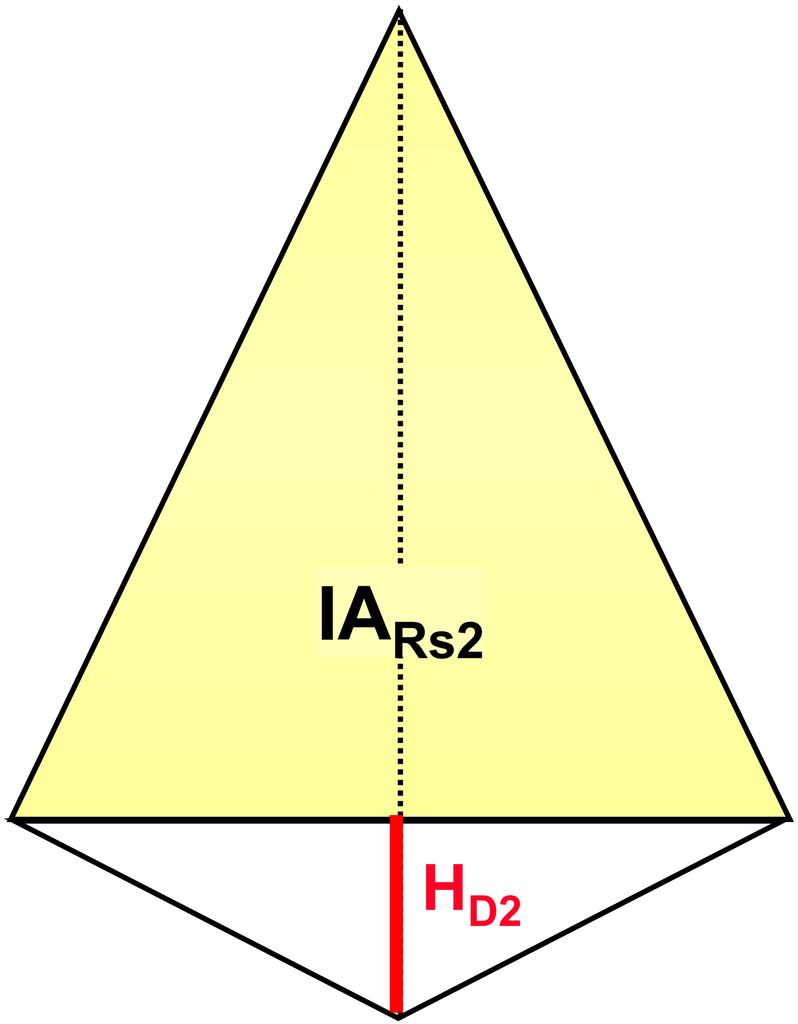
Inundated Area (IA_{Rs})

Height of Dam (H_D)

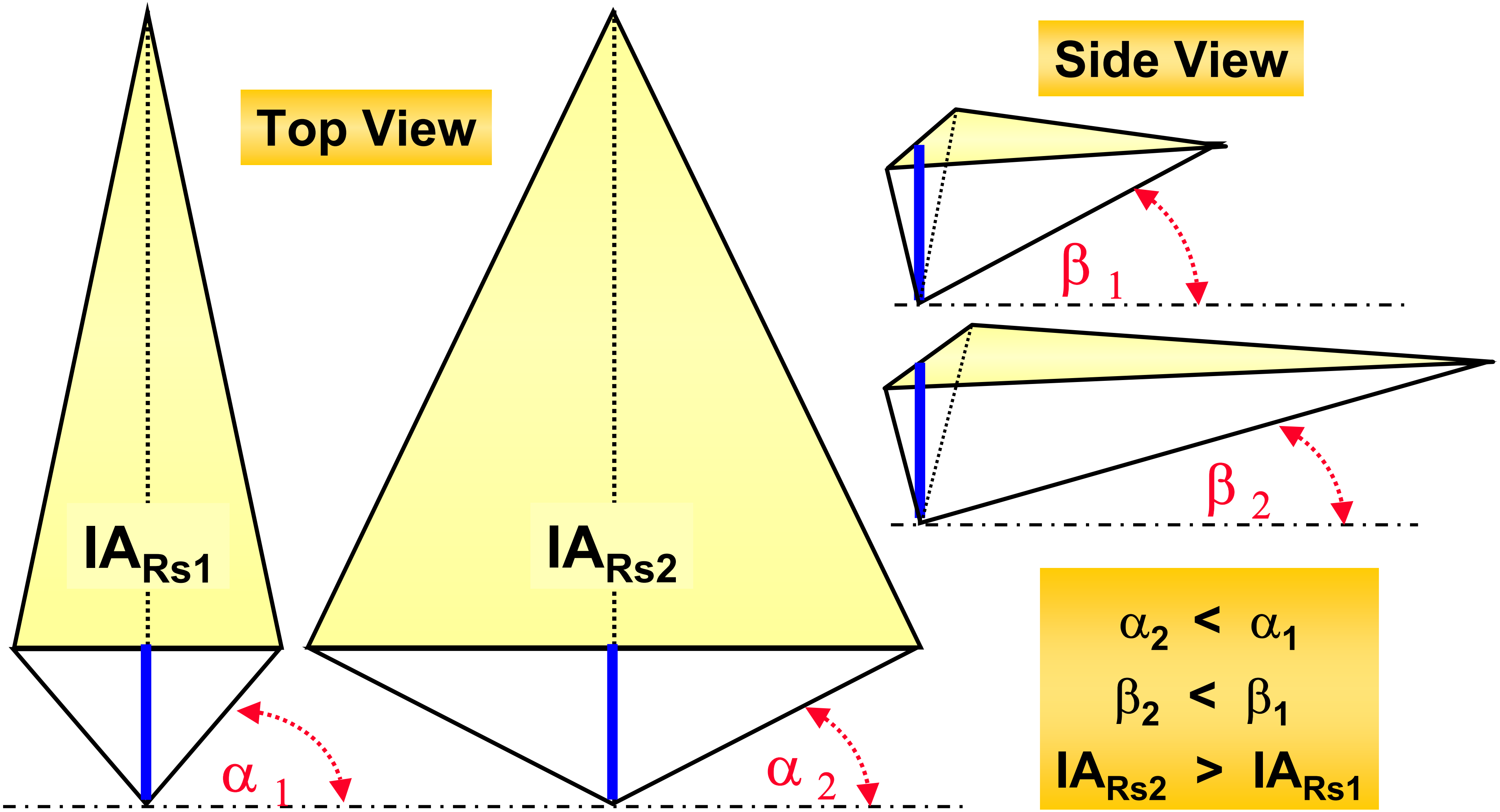
$$A = f(H_D)$$

$$H_{D1} < H_{D2}$$

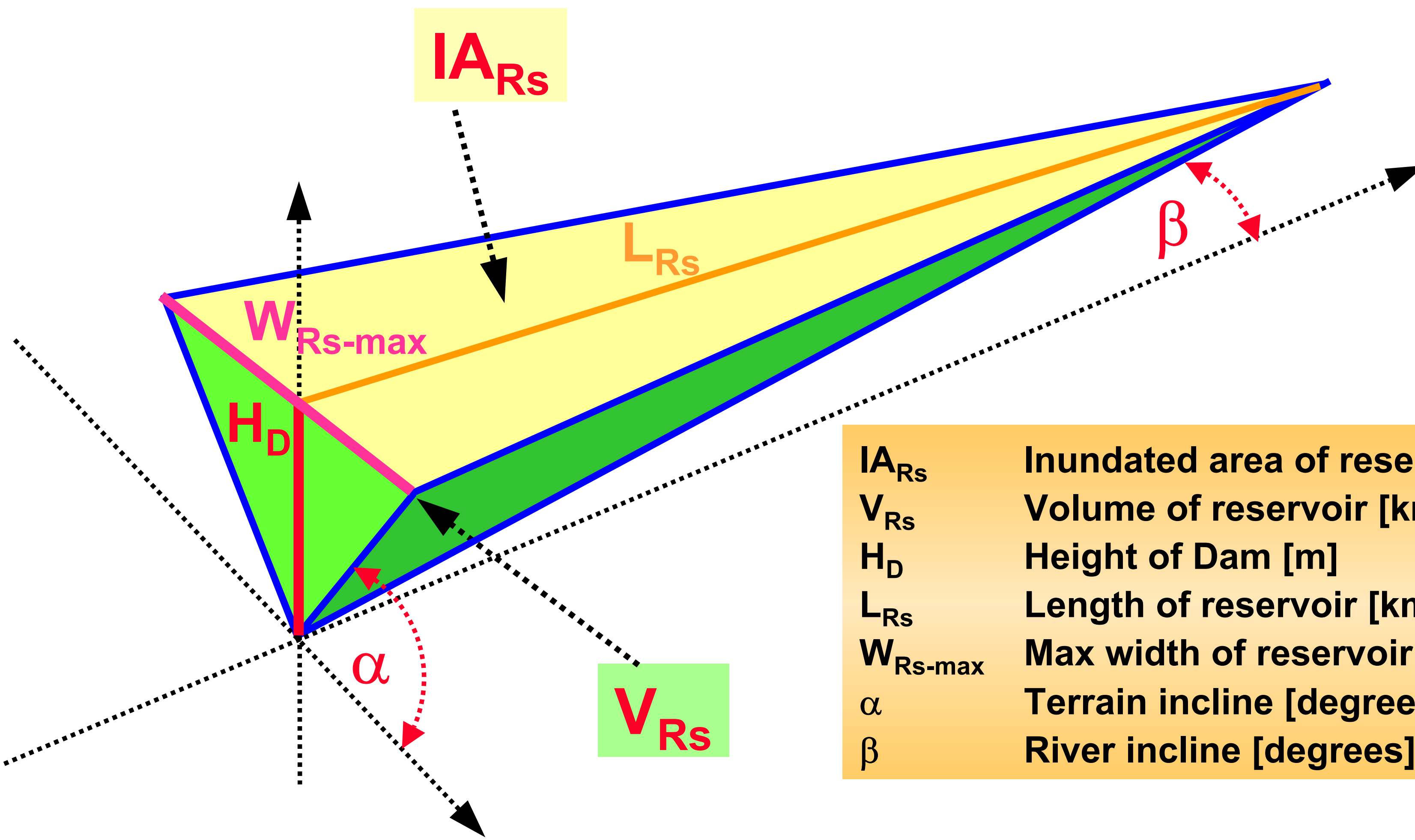
$$IA_{Rs1} < IA_{Rs2}$$



Area Inundated by the Reservoir is a Function of the Terrain (at Constant Dam Height)



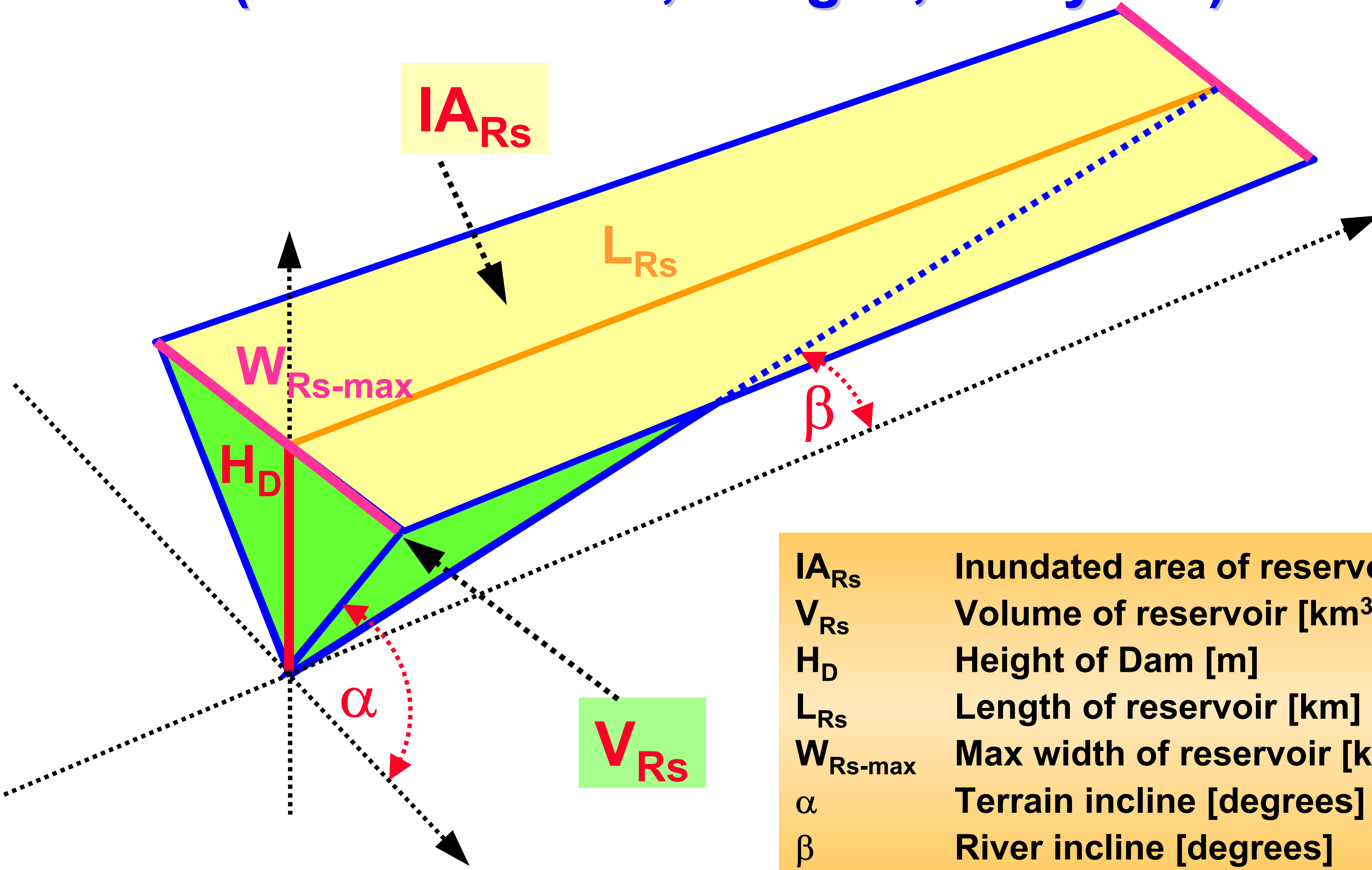
Simple 3D Model of Reservoir – Triangular Cube (for Flatlands)



IA_{Rs}	Inundated area of reservoir [km^2]
V_{Rs}	Volume of reservoir [km^3]
H_D	Height of Dam [m]
L_{Rs}	Length of reservoir [km]
W_{Rs-max}	Max width of reservoir [km]
α	Terrain incline [degrees]
β	River incline [degrees]

If a user choose type of terrain=2 (flatland/plane), the model will choose Triangular reservoir shape

Simple 3D Model of Reservoir – Rectangular Cube (for Mountains, Gorges, Canyons)



IA_{Rs}	Inundated area of reservoir [km^2]
V_{Rs}	Volume of reservoir [km^3]
H_D	Height of Dam [m]
L_{Rs}	Length of reservoir [km]
$W_{Rs\text{-}max}$	Max width of reservoir [km]
α	Terrain incline [degrees]
β	River incline [degrees]

If a user choose type of terrain=1 (gorges, narrow valleys, steep mountains), the model will choose Rectangular reservoir shape

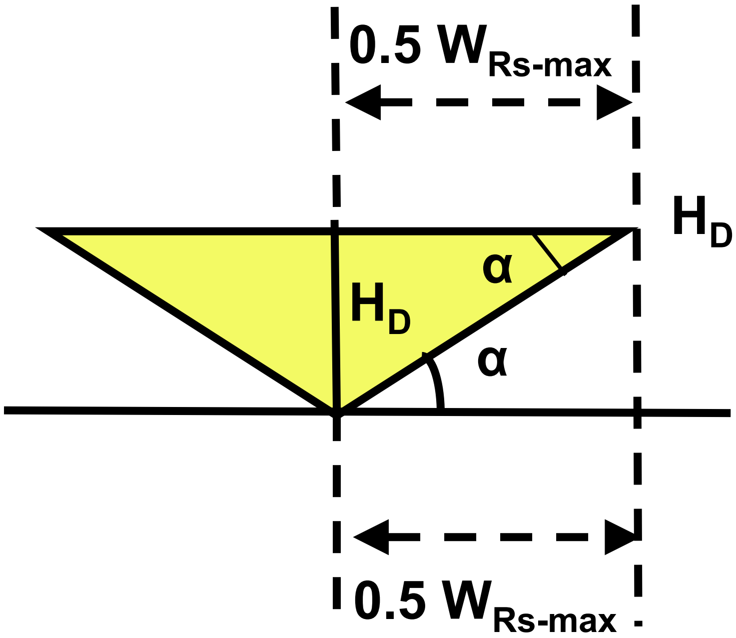
Relation between dam height and width of reservoir

Tan α = Perpendicular / Base

$$\tan\alpha = \frac{H_D\ (m)}{0.5\ W_{Rs\text{-}max}\ [km] \times 1000 (m/km)}$$

$$\tan\alpha = \frac{H_D\ [m]}{0.5 \times 1000 \times W_{Rs\text{-}max}}$$

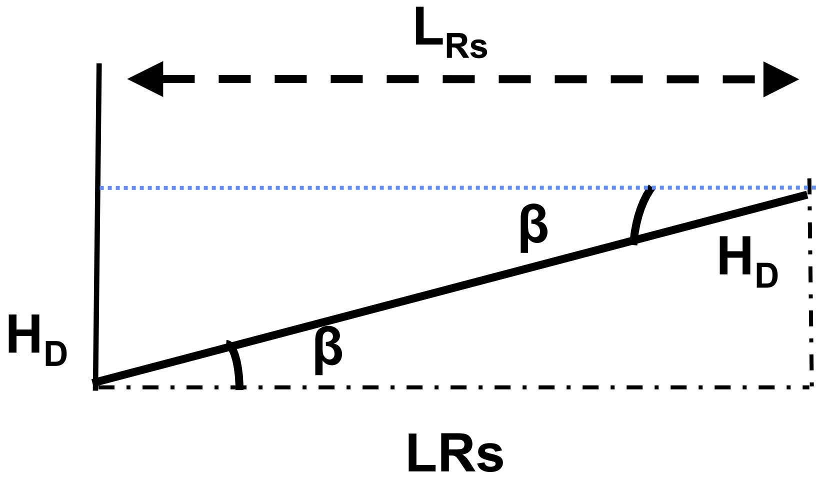
$$W_{Rs\text{-}max} = \frac{H_D}{0.5 \times 1000 \times \tan\alpha}$$



Relation between dam height and length of reservoir

$$\tan\beta = \frac{H_D\ [m]}{LRs\ [km] \times 1000\ m\ /\ km}$$

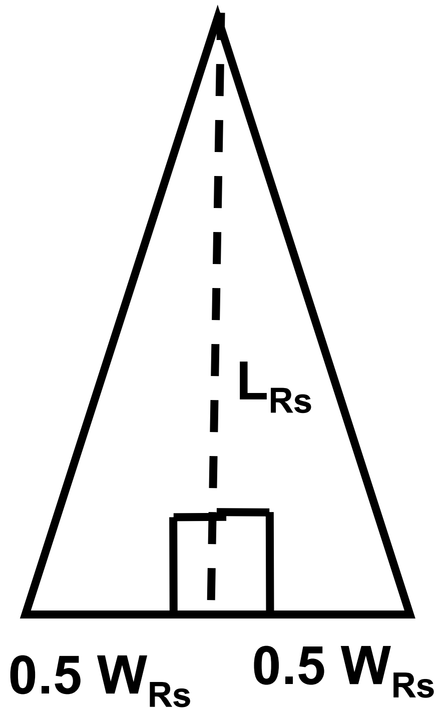
$$L_{Rs} = \frac{H_D\ [m]}{1000 \times \tan\beta}$$



Reservoir Area

Triangular-Shape Reservoir

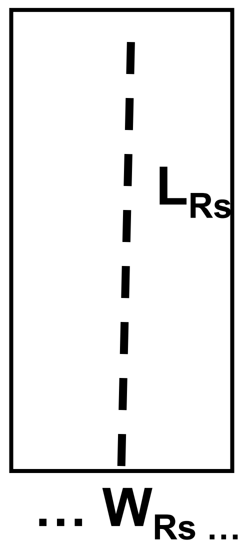
$$IA_{Rs} = \left\{ 1/2 \, (L_{Rs} \times 0.5 \, W_{Rs}) \right\} \times 2$$
$$= 0.5 \; L_{Rs} \times W_{Rs}$$
$$= 0.5 \; \frac{H_D \, [m]}{0.5 \times 1000 \times \tan\beta} \times \frac{H_D \, [m]}{1000 \times \tan\beta}$$
$$= \frac{H_D^2}{\tan\alpha \times \tan\beta \times 10^6}$$



Terrain index

Rectangular-Shape Reservoir

$$IA_{Rs} = L_{Rs} \times W_{Rs}$$
$$= \frac{H_D \, [m]}{0.5 \times 1000 \times \tan\beta} \times \frac{H_D \, [m]}{1000 \times \tan\beta}$$
$$= \frac{H_D^2}{0.5 \times \tan\alpha \times \tan\beta \times 10^6}$$



Reservoir Area

Triangular-Shape Reservoir

$$IA_{Rs} = 1/2 \left\{ \left(L_{Rs} \times 0.5\, W_{Rs} \right) \times 2 \right\}$$

$$= 0.5\ L_{Rs} \times W_{Rs}$$

$$= \frac{0.5\ H_D\,[m]}{0.5 \times 1000 \times \tan\beta} \times \frac{H_D\,[m]}{1000 \times \tan\beta}$$

$$= \frac{H_D^2}{\tan\alpha \times \tan\beta \times 10^6}$$

Terrain index

Rectangular-Shape Reservoir

$$IA_{Rs} = L_{Rs} \times W_{Rs}$$

$$= \frac{H_D\,[m]}{0.5 \times 1000 \times \tan\beta} \times \frac{H_D\,[m]}{1000 \times \tan\beta}$$

$$= \frac{H_D^2}{0.5 \times \tan\alpha \times \tan\beta \times 10^6}$$

The user has to enter either terrain index or inclinations of river and terrain (α, β) . Currently 8 terrain indices are available in the model. The user inputs for α and β have priority over the terrain index

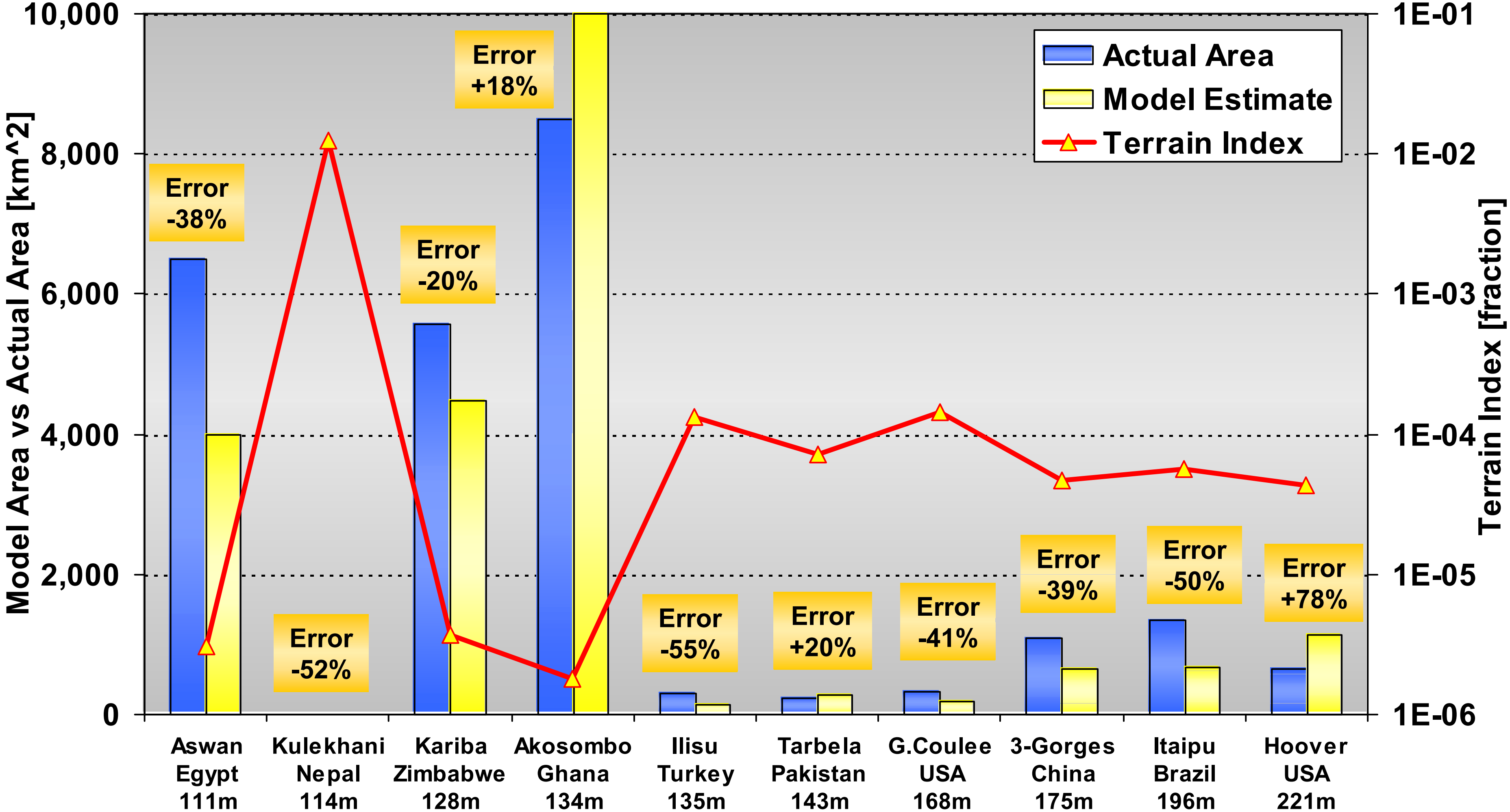
TERRAIN INDEX

1: Ghana, Akosombo(1.80e-6)
2: Zimbabwe, Kariba(3.66e-6)
3: China, 3 Gorges(4.65e-5)
4: Brazil, Itaipu(5.65e-5)
5: Pakistan, Tarbela(7.10e-5)
6: USA, Hoover(4.29e-5)
7: USA,Grand Coulee(1.44e-4)
8: Egypt, Aswan(3.08e-6)

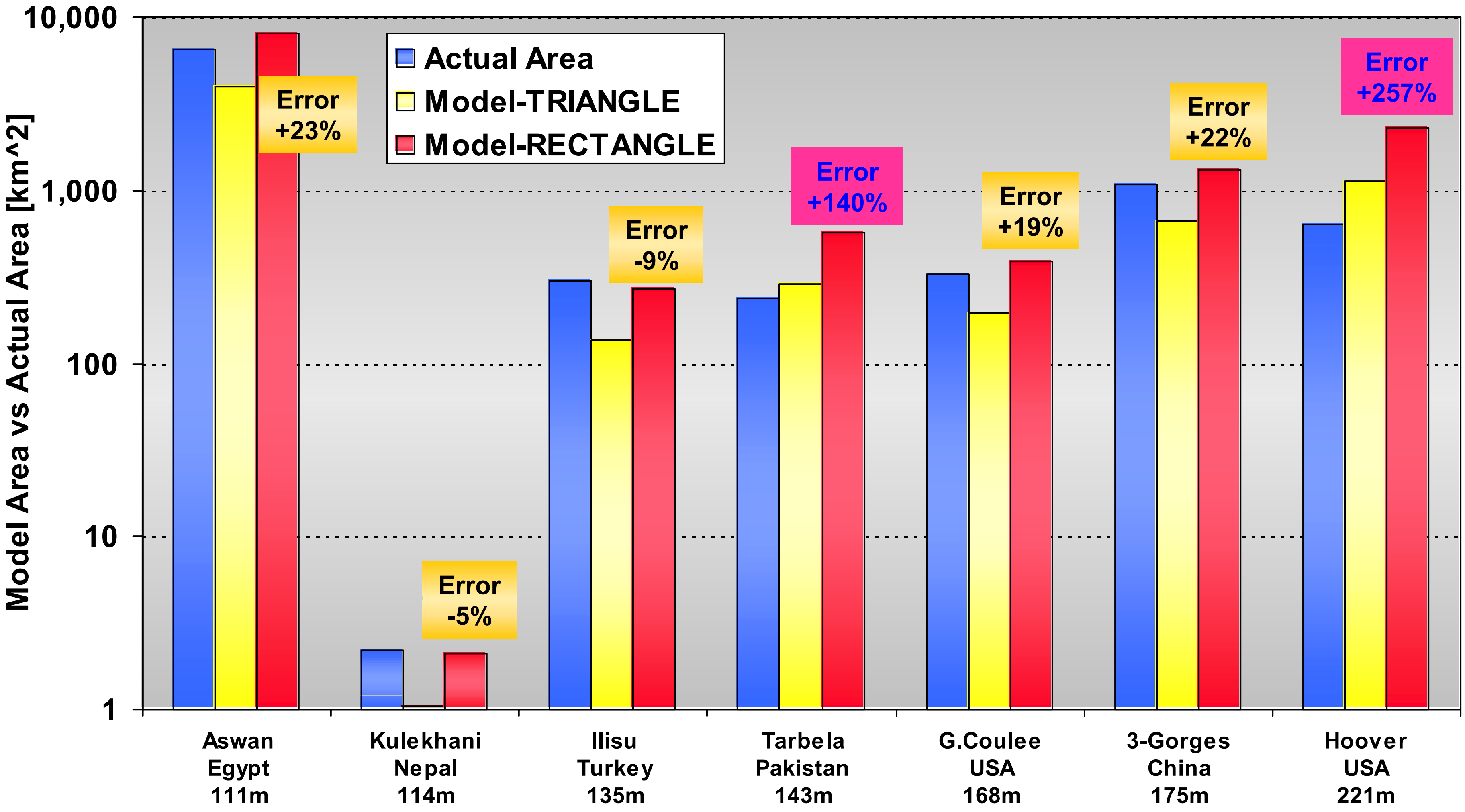
Reservoir Area

The users inputs for reservoir area has priority over the calculated reservoir area

Model Results for 10 Locations: Triangular Shape Assumed For All Location



Model Results for 7 Mountain Locations: Assumes Rectangular Shape



Do you know dam height?

If yes. The model will use it. Otherwise model will estimate the dam height based on:

(i) head.
(ii) capacity and flow.

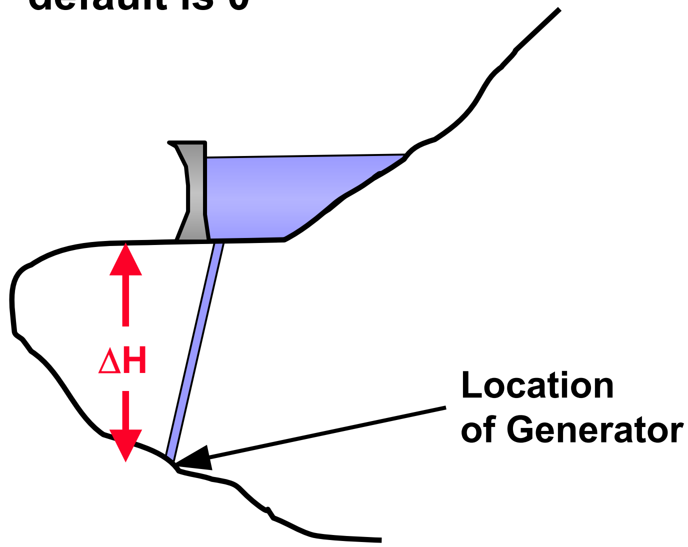
Estimating Dam Height

- Default assumption for ΔH is 0, that is, head equals dam height

$$H_D = Head - \Delta H$$

ΔH: Additional Head Correction [m] default is 0

- ΔH < 0, if head is expected to be noticeably smaller than dam height. If generator house is expected to be located substantially down stream ΔH > 0



Estimation of Dam Height

$$Head = \frac{P \ x \ 1000}{9.81 \ x \ \eta \ x \ Q_W}$$

P: **Power Output [MW]**

η: **Overall Plant Efficiency [fraction]**

Q_W: **Discharged water flow from turbine [m^3/s]**

The model uses the following priority for dam height :

i) Users inputs for dam height .

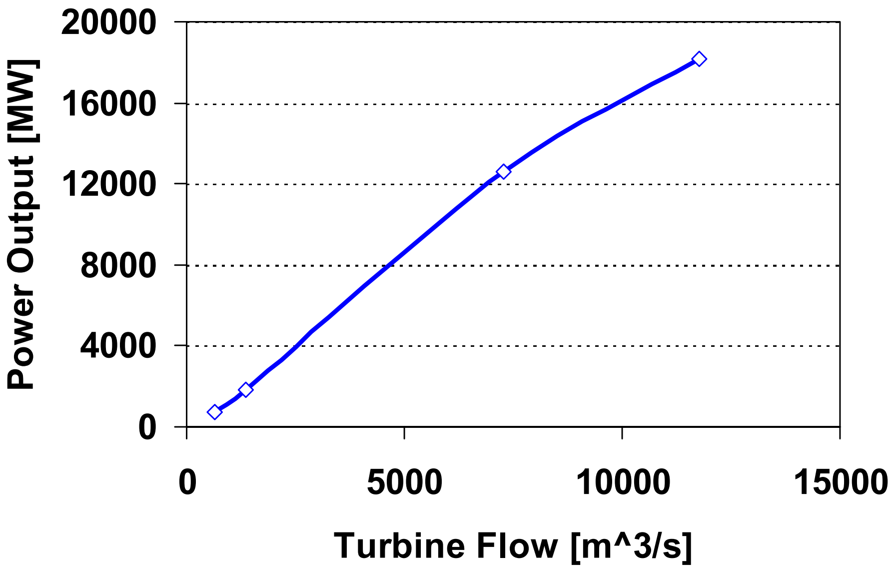
ii) Dam height calculated based on head.

iii) Dam height calculated based on capacity and flow.

Impact of Design Turbine Flow

- If power output and turbine design flow is known, the model will use the previous equation

- If the flow information is unknown, use 5000 m^3/s and then scale up and down as part of a sensitivity analysis



Physical and Economic Impact Estimation of Displacement

- **Estimation of displacement follows similar routine than air impacts and is based on regional population density**

$$POP_{DIS} = IA_{RS}\left[km^2\right] x \; POP_{Density}\left[\frac{persons}{km^2}\right]$$

Estimating the External Cost of Population Displacement (Levelized per MWh)

- **Resettlement cost from Markandya**
- **As resettlement costs are usually internalized, we calculate the external cost based on people displaced but not resettled or compensated**

$$Cost_{DIS} = POP_{DIS}\,[persons]\; x \left(1.33\; x\; GDP_{PerCapita}\left[\frac{US\$}{person}\right]\right)$$

$$Cost_{DIS,EXT} = Cost_{DIS}\,[US\$]\; x\;\; Fraction_{DIS,NOTRES}$$

$$Cost_{DIS,MWh,EXT} = \frac{Cost_{DIS,EXT}\,[US\$]\; x \left(\dfrac{IR\;\; x\;\; (1 + IR)^{ELife}}{(1 + IR)^{ELife} - 1}\right)}{P\,[MWe]\; x\;\; 8{,}760\;\; x\;\; \dfrac{CF\,[\%]}{100}} \qquad for\;\; IR > 0$$

$$Cost_{DIS,MWh,EXT} = \frac{Cost_{DIS,EXT}\,[US\$]}{P\,[MWe]\; x\;\; 8{,}760\;\; x\;\; \dfrac{CF\,[\%]}{100}\;\; x\;\; ELife\,[years]} \qquad for\;\; IR = 0$$

GHG Emissions during Construction and Operation

GHG Emissions during Construction Phase (Life Cycle)

- **Equation below uses the emission factors in g/kWh (*EFConstr*), the plant capacity in MWe (*P*) and the average capacity factor in % (*CF*).**

$$Emissions_{Constr,Year} = \frac{EF_{Constr}\left[\frac{g}{kWh}\right] \; x \; P\left[MWe\right] \; x \; 8{,}760\left[\frac{h}{year}\right] \; x \; CF\left[\%\right]}{1{,}000}$$

Emissions Factors for Construction Phase

- **Emissions during construction phase depend on the type of dam**
  - Concrete dams (concrete gravity, concrete arch, etc) account for 72% of all dams
  - Embankment dams using earth and rock fill material account for 25% of all dams
- **Material, associated energy requirements, and resulting emissions vary with the type of material used for construction**

	CO_2 (g/kWh)		SO_2 (g/kWh)	NO_X (g/kWh)
	Concrete	Earth + Rock Fill		
Low	1.00	0.10	0.008	0.003
High	5.90	1.00	0.100	0.013
Mean	2.733	0.55	0.035	0.006
Source: [IEA, 1998]				

GHG Emissions During Operation Phase

- Once flooded, biomass (vegetation and soil) and carbon inflows from catchment area are decomposed by microbes via aerobic and anaerobic bio processes
- Byproducts are CO2, CH4, and to a lesser extent, N2O
- Measurements in tropical and boreal regions show large range of GHG emissions within countries and between regions
- Larger variation in tropical regions
- In addition, there appear to be strong seasonal and annual variations
- Decomposition varies with time: three phases can be distinguished: (1) initial phase lasting 1-3 years after flooding, (2) erosion phase lasting up to 7-10 year, and (3) balanced phase lasting 10-30 years

Model has two options, Region ID = 1 for Tropical , Region ID = 2 for Boreal

GHG Emissions During Operation Phase (ton/km²/year)

	Tropical		Boreal	
	CO_2	CH_4	CO_2	CH_4
Low	150	1.5	183	1.8
High	4,000	40	1,350	13.5
Mean	1,798	18	693	6.9

Sources: [WCD, 2000], [IEA, 1998]
Assumes that 1% of emissions are in form of methane

$$Emissions_{Operat,Year} = IA_{RS}\left[km^2\right] x \; EF_{Operat}\left[\frac{ton}{km^2 - year}\right]$$

$$GHG_{CE,Total,Year} = CO_2,_{Const}\left[\frac{tons}{year}\right] + CO_2,_{Operat}\left[\frac{tons}{year}\right] + \left(21 \; x \; CH_4,_{Operat}\left[\frac{tons}{year}\right]\right)$$

Accidental Dam Breach

Accidental Dam Breach

- **Several causes for dam failure**
  - Seepage
  - Overtopping or inadequate spillway
  - Seismic
  - Slides
  - Others

Cause of Failure	Occurrence
Overtopping or inadequate spillway	23 – 38%
seepage	30 – 44%
Slides	2 – 15%
Others	9- 35%
Source: [Christian and Baecher, 1999]	

Risk of Dam Failure and Factors Influencing the Impact Level

- **Risk of dam failure is estimated at 1E-4 per dam per year**
- **Risk is not uniformly distributed over dam lifetime**
  - Higher risk at the beginning
  - About 50% of all dam failures occur during initial reservoir filling to capacity
  - Residual risk more or less uniform over lifetime
- **Damage resulting from failure is determined by**
  - Population and property at risk
  - Warning time (time for evacuation)
  - Type of terrain
- **Warning time has strong influence on impact level**
  - 13% average fatalities with warning times less than 1.5 hours, and a fatality rate of 0.04% if the warning time was more than 1.5 hours
- **Downstream terrain affects the height and extent of the flood wave as well as the ability to evacuate and avoid the impact of the wave**

Determining the Number of Lives Lost per Accident and the Expected Lives Lost

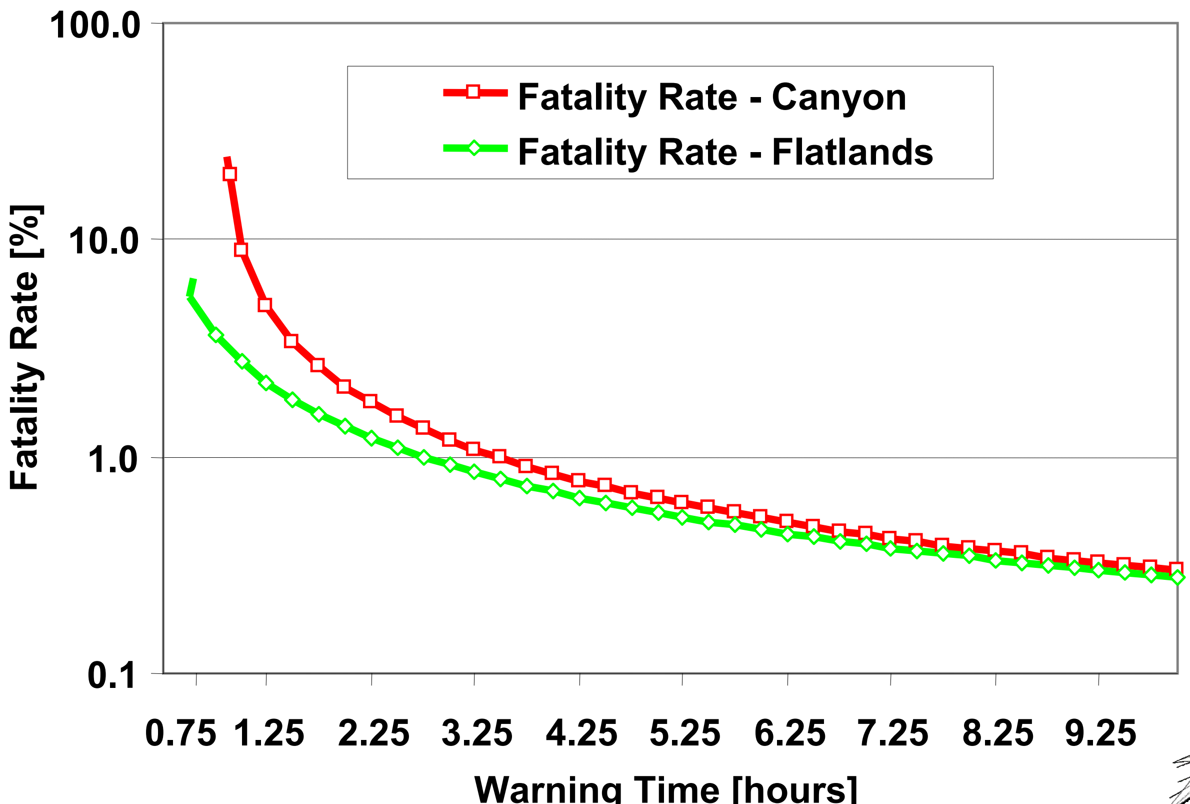
$$LIVES_{Lost,Acc} = \frac{POP_{Risk}\left[persons\right]}{(1+5.207)\ x\ (5.838\ x\ TIME_{Warn}\left[hours\right] - TER)}$$

$$TER_{Canyons} = 4.012$$

$$TER_{Flatlands} = 0$$

$$EXPLives_{Lost,Year} = FR_D\ x\ LIVES_{Lost,Acc}$$

- FR_D Default dam failure rate is 1E-4
- Equation works for warning times of 0.75 and higher
- Chart clearly shows effect of warning time and terrain



Estimating the External Cost of Accidents and Total External Cost (Levelized per MWh)

- **Allows adjustment of the value of statistical life (VSL)**

$$VSL_{CountryX} = \$1{,}500{,}000 \ x \ \frac{GDP_{PPP,CountryX}}{23{,}550}$$

$$Cost_{LossLife,MWh,EXT} = \frac{EXPLives_{Lost,Year} \ x \ VSL_{CountryX}}{P\left[MWe\right] \ x \ 8{,}760 \ x \ \frac{CF\left[\%\right]}{100}}$$

Estimating the External Cost of Land Loss (Levelized per MWh)

Estimating the External Cost of Land Loss (Levelized per MWh)

- For simplicity, three land categories: forest, farmland, other
- Similar to resettlement, accounts for internalizing most of the cost

$$Cost_{LandLoss,EXT} = (1 - FIC)\ x \sum_{i=1}^{3}\left(IA_{RS,i}\left[km^2\right]\ x\ Cost_{Landuse\ i}\left[\frac{US\$}{hectare}\right]\ x\ 100\right)$$

$$Cost_{LandLoss,MWh,EXT} = \frac{Cost_{LandLoss,EXT}\ [US\$]\ x\ \left(\frac{IR\ x\ (1 + IR)^{ELife}}{(1 + IR)^{ELife} - 1}\right)}{P\ [MWe]\ x\ 8{,}760\ x\ \frac{CF\ [\%]}{100}} \qquad for\ \ IR > 0$$

$$Cost_{LandLoss,MWh,EXT} = \frac{Cost_{LandLoss,EXT}\ [US\$]}{P\ [MWe]\ x\ 8{,}760\ x\ \frac{CF\ [\%]}{100}\ x\ ELife\ [years]} \qquad for\ \ IR = 0$$

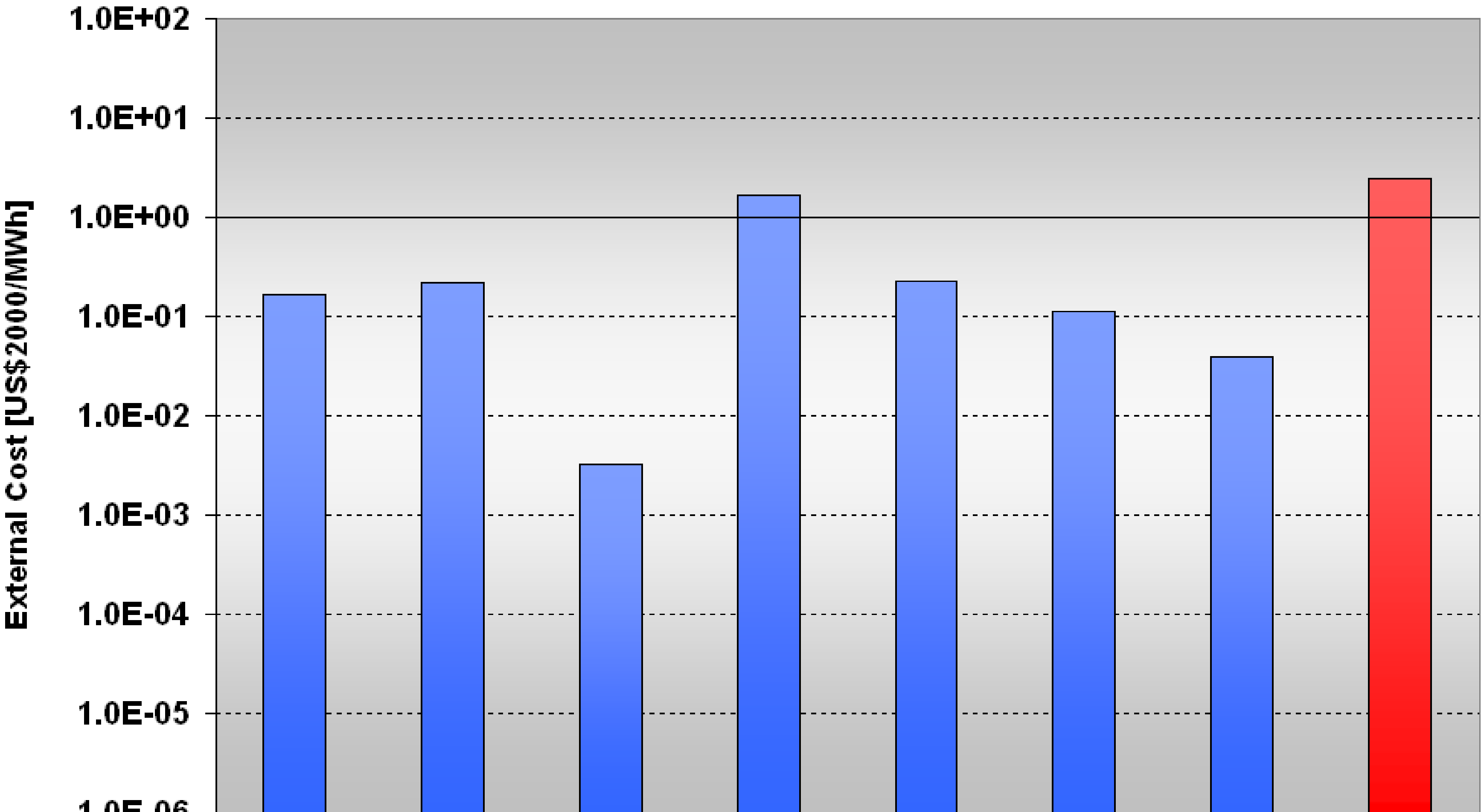
Total External Cost (Levelized per MWh)

- **If physical impacts are known, model allows to include cost of loss of agricultural and livestock production**

- **Total cost is sum of individual cost components**

$$Cost_{TOTAL,MWh,EXT} = \sum_{i=1}^{n} Cost_{MWh,EXT}$$

Model Results – Economic Summary



	Displacement	Loss of Land	Loss of Life	Emissions	Loss of Production	Loss of Resources	Increased Diseases	TOTAL
External Cost	1.69E-01	2.21E-01	3.223E-03	1.647E+00	2.295E-01	1.125E-01	3.851E-02	2.421E+00

Thank You