

Escola Politécnica da Universidade de São Paulo
Departamento de Engenharia Hidráulica e Ambiental
PHA 3203 - Engenharia Civil e Meio Ambiente

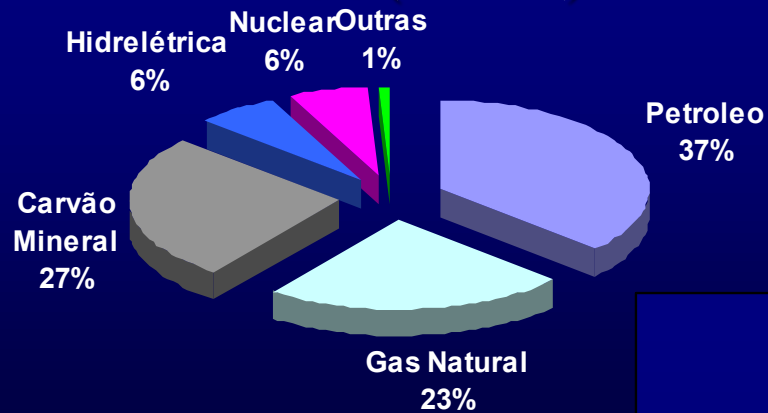
Energia e meio ambiente

Reservatórios, Hidrelétricas e Geração de Energia

Renato Carlos Zambon

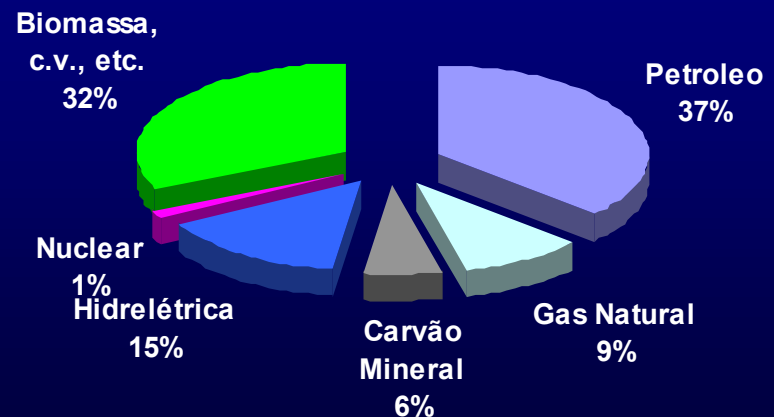
ENERGIA

Mundo (EIA 2008)



Energy Information
Administration

Brasil (EPE/MME 2008)

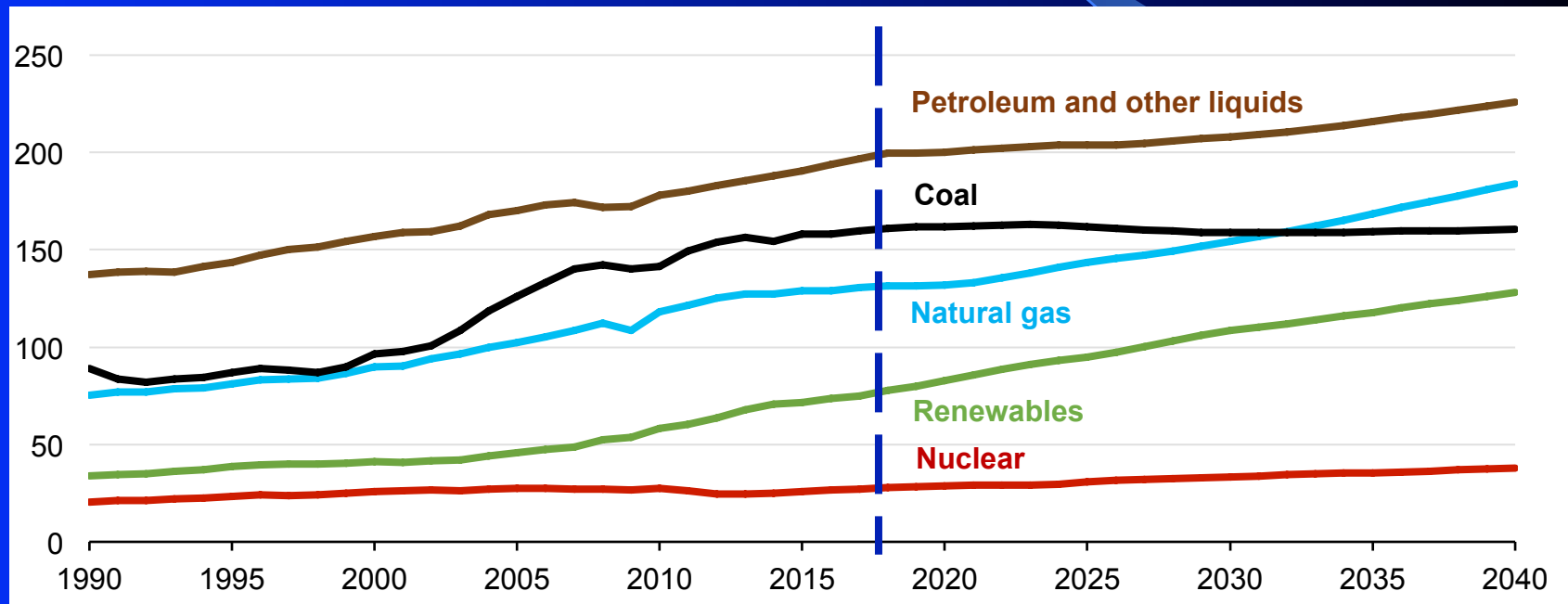


Empresa de
Pesquisa Energética

ENERGIA

World energy consumption by energy source (quadrillion Btu)

Reference case with renewables being the fastest-growing energy source



Source: EIA, International Energy Outlook 2017

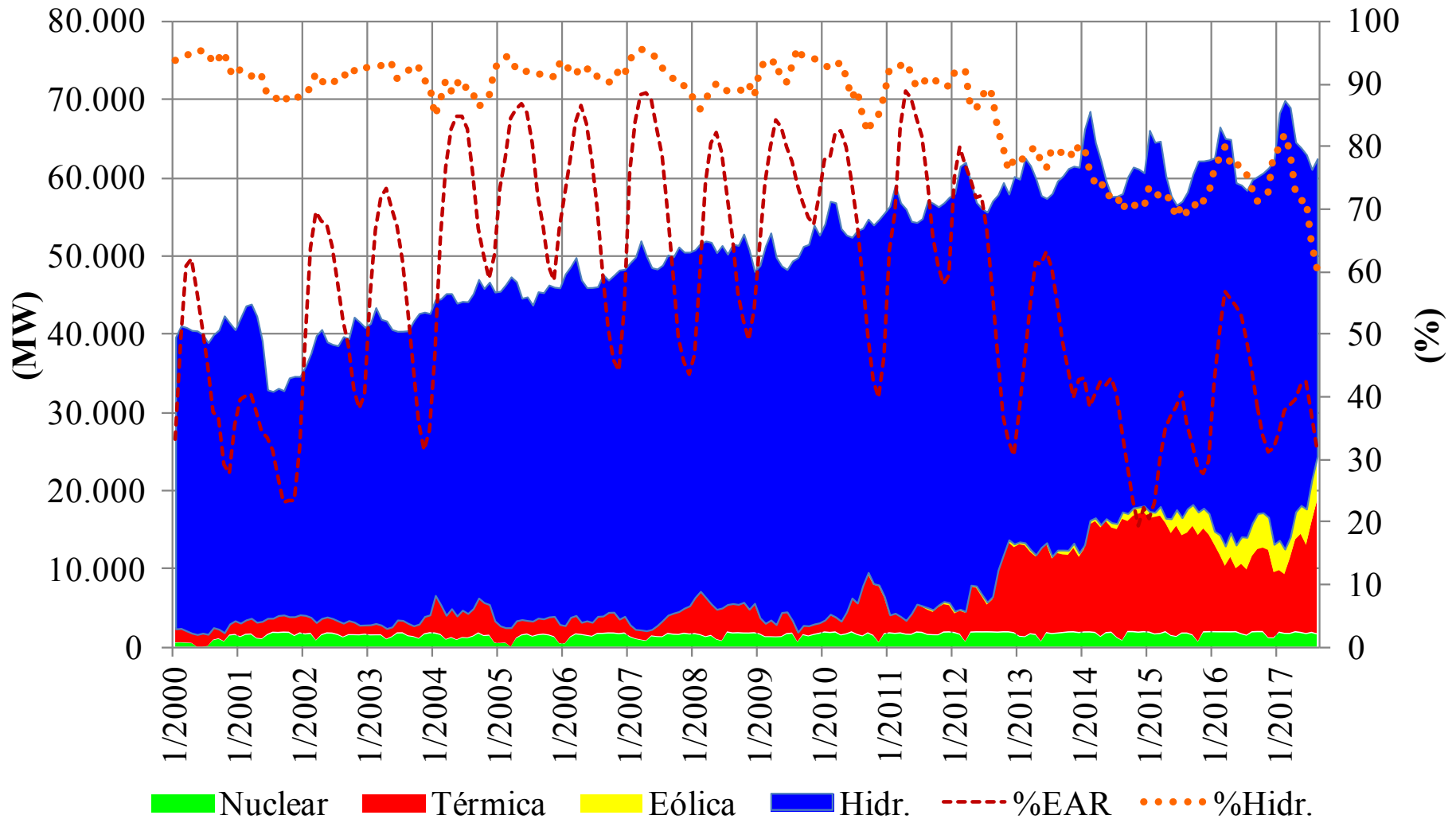
Empreendimentos em Operação							
Tipo		Capacidade		%	Total		%
		usinas	(kW)		usinas	(kW)	
Biomassa	Bagaço de Cana	399	10.883.904	6,81%	535	14.169.156	8,86%
	Biogás-AGR	3	1.822	0,00%			
	Capim Elefante	3	65.700	0,04%			
	Casca de Arroz	12	45.333	0,03%			
	Etanol	1	320	0,00%			
	Óleos Vegetais	2	4.350	0,00%			
	Carvão Vegetal	8	54.097	0,03%			
	Gás Alto Forno	11	332.265	0,21%			
	Lenha	2	14.650	0,01%			
	Licor Negro	17	2.261.136	1,41%			
	Res. Florestais	50	386.100	0,24%			
	Biogás-RA	11	2.099	0,00%			
	Biogás-RU	15	114.680	0,07%			
	Carvão-RU	1	2.700	0,00%			
Eólica		420	10.525.642	6,58%	420	10.525.642	6,58%
Fóssil	Calor de Processo - CM	1	24.400	0,02%	2.415	26.941.481	16,85%
	Carvão Mineral	13	3.389.465	2,12%			
	Gás de Alto Forno - CM	9	199.130	0,12%			
	Calor de Processo - GN	1	40.000	0,03%			
	Gás Natural	159	12.968.689	8,11%			
	Calor de Processo - OF	1	147.300	0,09%			
	Gás de Refinaria	6	315.560	0,20%			
	Óleo Combustível	43	4.056.847	2,54%			
	Óleo Diesel	2164	4.819.762	3,01%			
	Outros En. de Petróleo	18	980.328	0,61%			
Hídrica		1263	98.084.657	61,34%	1.263	98.084.657	61,34%
Nuclear		2	1.990.000	1,24%	2	1.990.000	1,24%
Solar		44	23.761	0,01%	44	23.761	0,01%
Importação	Paraguai		5.650.000	3,53%		8.170.000	5,11%
	Argentina		2.250.000	1,41%			
	Venezuela		200.000	0,13%			
	Uruguai		70.000	0,04%			
Total		4.679	159.904.697	100,00%	4.679	159.904.697	100,00%

fonte: www.aneel.gov.br, atualizado em 10/03/2017

Geração de Energia Elétrica - Brasil

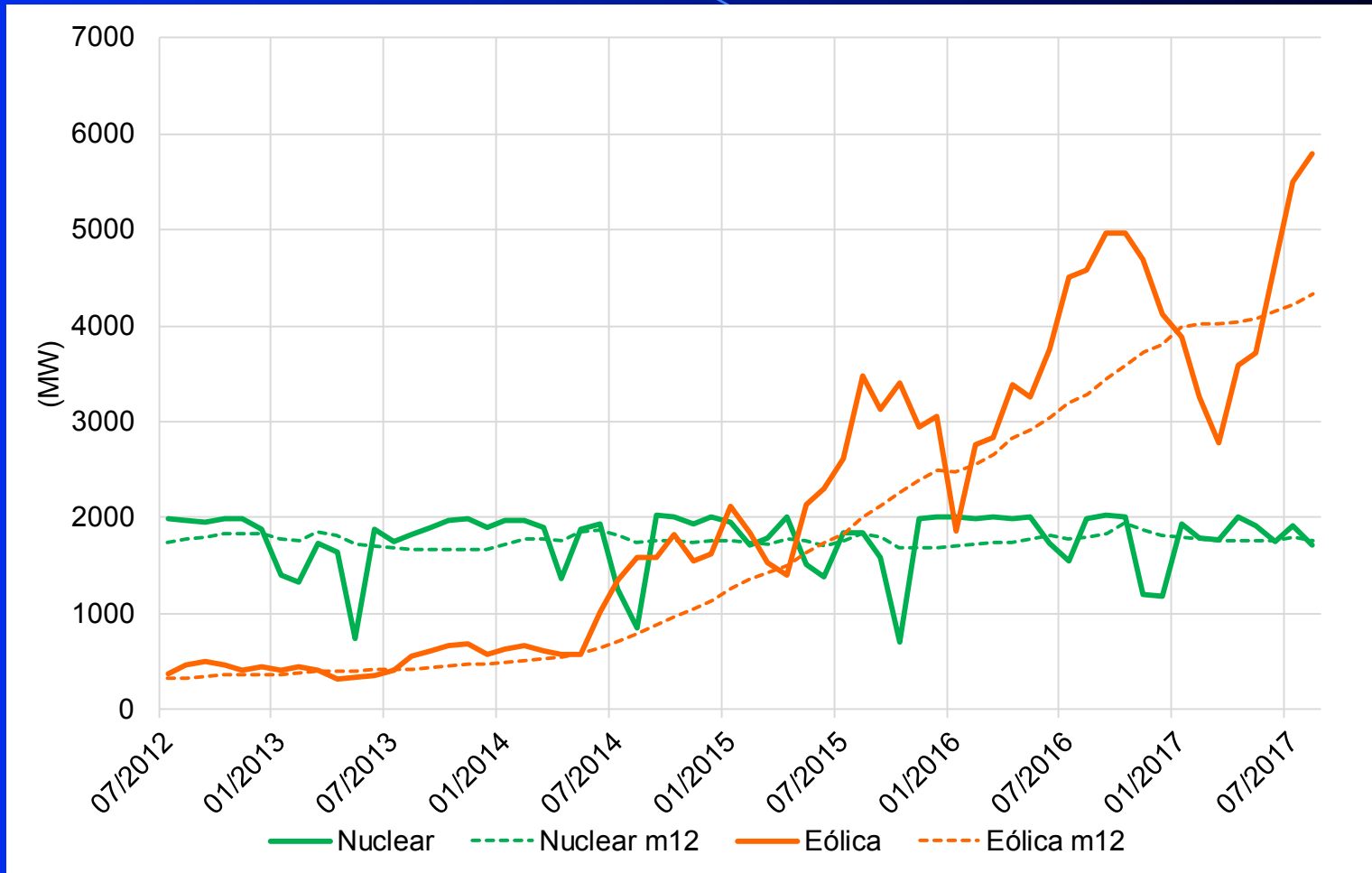
- **hidrologia desfavorável:** despacho de uma fração maior da capacidade das termelétricas, contribui para a segurança do suprimento;
- **hidrologia favorável:** as termelétricas são menos utilizadas e reduz o custo de operação, a queima de combustíveis fósseis (não renováveis) e a emissão de poluentes;
- **planejamento da operação:**
 - Operador Nacional do Sistema Elétrico (ONS)
 - Sistema Interligado Nacional (SIN)
(apenas 1,7% da capacidade fora do SIN)
 - Programa Mensal da Operação (PMO)

Geração de Energia Elétrica - Brasil



Composição da Carga por Fonte Geradora (médias mensais)

Geração Eólica e Nuclear - Brasil

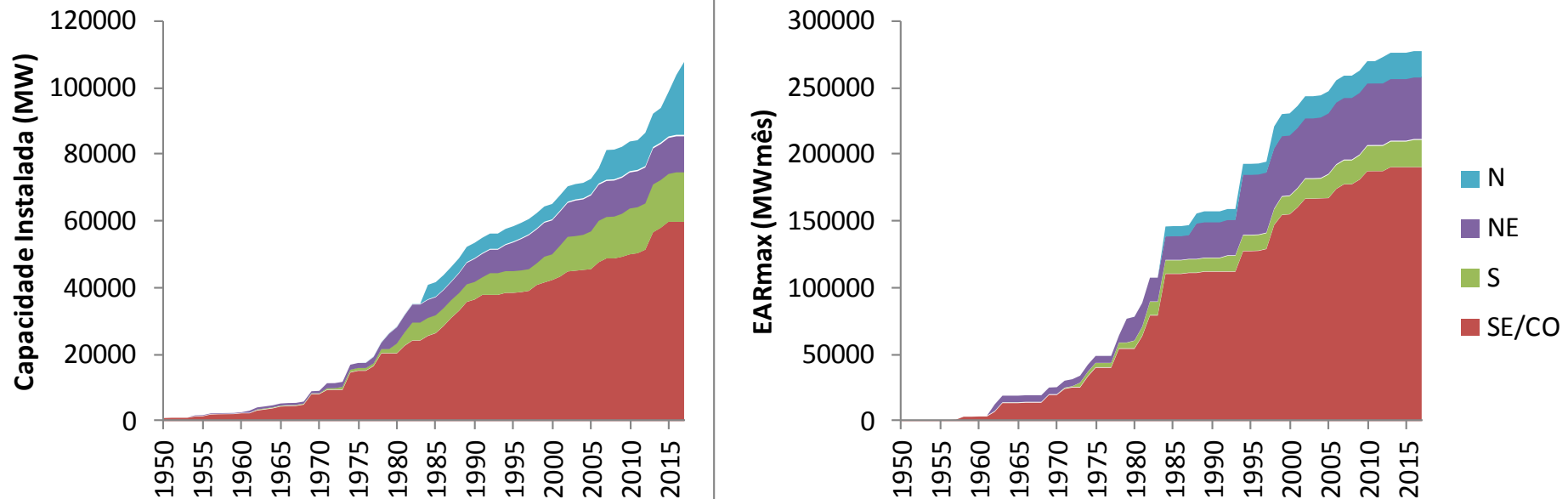


Geração nuclear e eólica no SIN de jul/2012 a ago/2017
(médias mensais e médias móveis de doze meses)

Reservatórios e Usinas Hidrelétricas - Brasil

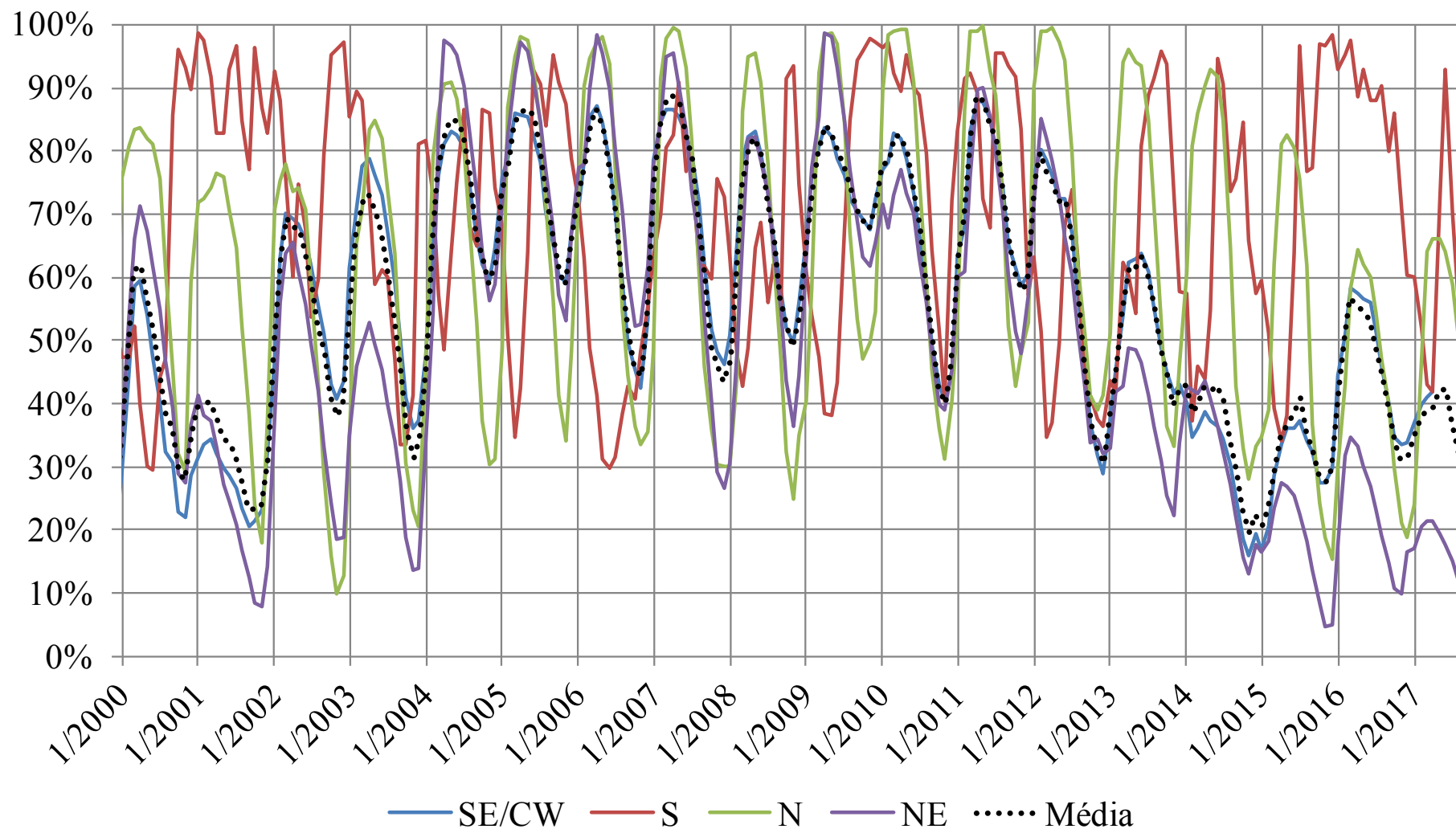
- Mais de 150 reservatórios de médio e grande porte, e mais de 1000 PCHs
- Volumes de 286.174 Mm³ a 573.600 Mm³
- Áreas de 22.715 km² to 37.894 km²
- 37.894 km² / 8.511.965 km² = ...
- 286 a 574 Gm³ / 8.511.965 km² = ...

Reservatórios e Usinas Hidrelétricas - Brasil

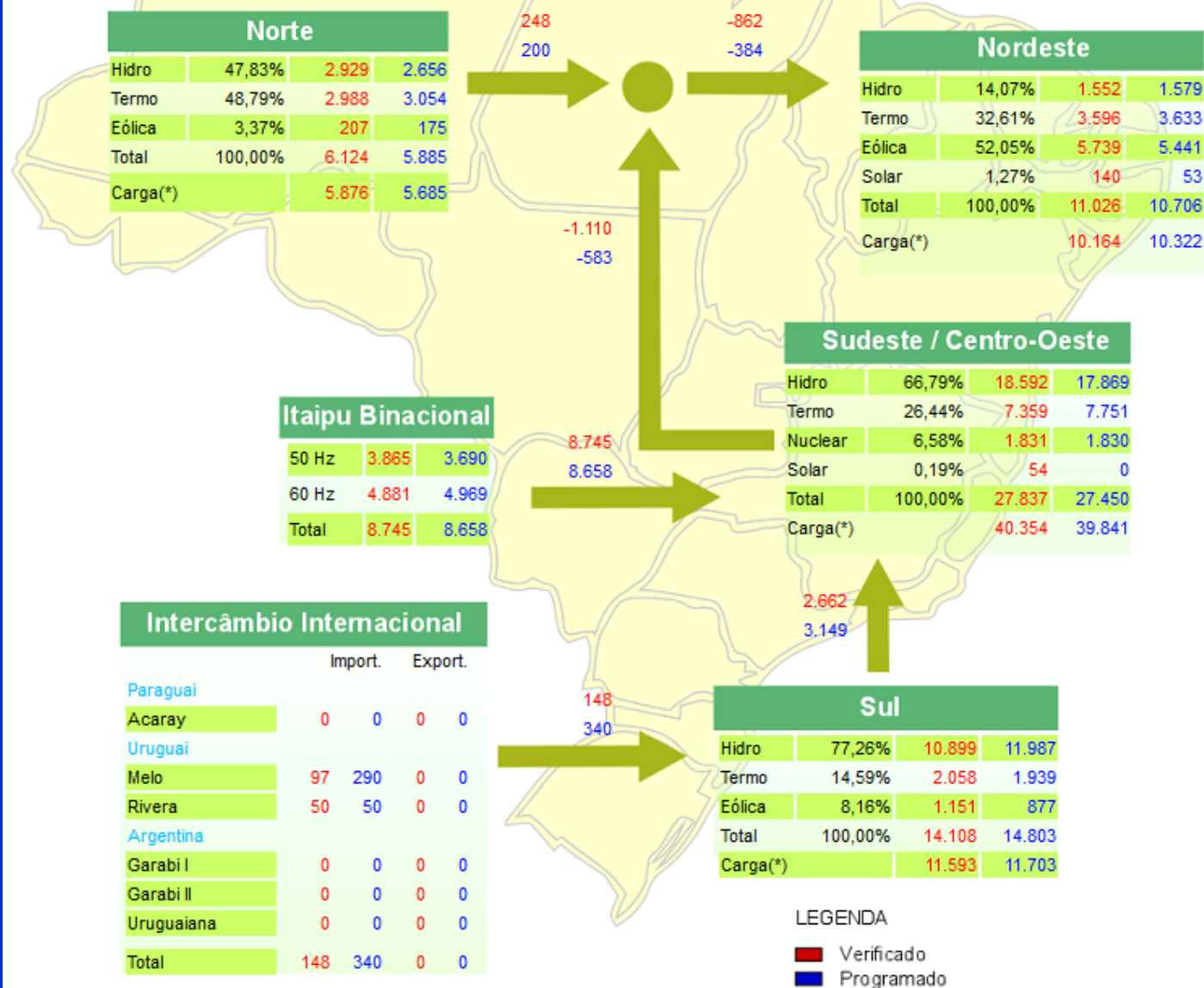


Evolução da capacidade hidrelétrica instalada e de armazenamento no Sistema Interligado Nacional (SIN), incluindo expansão até 2017
(Falcetta, Zambon & Yeh, EWRI 2014)

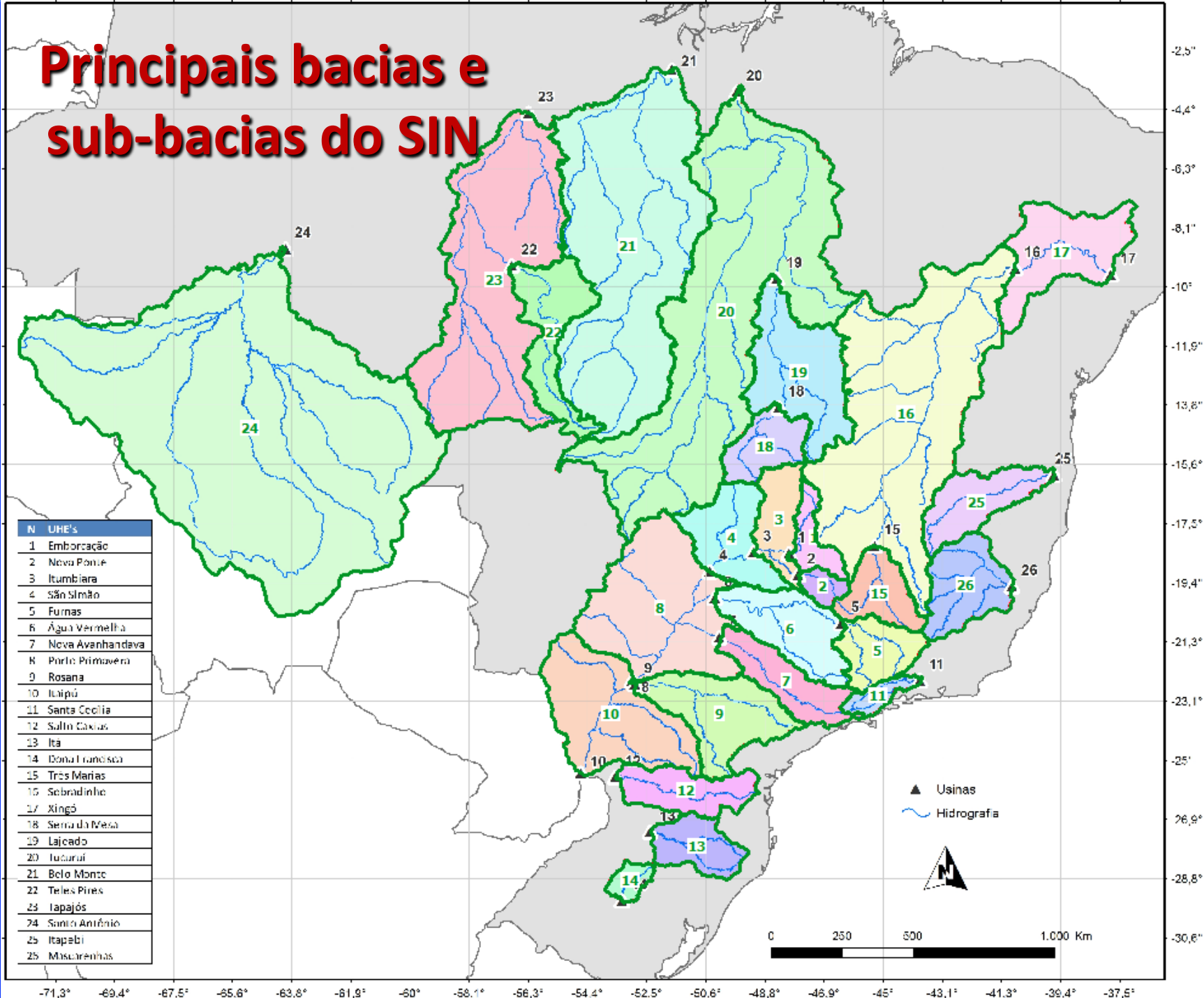
Armazenamento de “energia” no SIN



Balanço semanal de 7 a 13/10/2017



Principais bacias e sub-bacias do SIN



Furnas



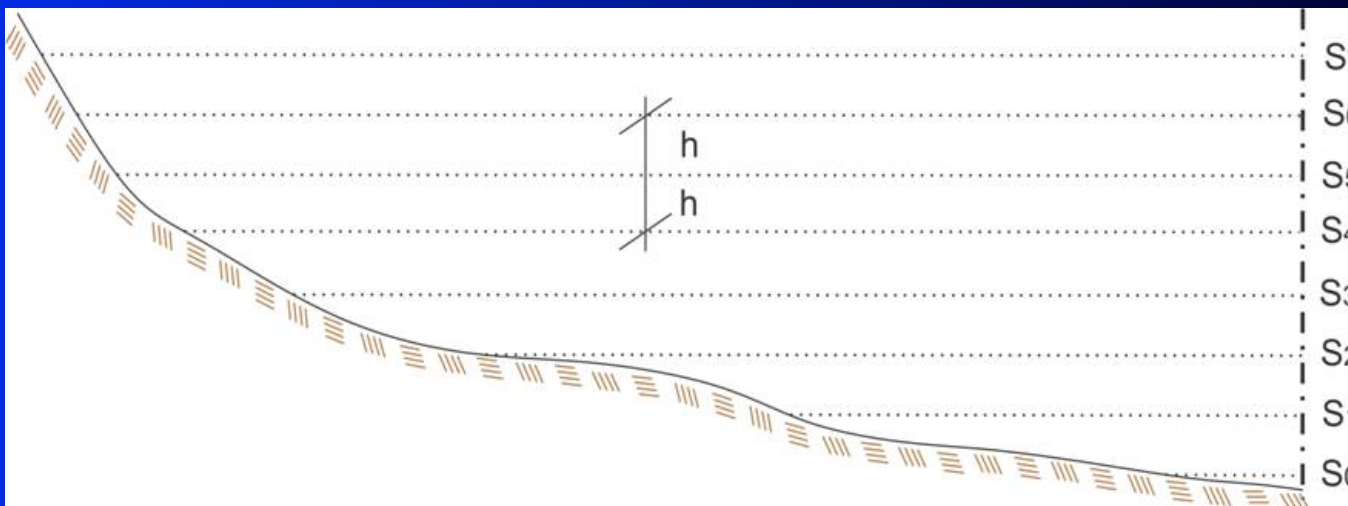
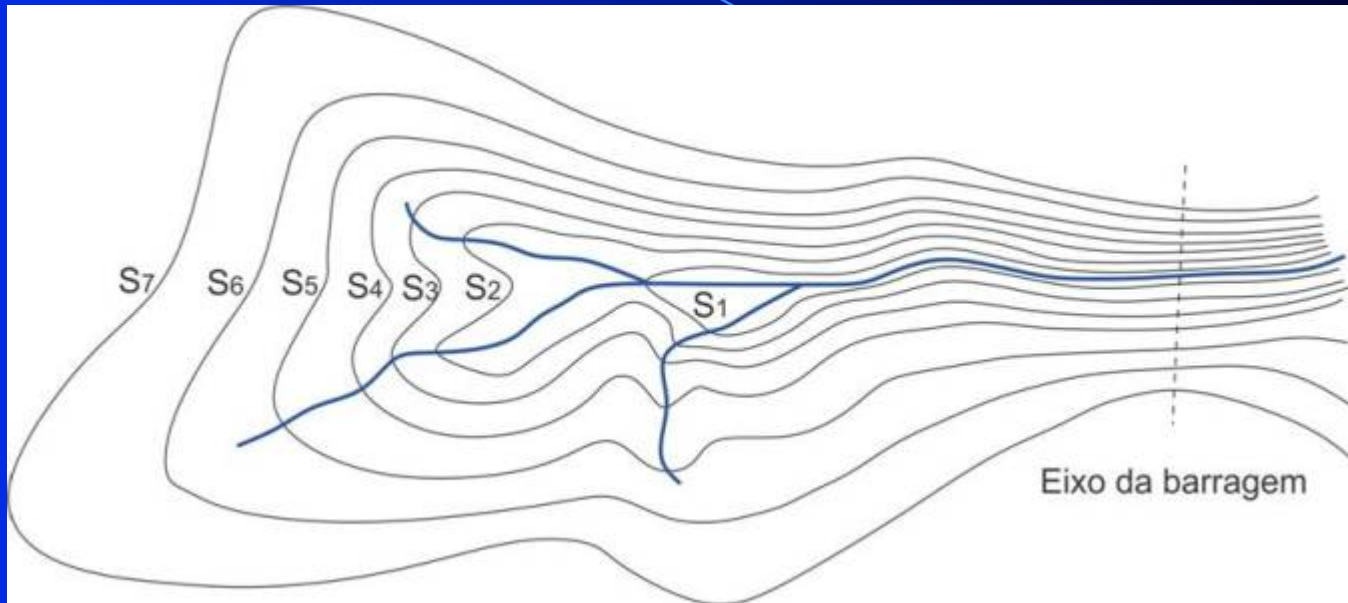
Smax: 22950 hm³
Smin: 5733 hm³

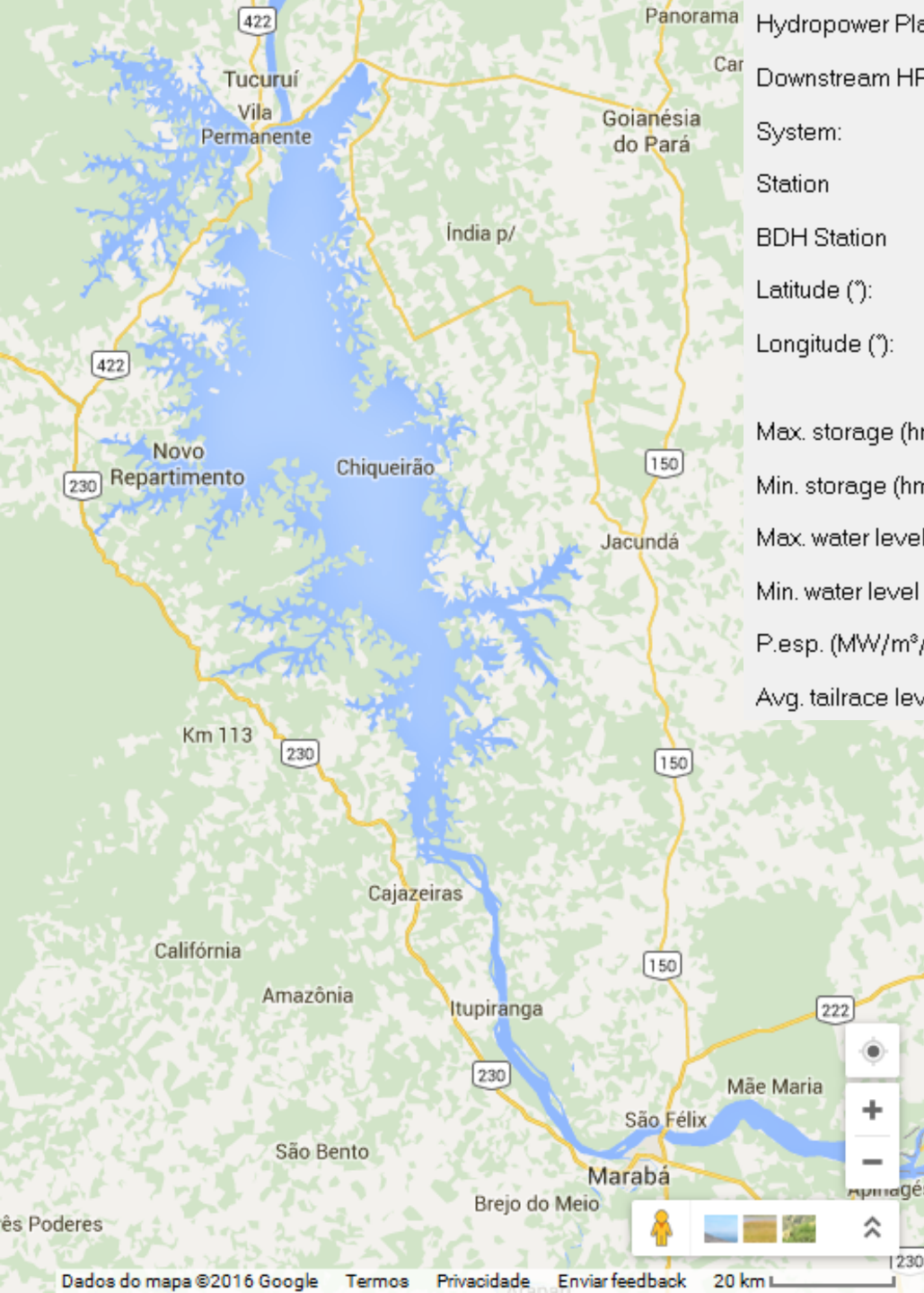
Itaipu



$V_{\max}: 29000 \text{ hm}^3$
 $V_{\min}: 29000 \text{ hm}^3$
fio d'água!

Curvas cota x área x volume





Hydropower Plant: 275 TUCURUI

Downstream HP: 0

System: 4

Station 275

BDH Station 0

Latitude (°): -3.7505

Longitude (°): -49.66717



Max. storage (hm³): 50275

Min. storage (hm³): 11293

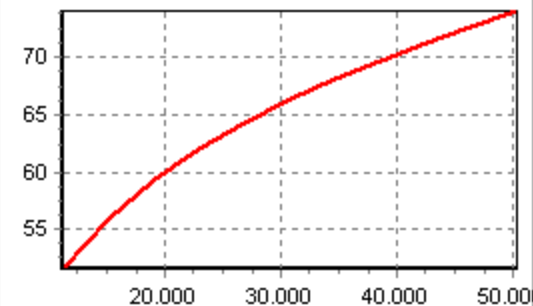
Max. water level (m): 74

Min. water level (m): 51.5999984741

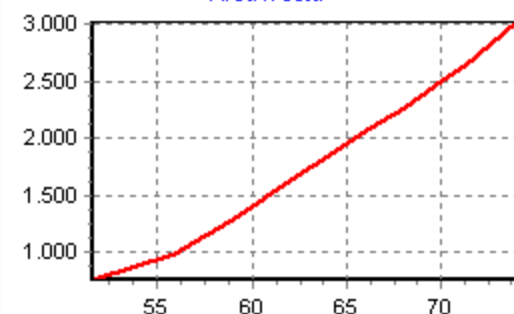
P.esp. (MW/m³/s/m): 0.0091819996014

Avg. tailrace level (m): 8.60000038147

Cota x Volume



Área x cota



Tucuruí

Hydropower Plant: 169 SOBRADINHO

Downstream HP: 172

System: 3

Station 169

BDH Station 0

Latitude (°): -9.41667

Longitude (°): -40.83333



Max. storage (hm³): 34116

Min. storage (hm³): 5447

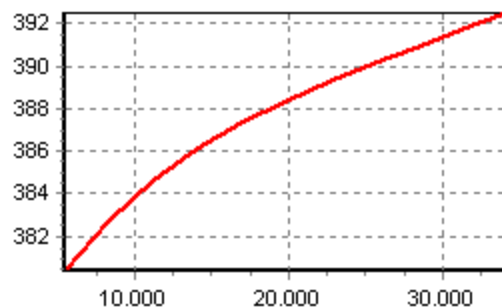
Max. water level (m): 392.5

Min. water level (m): 380.5

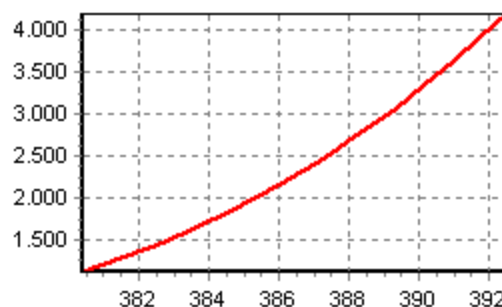
P.esp. (MW/m³/s/m): 0.0090229995548

Avg. tailrace level (m): 362.5

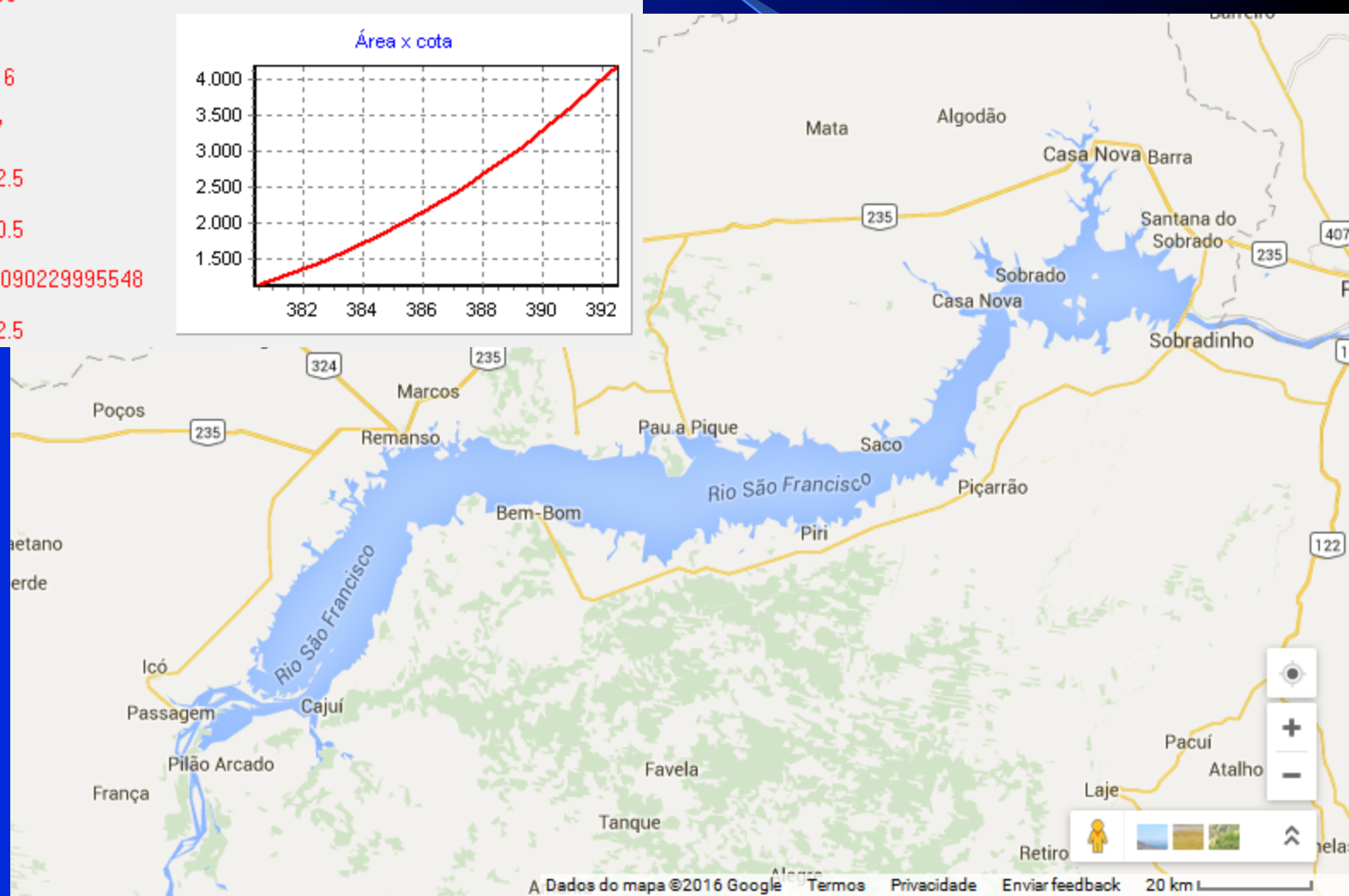
Cota x Volume



Área x cota



Sobradinho



Hydropower Plant: 156 TRES MARIAS

Downstream HP: 169

System: 1

Station 156

BDH Station 0

Latitude (°): -18.16667

Longitude (°): -45.26667



Max. storage (hm³): 19528

Min. storage (hm³): 4250

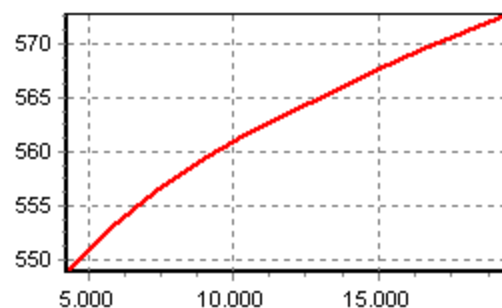
Max. water level (m): 572.5

Min. water level (m): 549.200012207

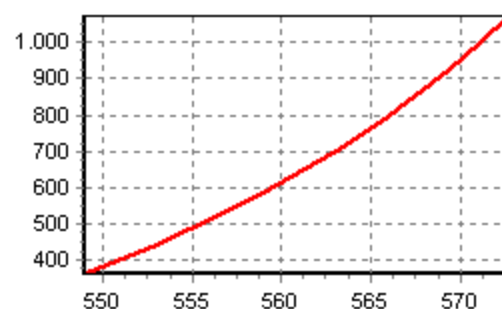
P.esp. (MW/m³/s/m): 0.0085640000179

Avg. tailrace level (m): 515.700012207

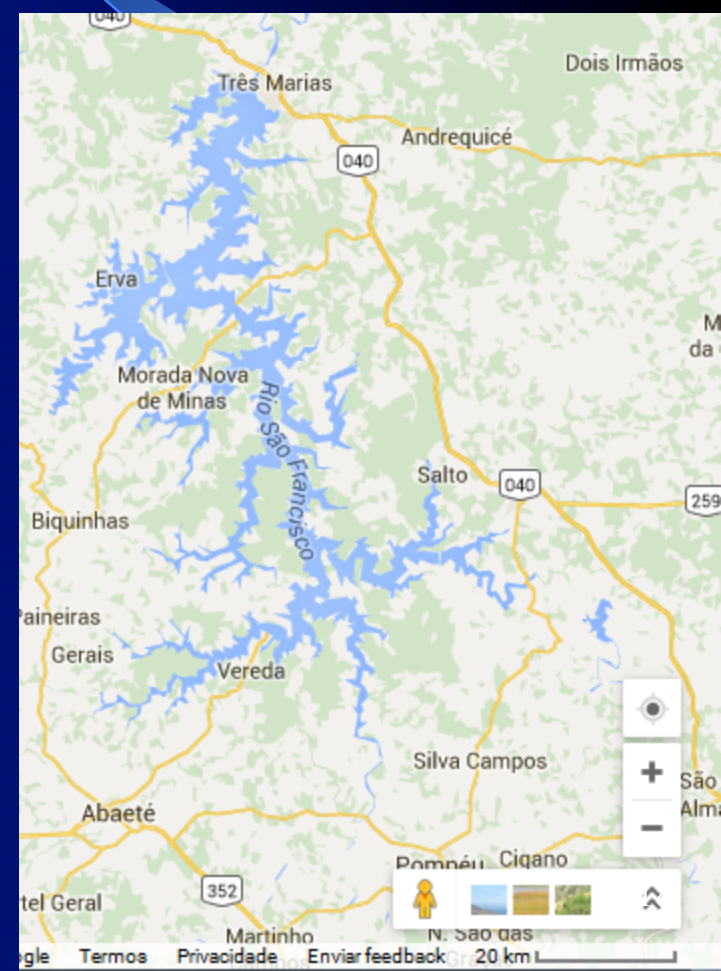
Cota x Volume

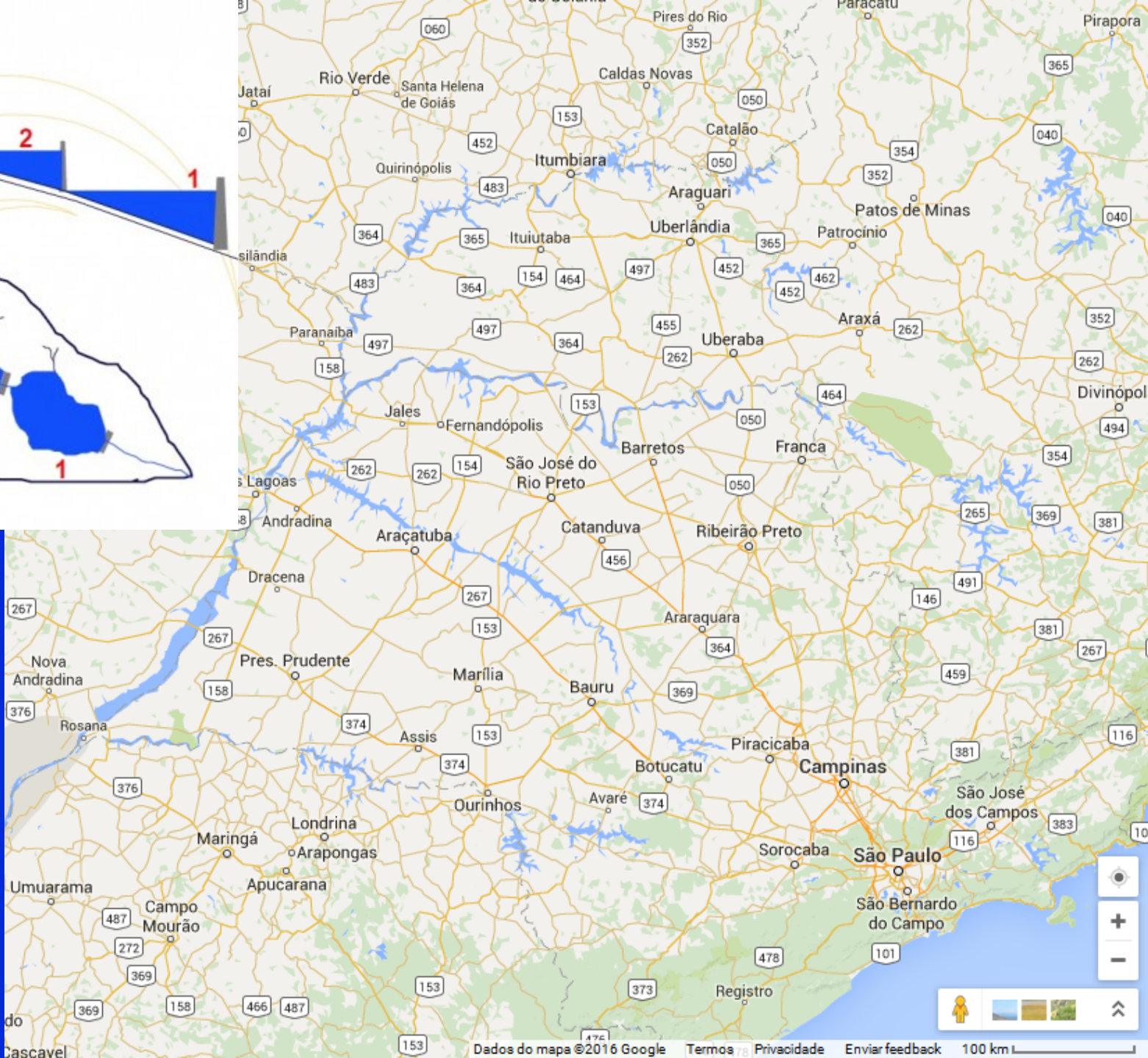
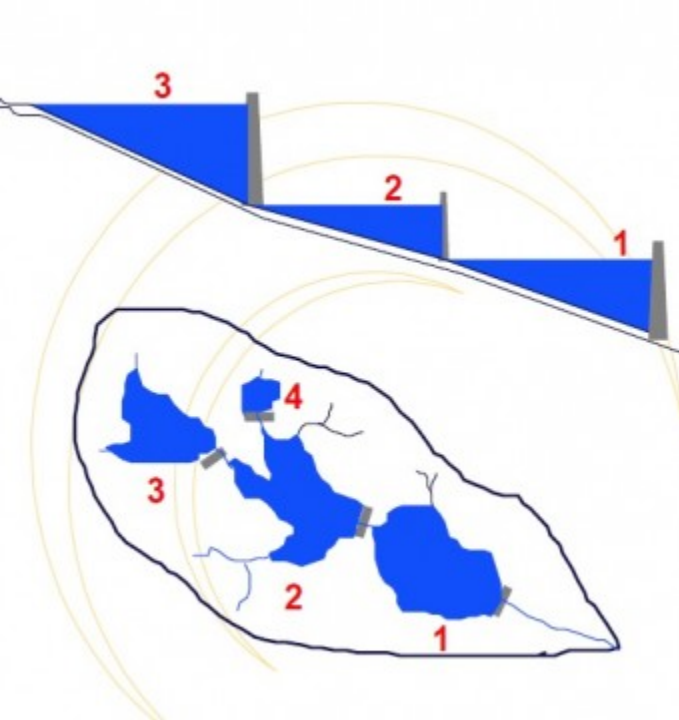


Área x cota



Três Marias



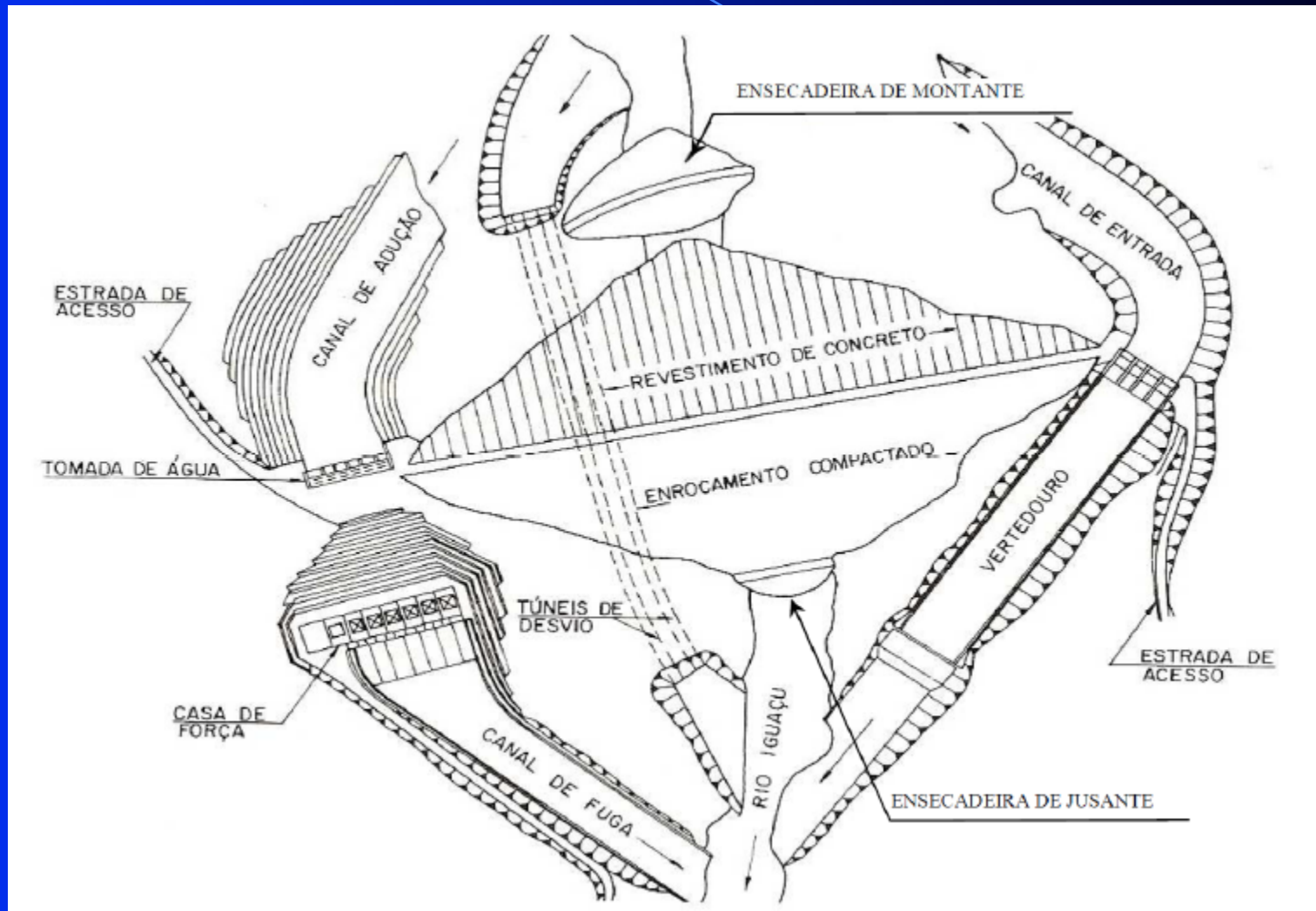


Divisão de quedas

Constituintes de uma barragem

- Maciço ou barramento
- Ombreiras ou encontros
- Fundações
- (Canal de aproximação) e vertedor
- Dissipador de energia (e canal de restituição)
- Canais ou condutos (penstocks) de adução
- Tomada d'água e casa de força
- Canal de fuga
- Estruturas de desvio (na construção)
- Eclusas
- Escadas de peixes

Foz do Areia PR (Iguaçu)



Foz do Areia PR (Iguaçu)



IMPACTOS

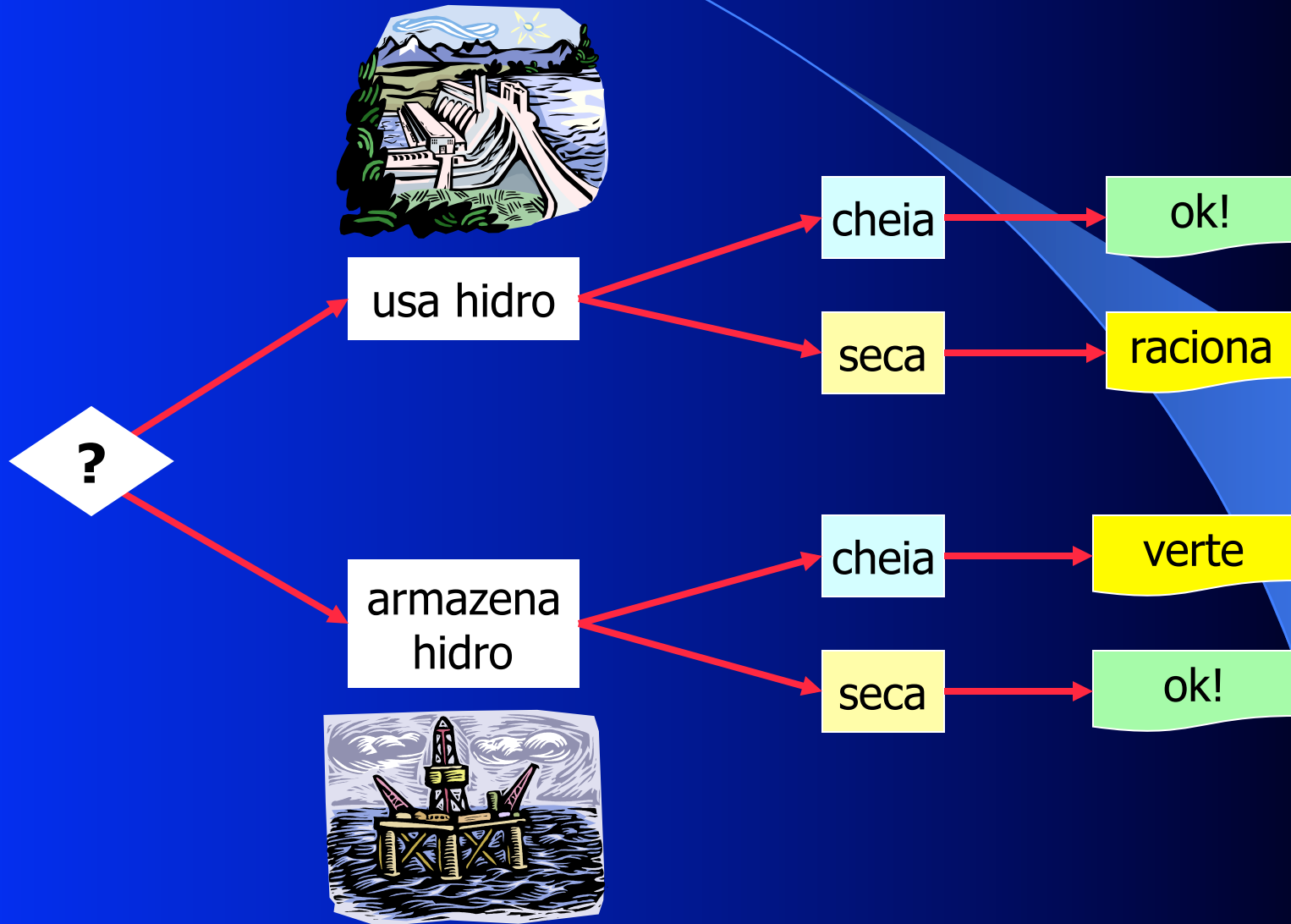


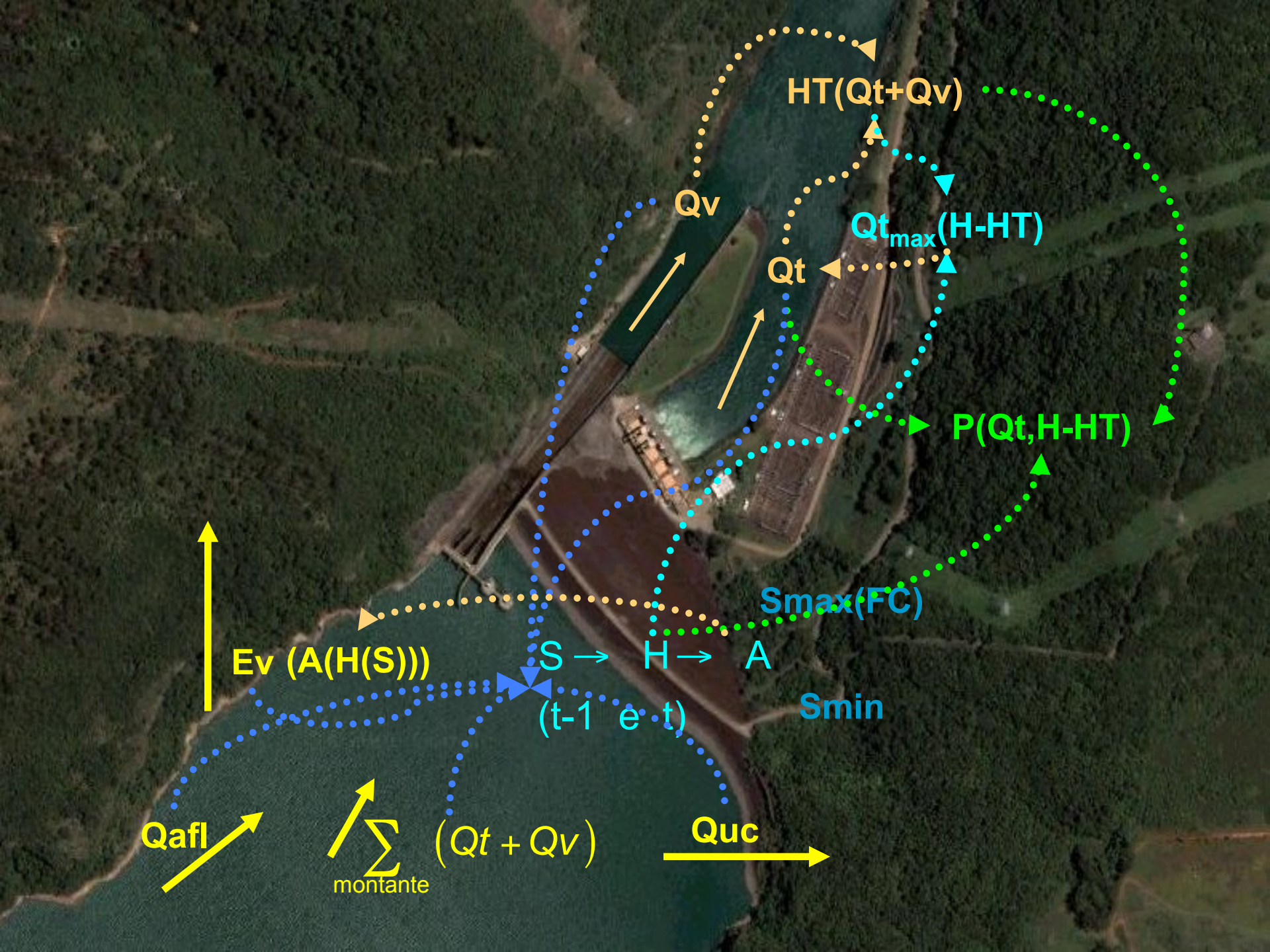
Itaipu: 14000 MW / 1350 km²
Tucuruí: 8365 MW / 2414 km²
Balbina: 250 MW / 2360 km²

- Reservatórios;
- Impactos Sociais;
- Atividades Econômicas;
- Impacto na Paisagem;
- Impactos na Flora e na Fauna.



DECISÕES DA OPERAÇÃO





Exemplo: HIDROTERM

HidroTerm - Hydro-Thermal Power System Optimization

File Drawing Simulate Optimize Help

Main Drawing User Data Physical Data Polynomials Flood Control Evap UC Expansion Thermal Data GAMS Model GAMS Listing

CodUsina	Usina	Sistema	Empresa	Latitude
39	IBITINGA	1	56	-21.75
40	PROMISSAO	1	56	-21.366
42	NAVANHANDAVA	1	56	-21.117
43	TRES IRMADS	1	16	-20.683
44	I. SOLT. EQV	1	16	-20.383
45	JUPIA	1	16	-20.816
46	P. PRIMAVERA	1	16	-22.466
47	A.A. LAYDNER	1	55	-23.216
48	PIRAJU	1	65	-23.183
49	CHAVANTES	1	55	-23.116
50	L.N. GARCEZ	1	55	-22.902
51	CANDAS II	1	55	-22.9
52	CANDAS I	1	55	-22.938
58	SAO JERONIMO	2	186	-23.722
61	CAPIVARA	1	55	-22.6
62	TAQUARUCU	1	55	-22.5

Choose plants to show in graph:

CodUsina	Ativa	Mostra
47	True	True
49	True	True
50	True	False
51	True	False
52	True	False
61	True	True
62	True	False
63	True	False

Variable: S (hm³)

Sum data (or separated plants) ☐ Left scale from zero ☒

New Colors Update Graph

Options

GAMS executable file: c:\program files\gams\gams.exe

DOS window: Normal

Command line parameters for gams.exe: pagesize 60000

Nonlinear Solver: MINOS

GAMS options: ex: iterlim = 10000
reslim = 36000
iterlim = 200000

Model options: ex: nodlim = 10000
nodlim = 7000
workspace = 150
optfile = 1

Default Cancel OK

☒ A(i-1) ☐ F0BJ by subsystem

☒ fixed RTmax ☐ Use table in thermal data

☒ rot/res eqs ☐ HT with quadratic function

☒ with evaporation ☐ Iterative HIDRO with EH

☒ use direct A(S) ☒ consider expansion IDexp

☐ MLT Inflow

Usina

Usina: 47 A.A. LAYDNER

Usina a Jusante: 48

Sistema: 1

Posto: 47

Posto BDH: 0

Latitude (°): -23.21667

Longitude (°): -49.23333

Volume máximo (hm³): 7008

Volume mínimo (hm³): 3843

Cota máxima (m): 568

Cota mínima (m): 559.7

P. esp. (MW/m³/s/m): 0.008927

Canal fuga médio (m): 532.2

Expand/Collapse

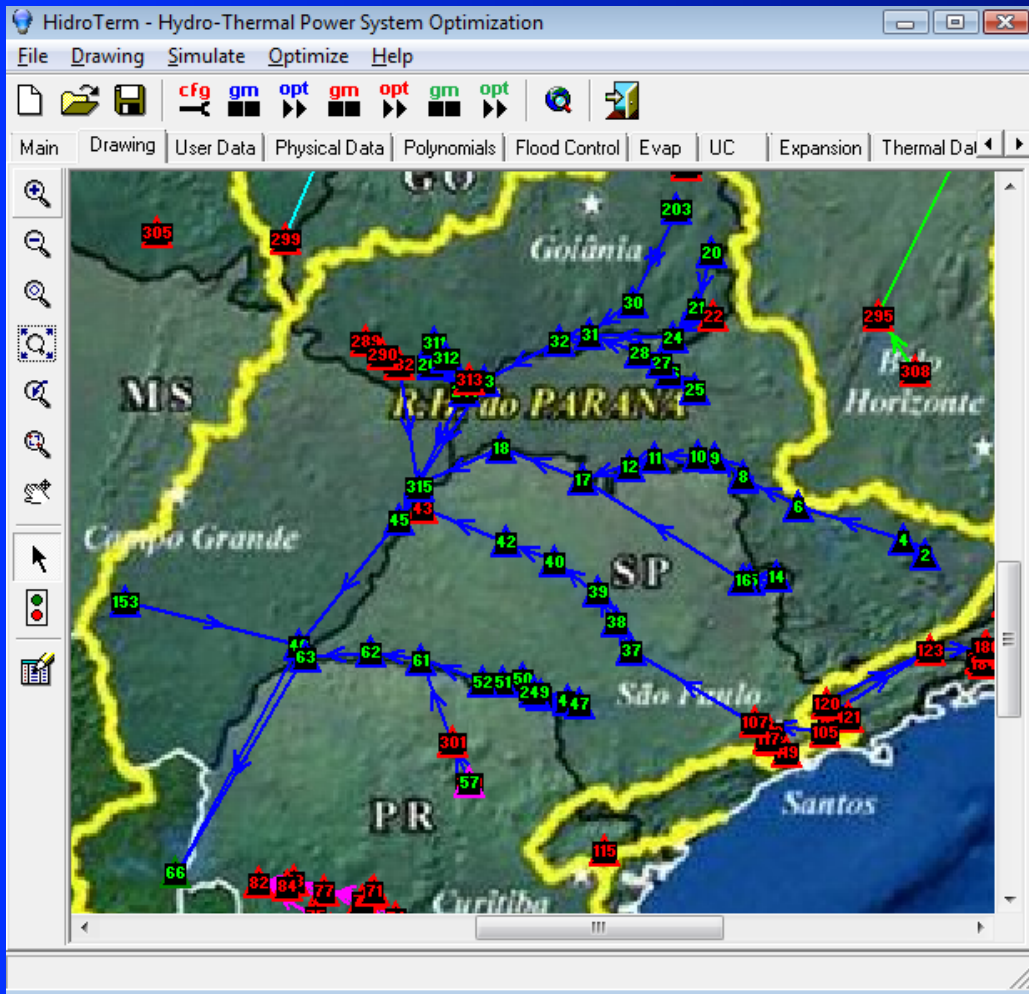
Atualiza Gráficos OK

Cota HT x vazão

535
534
533
532

0 500 1000 1500

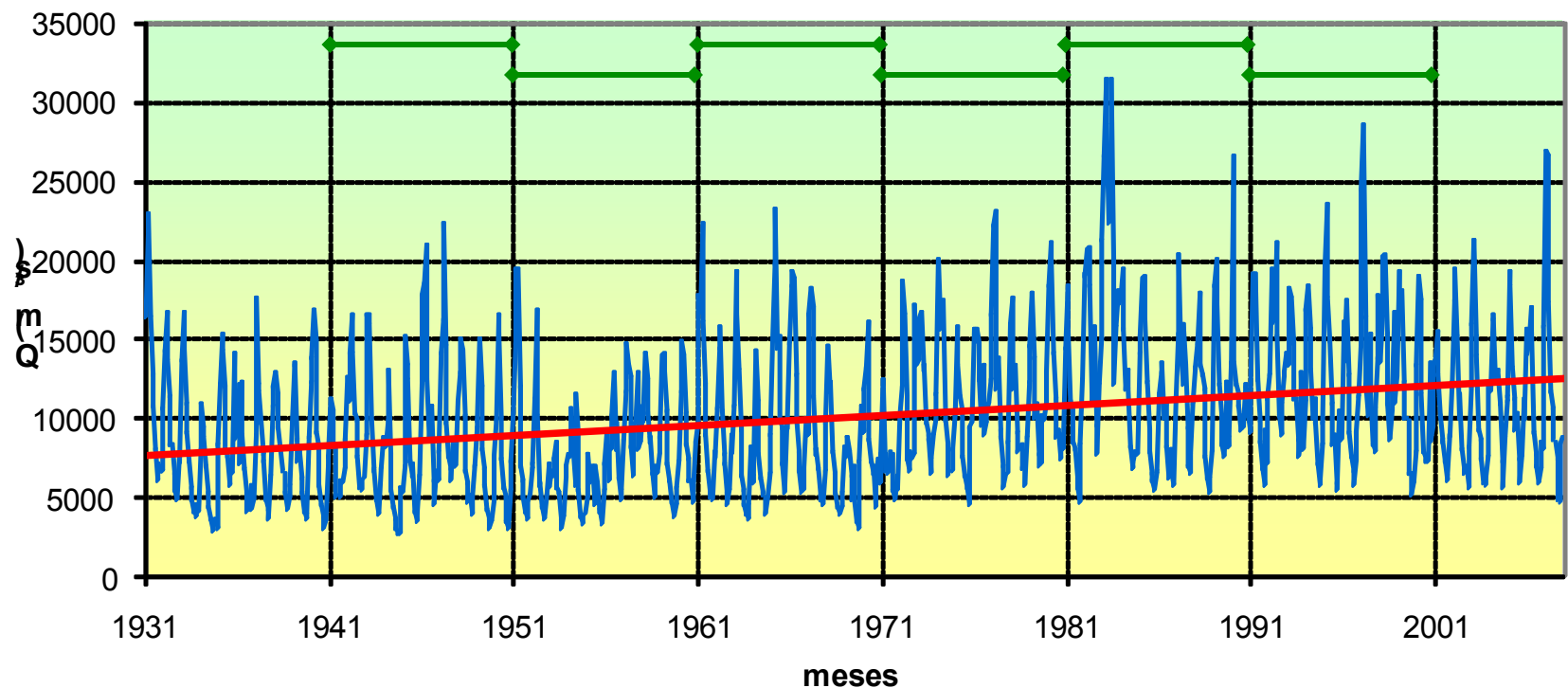
Exemplo: HIDROTERM (EWRI 2009)



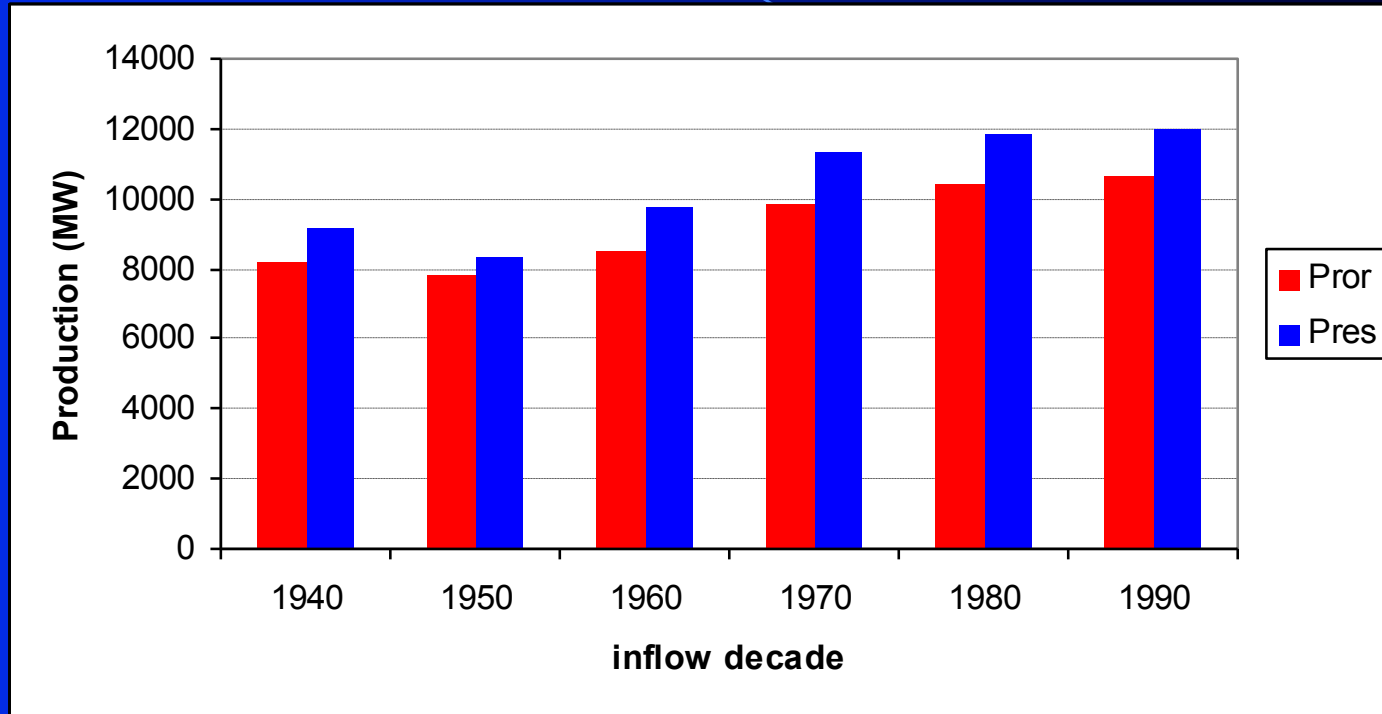
- Itaipu hydropower plant operates as a run-of-river reservoir...
- the Paraná river basin has a system of 55 hydropower plants
- 31 are run-of-river and 24 have storage capacity to regulate flows in the basin
- **how much of the hydropower production of Itaipu can be due to upstream storage reservoirs?**

Exemplo: HIDROTERM (EWRI 2009)

Vazões médias mensais afluentes em Itaipu: 1931-2007



Exemplo: HIDROTERM (EWRI 2009)



inflow	Pror(MW)	Pres (MW)	Δ (%)	Δ (MW)
1940	8186	9123	11.4%	937
1950	7839	8315	6.1%	476
1960	8499	9771	15.0%	1272
1970	9822	11283	14.9%	1460
1980	10398	11851	14.0%	1453
1990	10613	11977	12.8%	1363

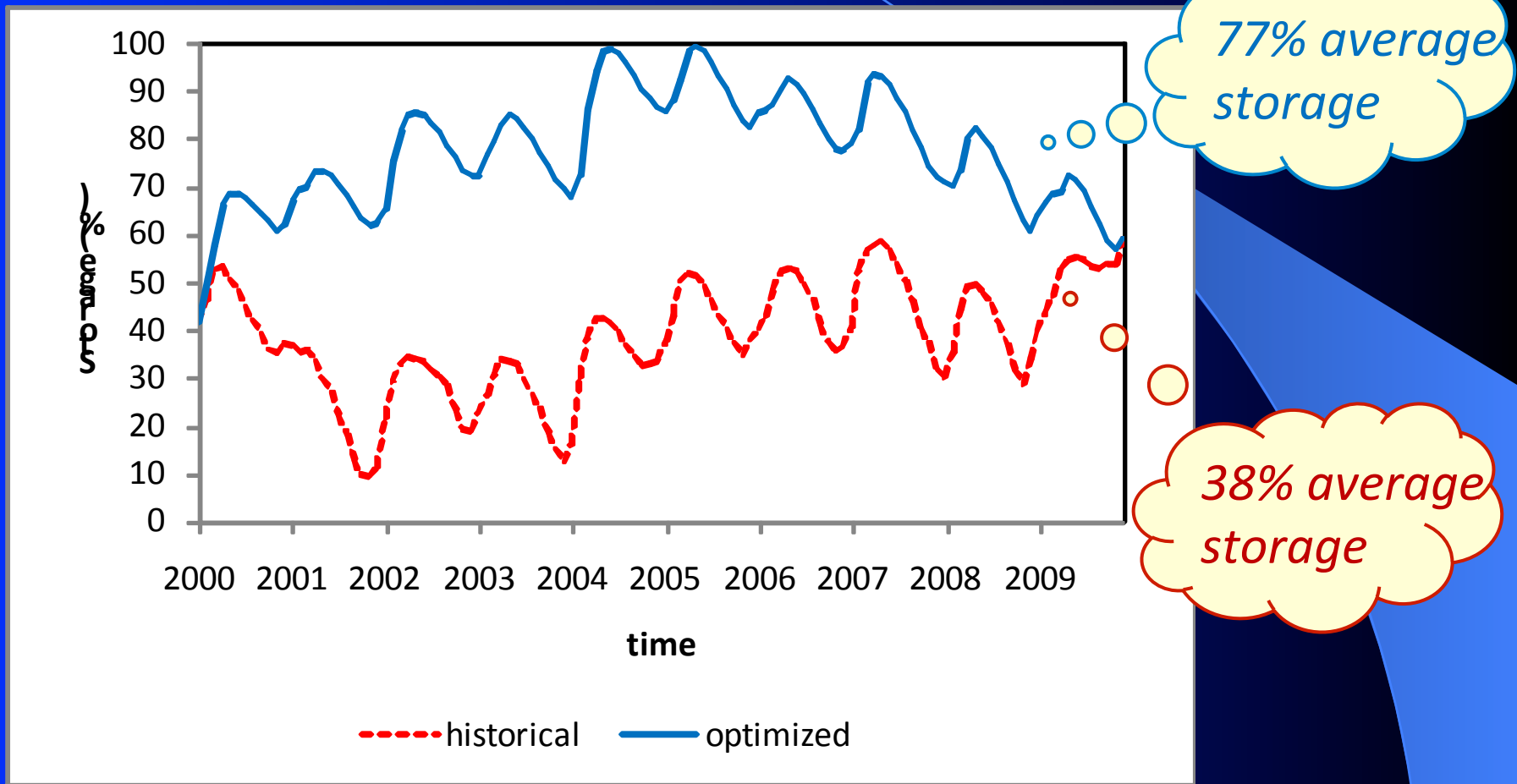
regularization => on average more 14% or 1426 MW against run-of-river

Exemplo: HIDROTERM (EWRI 2010)



- “Serra da Mesa” reservoir in Tocantins river, upstream to 7 other hydropower plants
- minimum requirement $300 \text{ m}^3/\text{s}$
 - minimum historical $97 \text{ m}^3/\text{s}$
 - operating since 1998
- installed capacity: 1,275 MW
 - head: 83,2 to 125,9 m
 - $S_{\min}$: $11,150 \text{ hm}^3$
- $S_{\max}$: $54,400 \text{ hm}^3$ (largest in Brazil) and $1,784 \text{ km}^2$

Exemplo: HIDROTERM (EWRI 2010)



Storage in "Serra da Mesa" reservoir



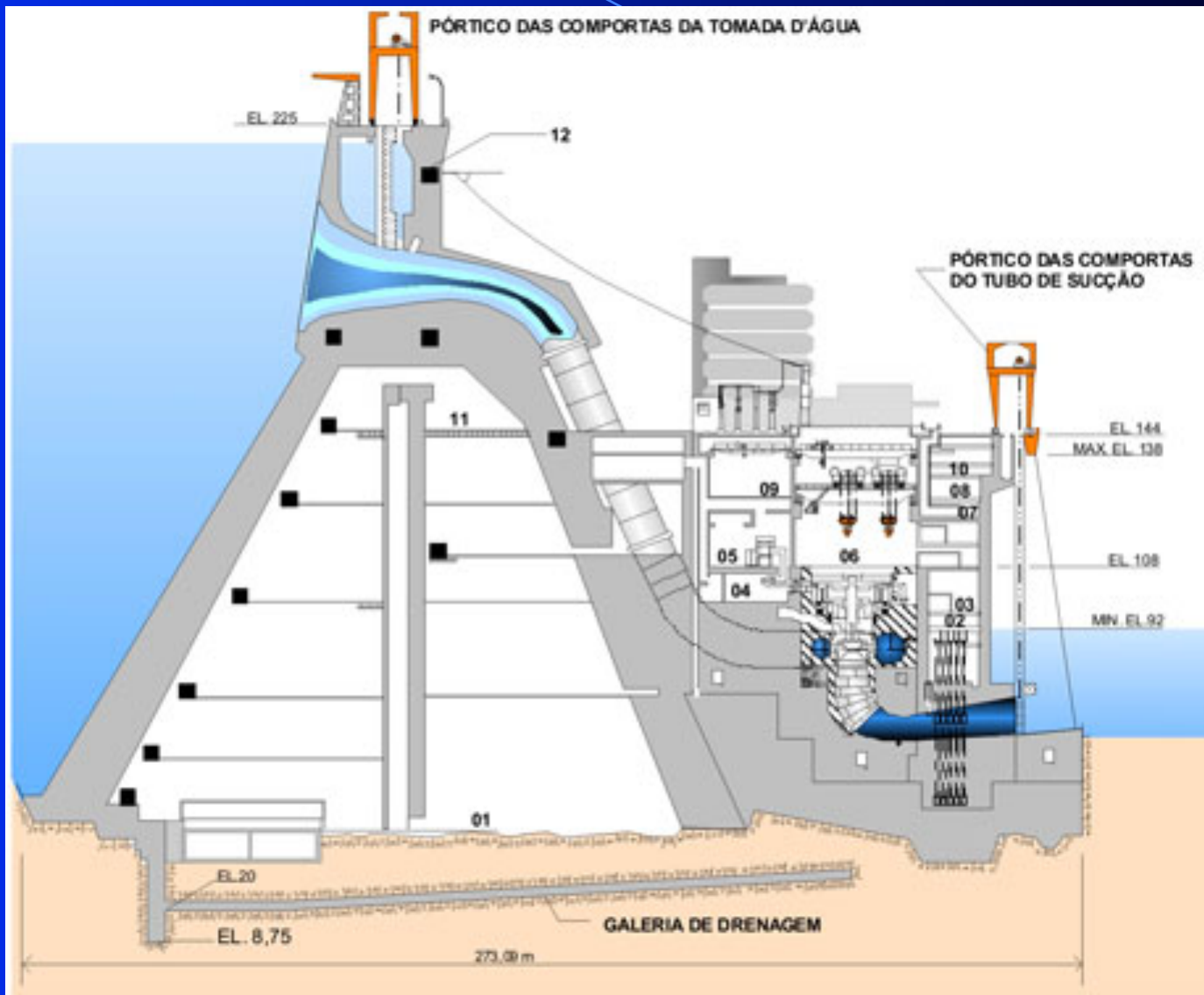




Itaipu



Itaipu



Itaipu



Bonneville Dam (Columbia River)



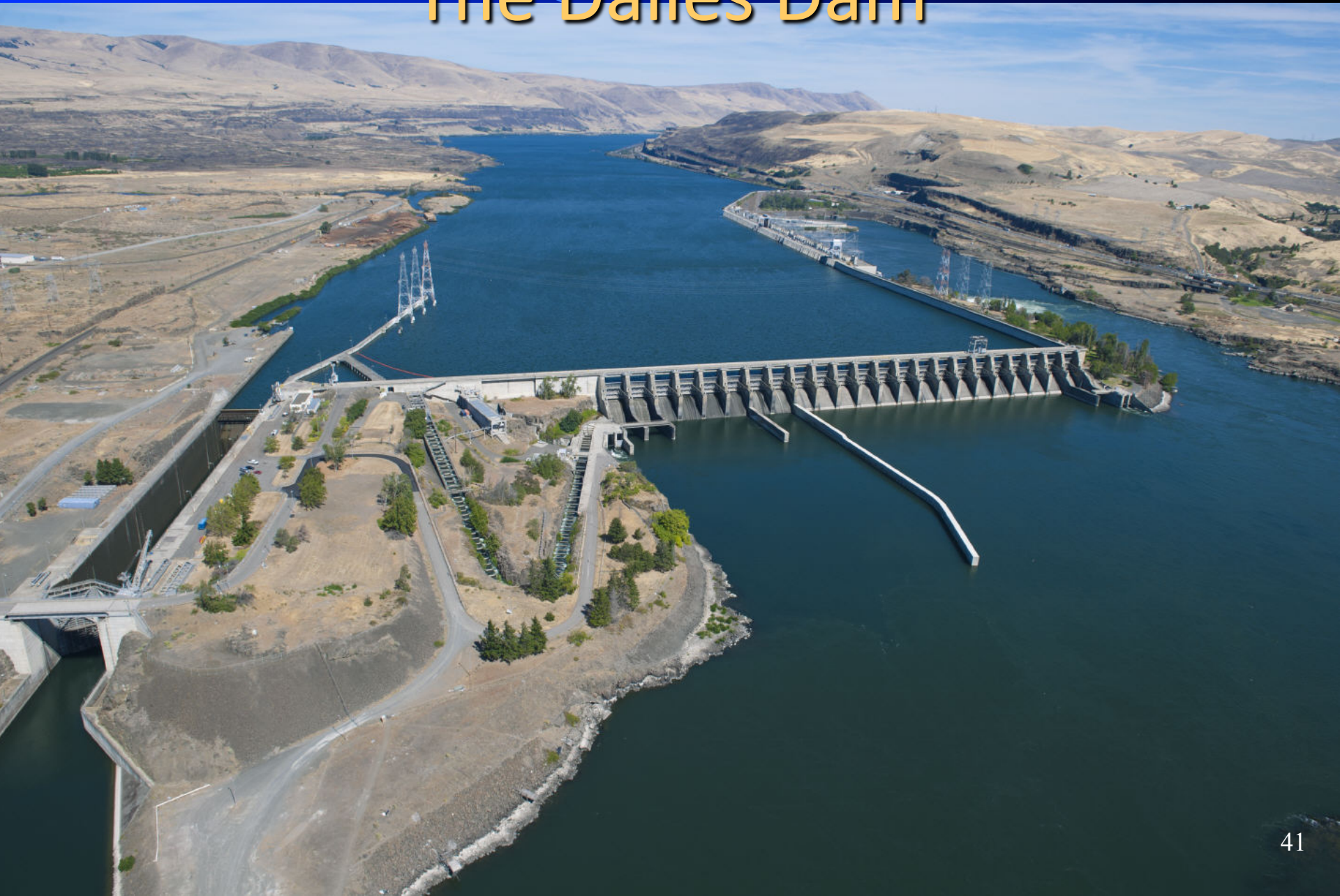
Bonneville Dam



Bonneville Dam



The Dalles Dam



Material complementar

- International Commission on Large Dams <http://www.icold-cigb.org>
- U.S. Energy Information Administration <https://www.eia.gov>
- Operador Nacional do Sistema Elétrico <http://ons.org.br>
- Agência Nacional de Energia Elétrica <http://www.aneel.gov.br>
- Empresa de Pesquisa Energética <http://www.epe.gov.br>