17-Hydro Power

ECEGR 4530

Renewable Energy Systems

Overview

- Introduction
- Hydro Resources
- Fundamentals
- Turbine Types
- Environmental Impacts
- Economics

Introduction

- Hydroelectric generation is the most prolific and mature of renewable energy sources
- It is mainstream enough for it to not be considered renewable in some circumstances
  - Renewable Portfolio Standards often do not count existing freshwater hydro
- We will assume the discussed applications are freshwater without losing generality

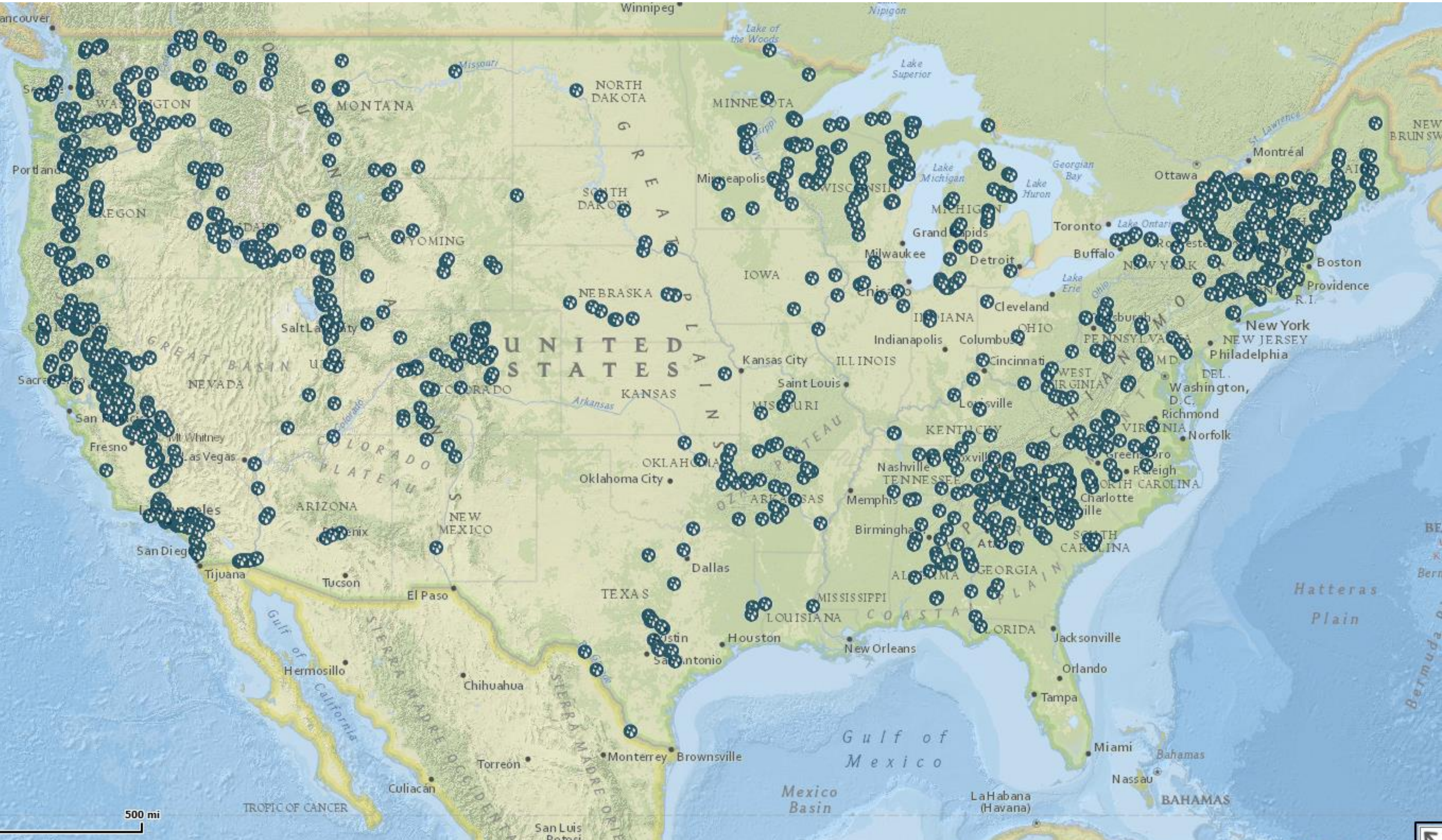
Introduction: Hydro in the U.S.

- Accounts for about 50% of energy production from all renewable resources
- 4,000 generators
- 78,000 MW of capacity (stagnant)
- Supplied
  - 249 TWh in 2015
  - 269 TWh in 2013
  - 319 TWh in 2011
- Largest: Grand Coulee Dam (6,800 MW)
- What state produced the most amount of energy from hydropower in 2012?

Introduction: Hydro in the U.S.

1. Washington (89 TWh)
2. Oregon (39 TWh)
3. California (27 TWh)
4. New York (24 TWh)

Hydro Facilities in the US



Introduction: Hydro in the U.S.

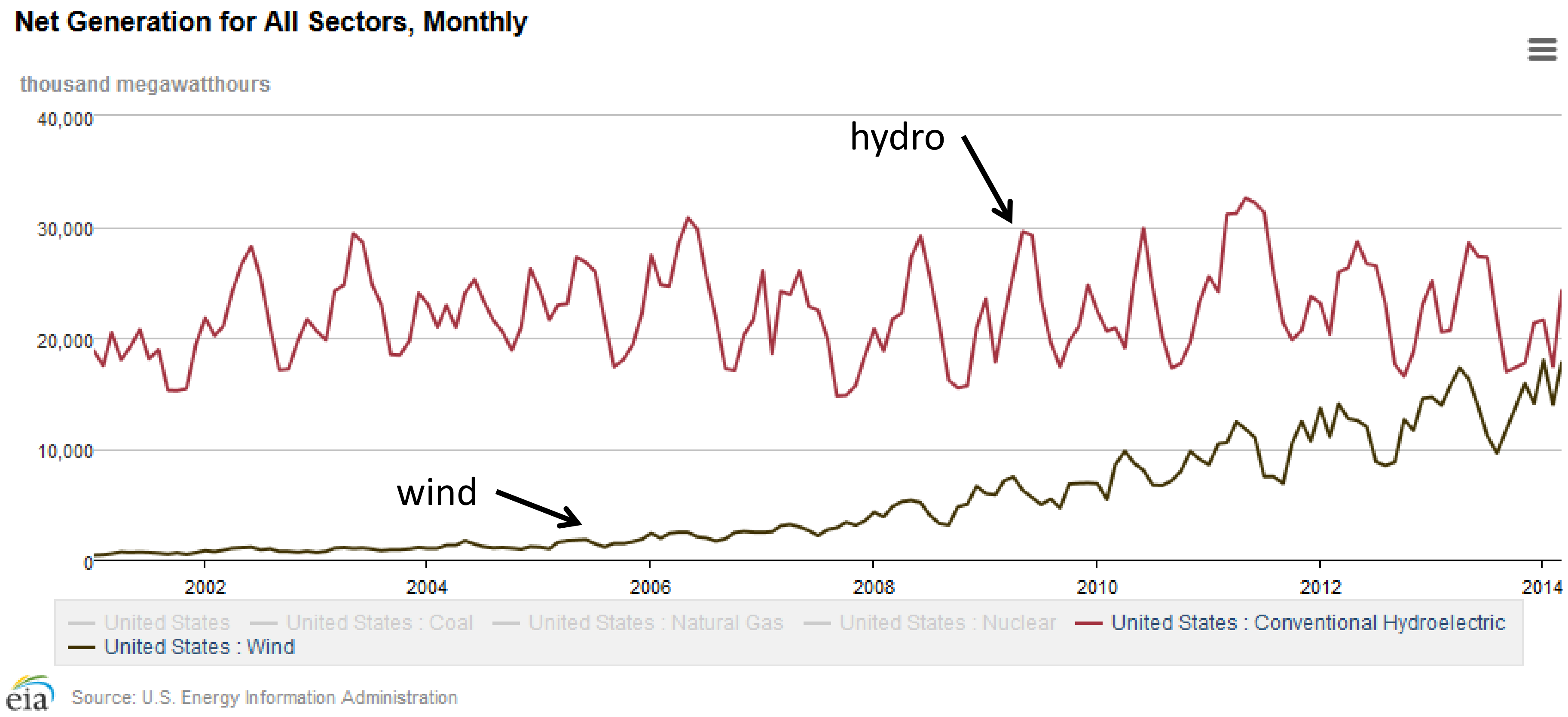
What was the capacity factor for hydroelectric generators in the U.S. in 2013?

Introduction: Hydro in the U.S.

What was the capacity factor for hydroelectric generators in the U.S. in 2013?

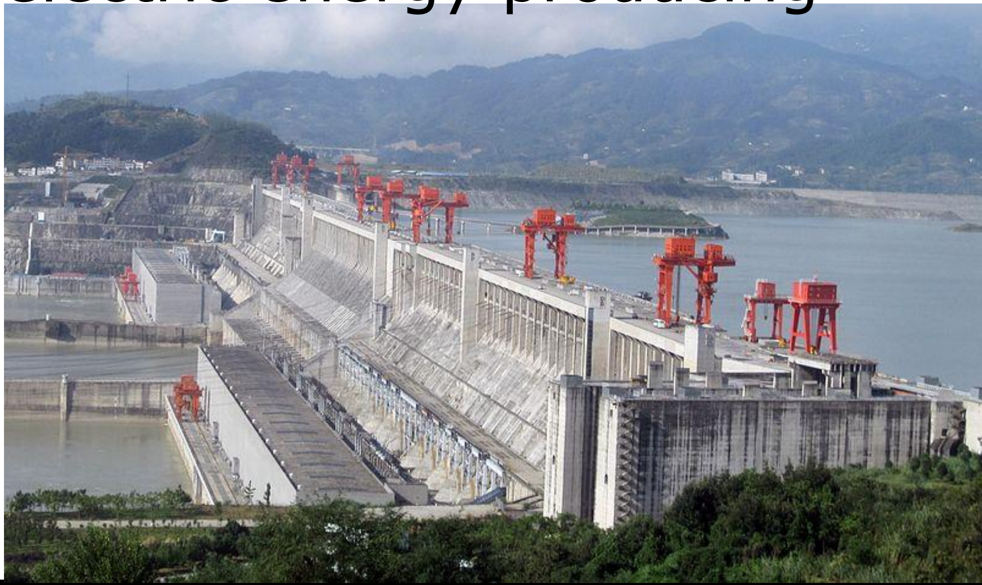
- Capacity Factor= 269 TWh/(8760 x 0.078 TWh) =39%

Trends

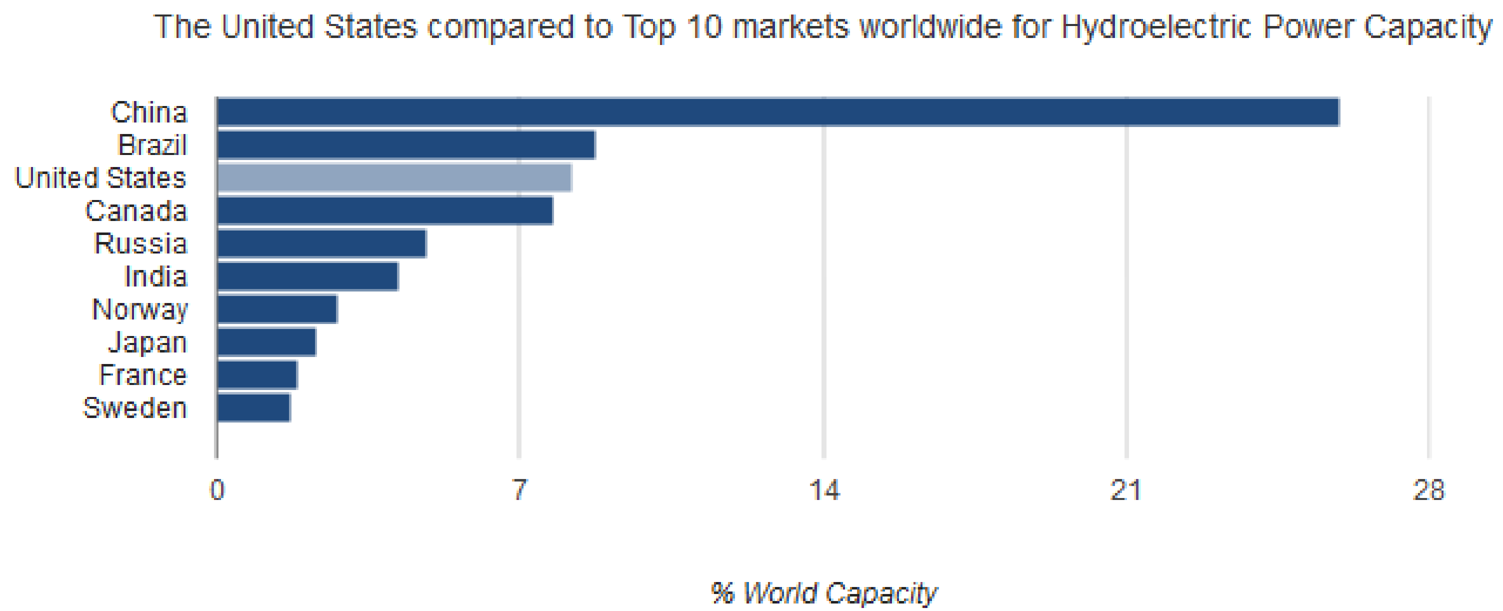

Net Generation for All Sectors, Monthly
thousand megawatthours
40,000
30,000
20,000
10,000
0
2002
2004
2006
2008
2010
2012
2014
hydro
wind
United States
United States : Coal
United States : Natural Gas
United States : Nuclear
United States : Conventional Hydroelectric
United States : Wind
Source: U.S. Energy Information Administration

Introduction: Hydro in the World

- Largest dam: Three Gorges (China), 22,500 MW when fully completed
- Worldwide hydro energy production: 3,000 TWh per year
- What are the top hydroelectric energy producing countries in the world?



Place the following in order from highest to lowest (by capacity)



source: http://www.renewablefacts.com/country/united-states/hydro

Introduction

- Total installed capacity is at >775 GW
- Additions of 15-20 GW per year

Hydro Resources

- Hydroelectric generation is the conversion of the kinetic energy of running water to electrical energy
- Energy flow:
  - solar energy evaporates water to create water vapor
  - water vapor rises in the atmosphere
  - as it rises, it gains potential energy
  - when the water vapor condenses, it falls to earth
  - the water flows downhill back to the ocean

Hydro Resources

- Flow of water to the ocean has kinetic energy which can be harnessed by the hydroelectric generator
- The source of energy for hydro electric generation is the sun

Hydro Resources

- Total hydro energy potential is about 40,000 TWh/year
- 14,000-15,000 TWh/year could be harnessed
- Is this enough to supply the world’s electrical energy needs?
  - worldwide consumption 16,000 TWh/year

Fundamentals

- Recall potential energy:

$$E_{PE} = m \times g \times h$$

  - m: mass, in kg
  - g: acceleration due to gravity: 9.8 m/s^2
  - h: height, m

Fundamentals

- What is the potential energy of 1 cubic meter of water at a height of 10 m?

Fundamentals

- What is the potential energy of 1 cubic meter of water at a height of 10 m?
  - 1 cubic meter = 1,000 liters
  - 1 liter = 1 kg
  - potential energy = 1000 x 9.8 x 10 = 98,000 J

Fundamentals

- What is the power of 1 cubic meter of water falling per second from a height of 10 m?
- $\dot{m}$: mass flow rate of water, kg/s

$$P_{water} = \dot{m} \times g \times h$$

Fundamentals

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$$P_{water} = \dot{m} \times g \times h = 98,000W$$

Fundamentals

- *Head*: height the water falls from
- *Effective head:* is the equivalent height after losses such as friction and turbulence are taken into account, i.e. it is the height that the water would fall from under ideal conditions to deliver the same amount of power
  - effective head is always less than the head (ranging from 75% to 95%)

Fundamentals

- Water turbines are also not ideal
- Efficiencies up to 95%
- Accounting for these losses:

$$P = \eta_{wt} \times \dot{m} \times g \times h$$

  - P: power output of the water turbine, W
  - h: effective head height, m
  - η_{wt} : efficiency of the water turbine

Lake Kariba North (Zambia)

- World's largest man-made reservoir
  - Volume at maximum retention level 180 billion cubic meters
  - Volume at minimum operating level 115 billion cubic meters
  - Live capacity of 65 billion cubic meters
  - Minimum operating level 474.8 meters above sea level
- Generating capacity: 720 MW (4 x 180MW Francis turbines)

Source: ZESCO

Lake Kariba: World's Largest Man-Made Reservoir

Lake Kariba North Bank Extension

- Located at Lake Kariba
- Completed in May 2014
- Two 180 MW turbines
- Designed as “peaking” generators, used only 3.5 hours per day

Exercise

Assuming an operating head height of 89 m and a turbine/generator efficiency of 95 percent, how many cubic meters of water are needed to generate 1 MWh of electricity?

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From equation for potential energy:

$$1\text{MWh} = 1\text{x}10^{6}\text{x}60\text{x}60 = 3.6\text{x}10^{9} \text{ joules}$$

$$E = mgh\eta \text{ (in joules)}$$

$$3.6\text{x}10^{9} = m\text{x}9.8\text{x}89\text{x}0.95$$

$$m = 4.34\text{x}10^{6}\text{kg}$$

Mass of water needed

$$v = \frac{m}{1000} = 4.34\text{x}10^{3} \text{ cubic meters}$$

1 cubic meter weighs 1000 kg

Exercise

The live (usable) capacity of Lake Kariba is 65 billion cubic meters. Given the generation capacity is 720 MW, how many hours will it take to completely use (drain) the live capacity?

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The live (usable) capacity of Lake Kariba is 65 billion cubic meters. Given the generation capacity is 720 MW, how many hours will it take to completely use (drain) the live capacity?

From before, 1 MWh uses 4340 cubic meters, so 720 MWh (one hour of operation) uses approximately 3.12 million cubic meters

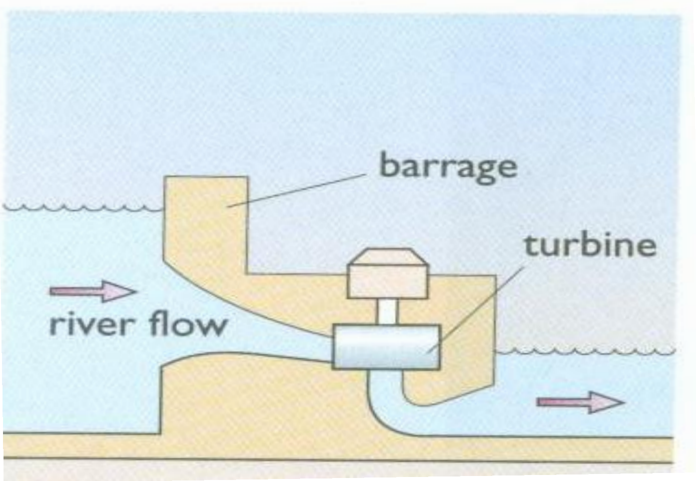
$$\text{time} = \frac{65\text{x}10^9}{3.1\text{x}10^6} = 20{,}833 \text{ hours} = 2.37 \text{ years}$$

Hydroelectric Generation

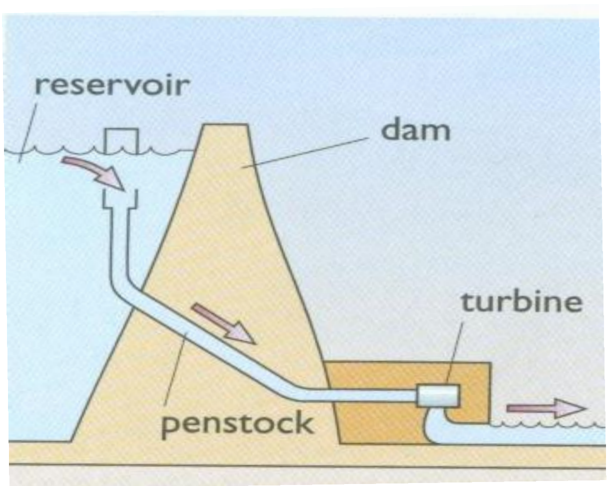
- Hydroelectric generation facilities can be classified according to their:
  - effective head
  - capacity (power rating)
  - type of turbine used
  - type of dam/reservoir

Hydroelectric Generation

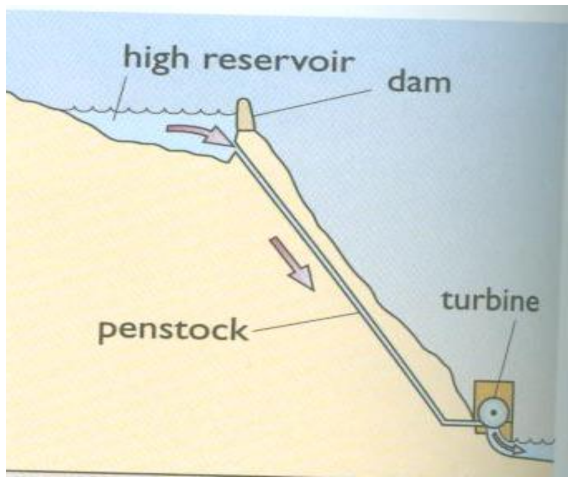
Consider three types of hydroelectric generation facilities: low, medium and high head



low head



medium head



high head

Hydroelectric Generation

- Low head dam (run-of-river)
- Must have a high mass flow rate, since the head is small $P = \eta_{wt} \times \dot{m} \times g \times h$
- Large/expensive civil structures due to the high flow rate
- No or little storage capacity

Hydroelectric Generation

- Medium and high head dam
- Flow rates can be smaller

$$P = \eta_{wt} \times \dot{m} \times g \times h$$

- Large storage capacity
- Floods large amount of land
- Compact turbines and generators, but under high pressure

Hydroelectric Generation

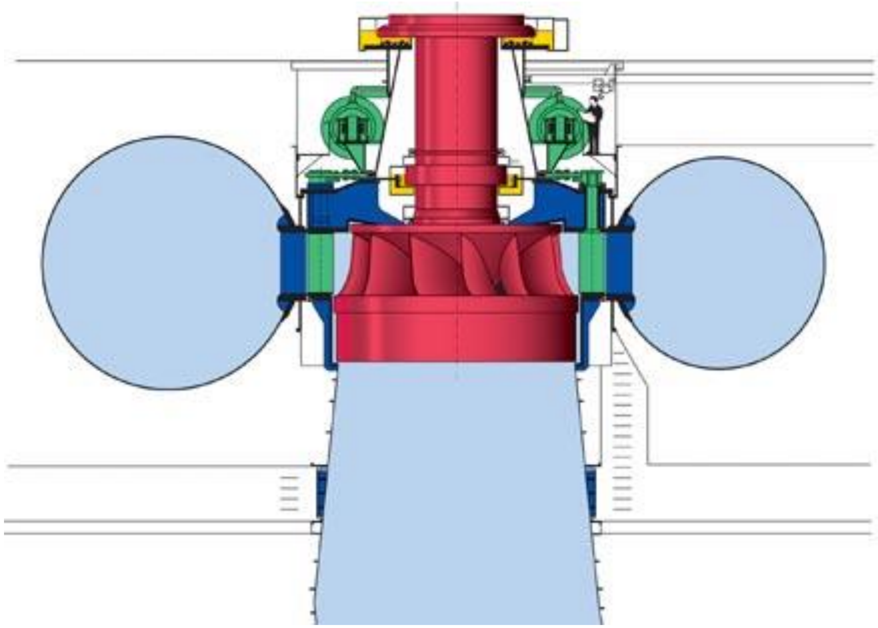
- Turbine types
  - Francis
  - propellers
  - impulse

Francis Turbine

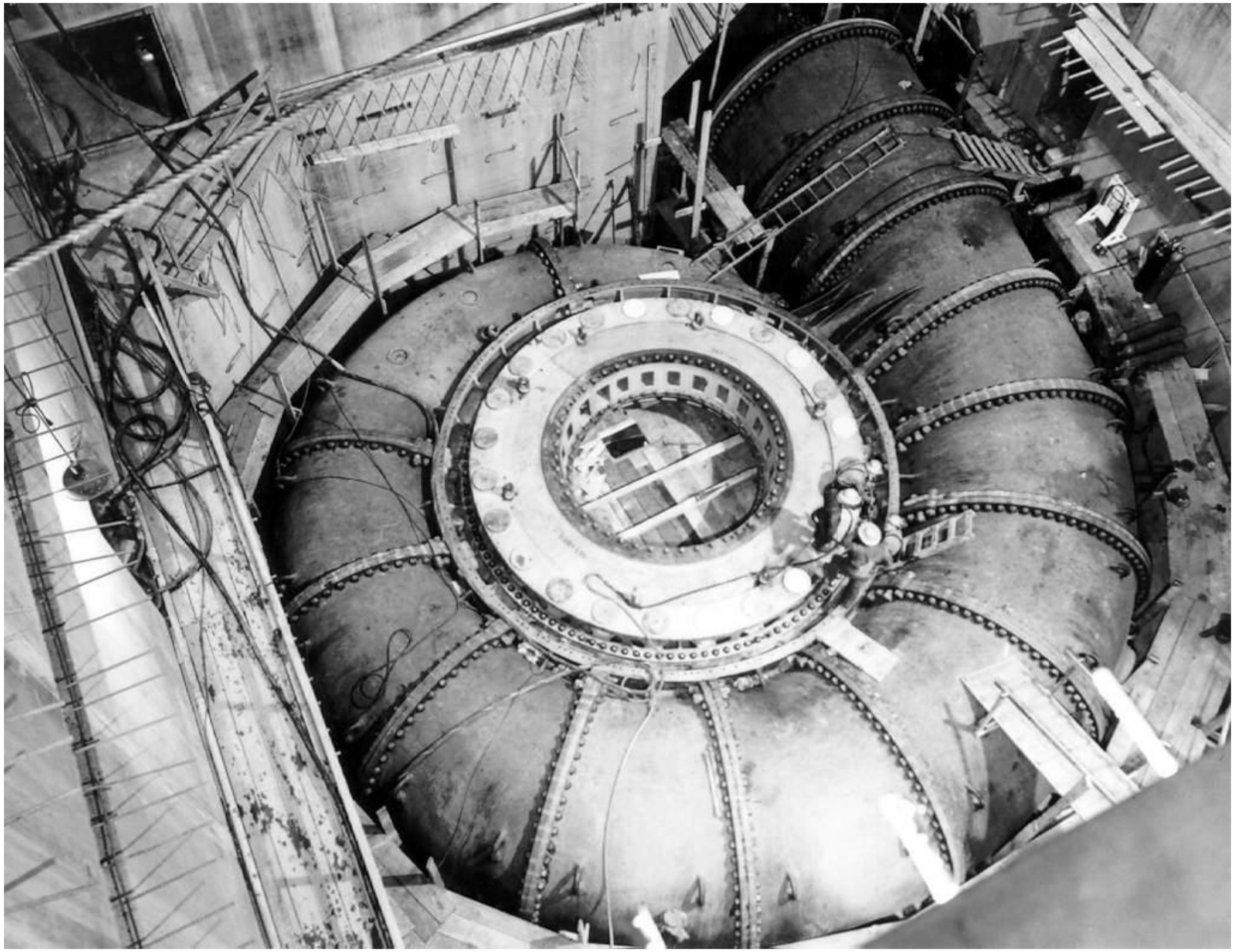
Three Gorges Dam

Francis Turbines

- horizontal or vertical axis of rotation
- completely submerged turbine blades
- common in medium and large capacity plants
- used in all types of head dams
- large drop in pressure



Francis Turbines

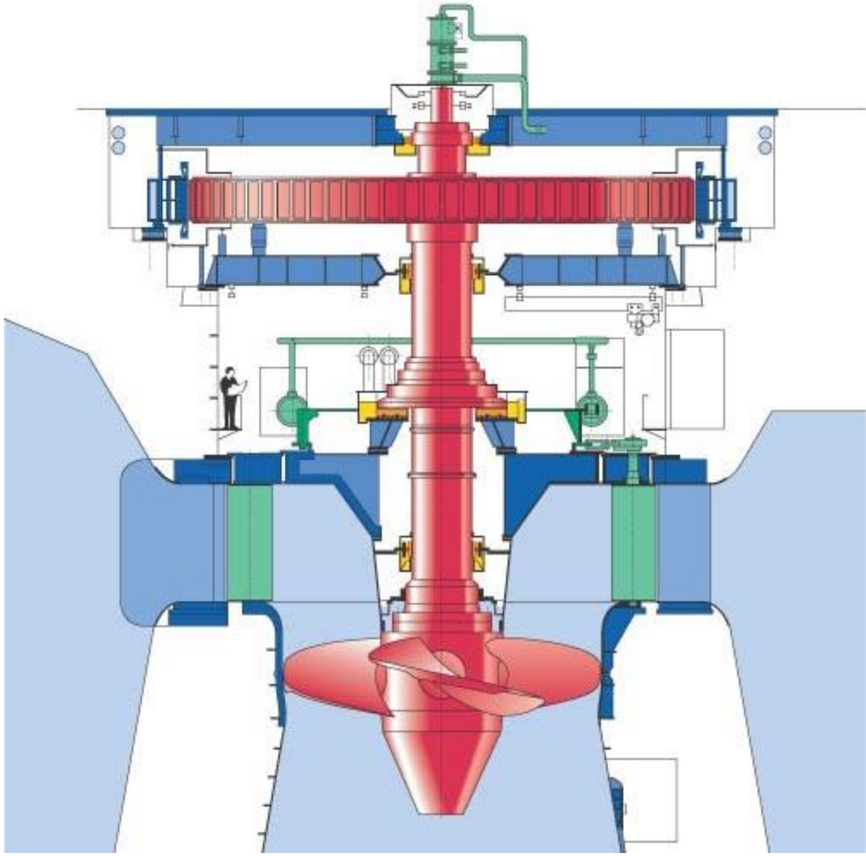


Grand Coulee Dam

Hydroelectric Generators

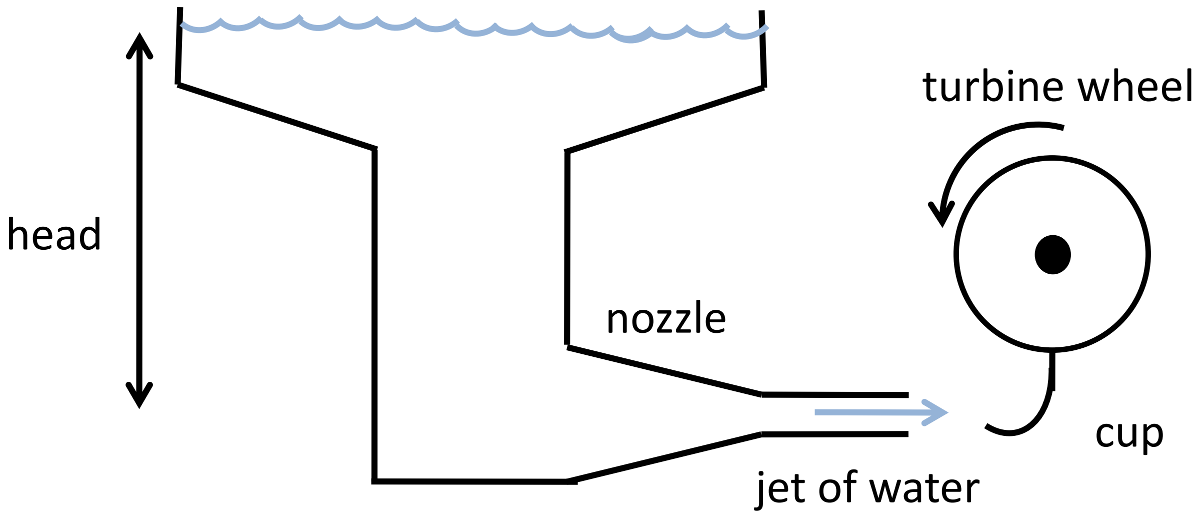
Propeller: Kaplan Turbine

- used in low-head, high flow applications
- completely submerged blades
- axial flow
- adjustable pitch blades



Impulse Turbine

- basic idea: use a jet of water to rotate the turbine wheel

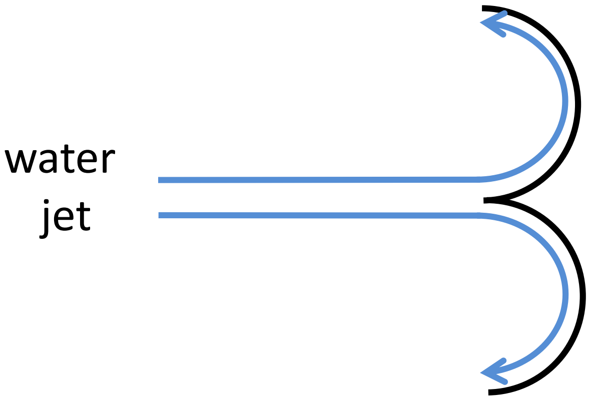


Pelton Turbine

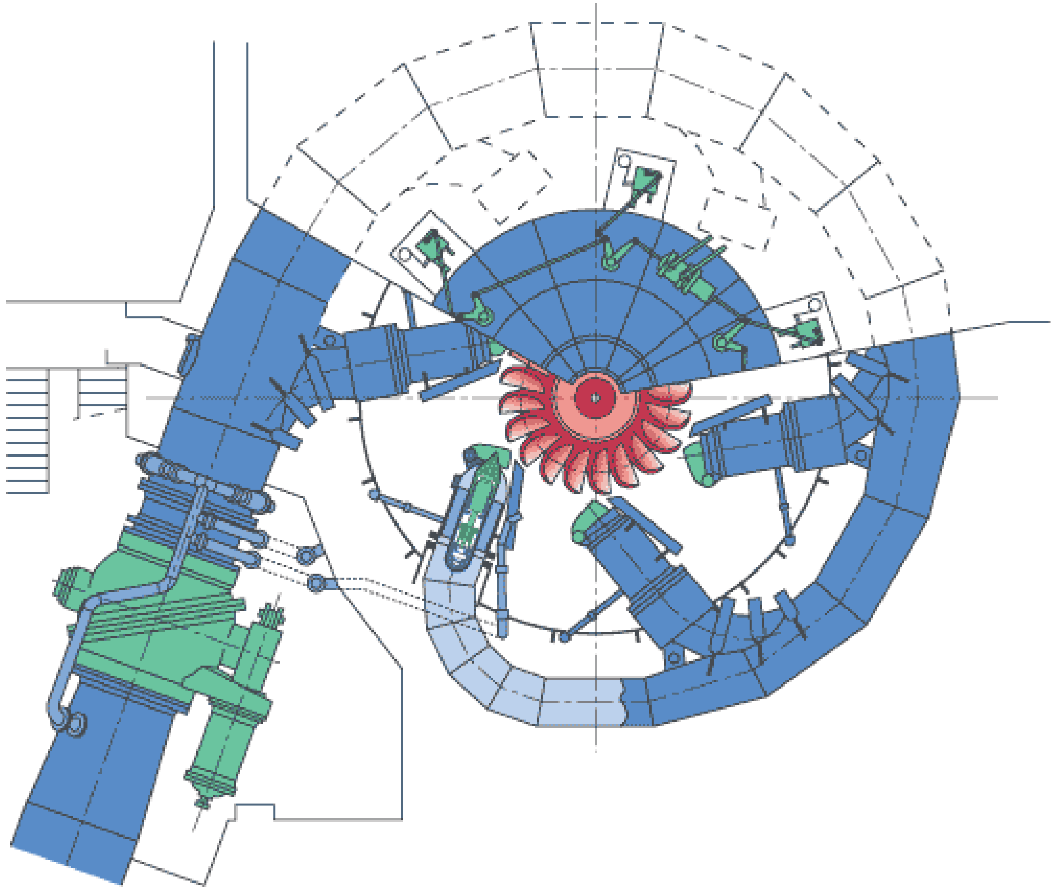
- 100% of kinetic energy can be harnessed
  - ideal conditions
  - unlike wind turbines (Betz Limit)
- cup is polished and smooth, with negligible friction

Pelton Turbine

Maximum efficiency is obtained when the velocity of the cup is equal to half the velocity of the water jet



Impulse Turbine: Pelton



Impulse Turbines

- velocity of water

$$E_{PE} = mgh$$

$$E_{KE} = \frac{1}{2}mv^2$$

$$\Rightarrow \frac{1}{2}mv^2 = mgh$$

$$\Rightarrow v = \sqrt{2gh}$$

- mass flow rate of water:

$$\dot{m} = 1000 \times A \times \sqrt{2gh}$$

  - *A*: area of nozzle, m^2

Impulse Turbine

- From before:

$$P = \eta_{wt} \times \dot{m} \times g \times h$$

- Therefore

$$P = \eta_{wt} \times 1000 \times A \times \sqrt{2gh} \times g \times h$$

$$P \approx \eta_{wt} 45A\sqrt{h^3} \text{ (in kW)}$$

Impulse Turbine

- If A = 5.0 m^2, h = 81 m and the efficiency is 90%, find the power output of a hypothetical impulse turbine.

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$$P \approx 0.9 \times 45A\sqrt{h^3} = 0.9 \times 45 \times 5 \times \sqrt{81^3} = 148kW$$

- What is the mass flow rate?

Impulse Turbine

- If A = 5.0 m², h = 81 m and the efficiency is 90%, find the power output of a hypothetical impulse turbine.

$$P \approx 0.9 \times 45A\sqrt{h^3} = 45 \times 5 \times \sqrt{81^3} = 875kW$$

- What is the mass flow rate?

$$\dot{m} = 1000 \times A \times \sqrt{2gh} = 1000 \times 5 \times \sqrt{2gh} = 200{,}000 \text{ kg/s}$$

Impulse Turbines

- It is possible to use more than one nozzle, in which case:

  $P \approx 45An\sqrt{h^3}$ (in kW)

  - n: number of nozzles
- number of nozzles is usually limited to be four or less or they will start interfering with each other

Turbine Applications

- Propeller turbines:
  - high flow rates (10 m^3/s to 50 m^3/s)
  - low head (3 m to 50 m)
- Francis turbines:
  - medium flow rates
  - medium head
- Pelton turbines:
  - low flow rate (0.1 m^3/s to 10 m^3/s)
  - high head (10 m to 1000 m)

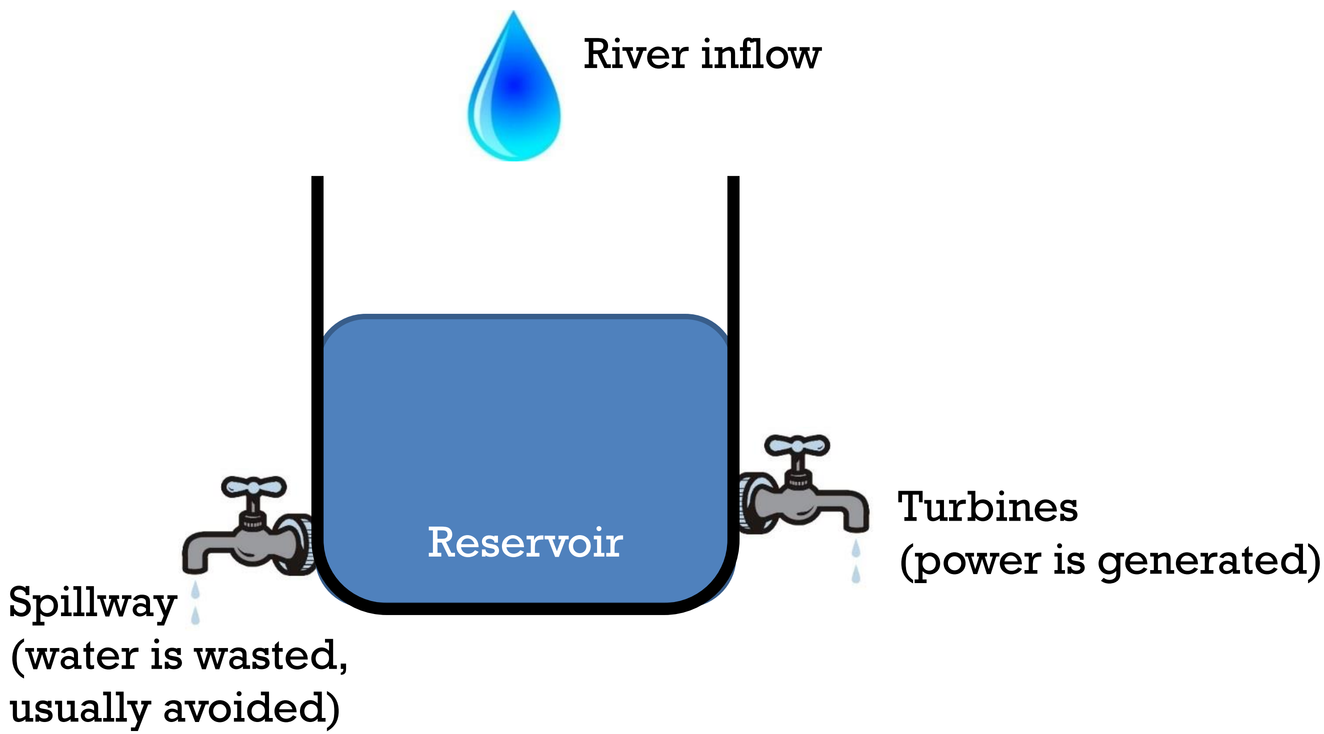
Turbine Applications

- each turbine type has an optimal range of rotational speeds
- Specific Speed:

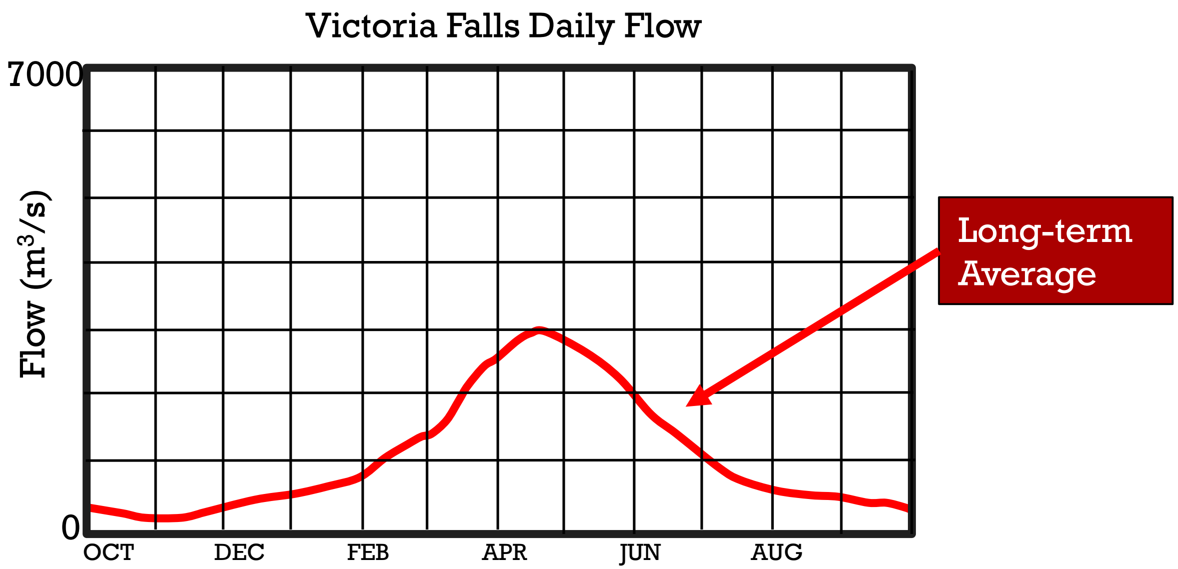
$$N_s = \frac{P^{1/2}\left(\omega/2\pi\right)}{h^{5/4}}$$

  - ω: angular velocity of the turbine (rad/s)
- Francis: N_s range 70-500
- Propeller: N_s range 350-100
- Pelton: N_s range 10-80

Reservoir Management

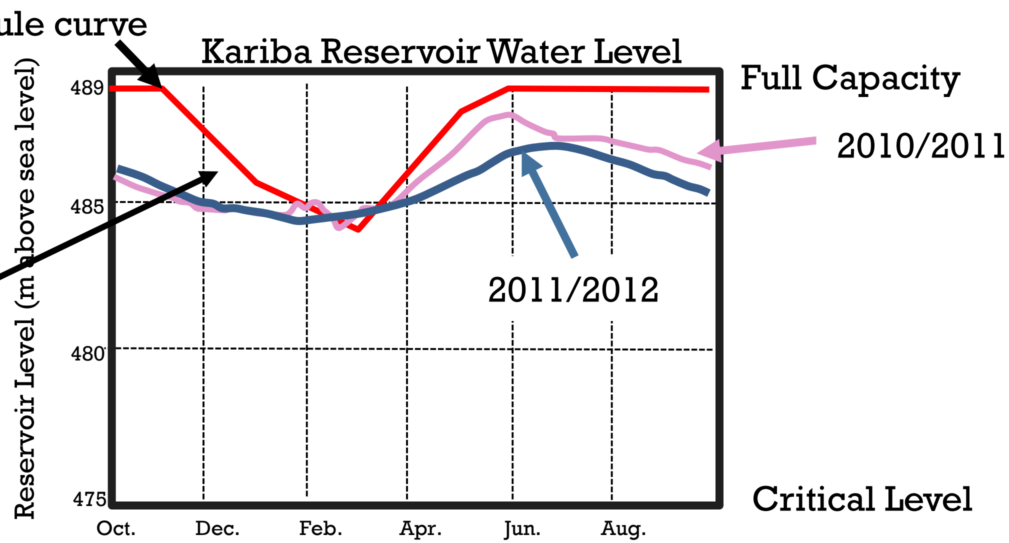

River inflow
Reservoir
Turbines
(power is generated)
Spillway
(water is wasted,
usually avoided)

Water flow into reservoirs is often seasonal (rainy season, snow pack melt, etc.)



Source: Zambezi River Authority

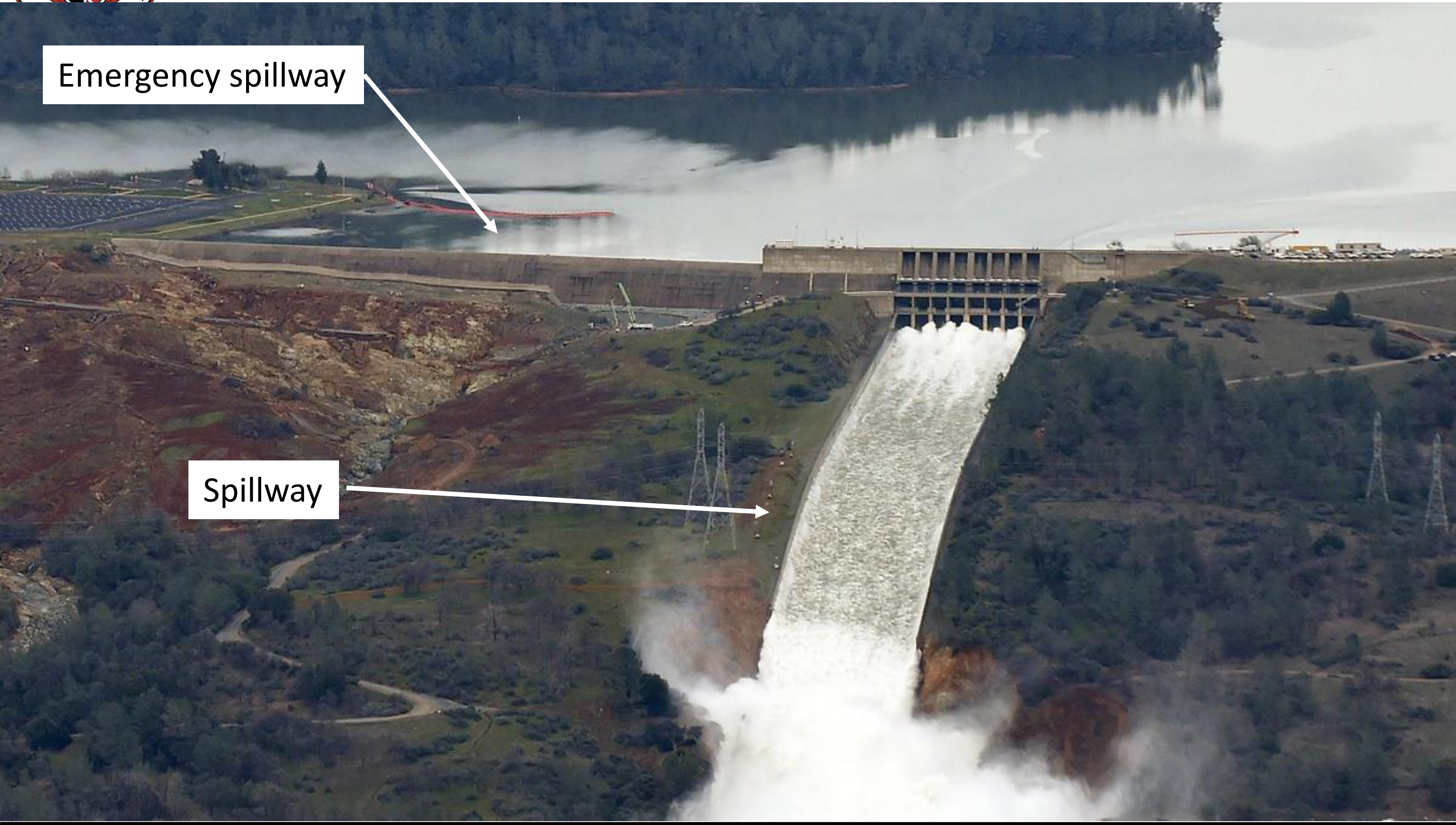
Rule Curves are used as guide for reservoir level management:
Above the Rule Curve: use more water
Below the Rule Curve: use less later



Water level should
decrease in anticipation
of rainy season incoming water

Source: Zambezi River Authority

Oroville Dam (California)



Environmental Impacts

- What are the positive environmental aspects of hydroelectricity?

Environmental Impacts

- What are the positive environmental aspects of hydroelectricity?
  - very low emissions (zero direct emissions)
  - no particulates
  - no radioactivity
  - irrigation

Environmental Impacts

- What are the negative environmental aspects of hydroelectricity?
  - population displacement
  - increased evaporation
  - silting
  - methane release from anaerobically decaying plants in the created reservoirs
  - construction process
  - fish
  - dam failure
    - In 1975, some 250,000 people died in China from several dam failures

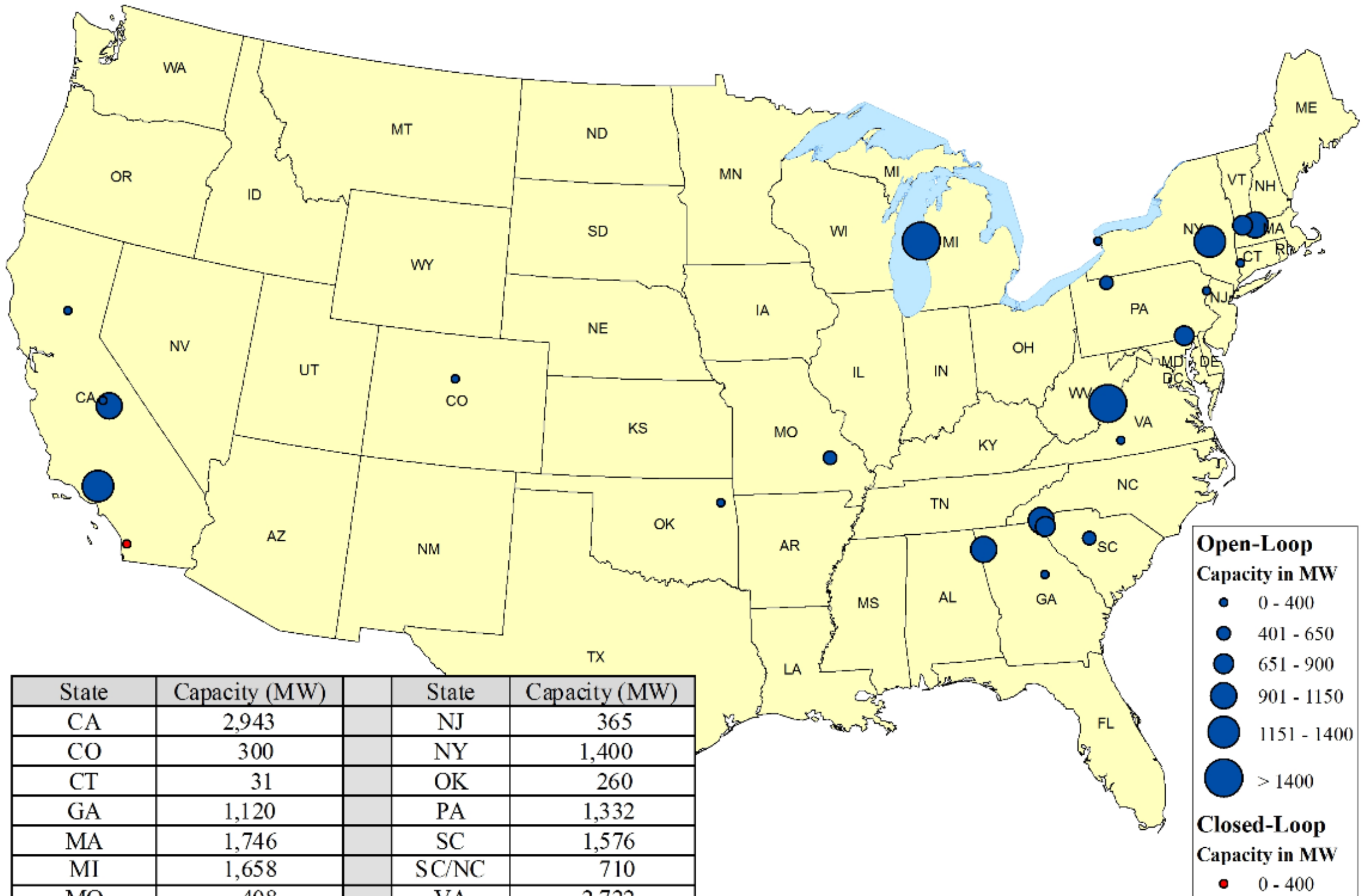
Environmental Impacts

- ecological damage from hydroelectricity generation is severe
- once built, it is difficult to modify the civil structure

Pumped Storage

- A unique characteristic of some hydroelectric facilities is the capability of pumped storage
- Water turbines are run as pumps (Pelton turbines cannot do it) to pump water back into the reservoirs
- Pumping occurs during the night and is supplied by base-loaded generators (coal or nuclear)
- This is the only commercial truly large-scale energy storage used
- Can be used for integrating renewable resources

Licensed Pumped Storage Projects



State	Capacity (MW)		State	Capacity (MW)
CA	2,943		NJ	365
CO	300		NY	1,400
CT	31		OK	260
GA	1,120		PA	1,332
MA	1,746		SC	1,576
MI	1,658		SC/NC	710
MO	408		VA	2,722
TOTAL CAPACITY				16,571 MW

Source: www.ferc.gov/industries/hydropower/gen-info/licensing/pump-storage.asp

Economics

- Capital costs:
  - $1,200 per kW for Three Gorges
  - $2,000/kW to $4,000 may be more typical
  - Mostly civil structure costs
  - Vary greatly from site to site
- No energy costs
- Machine lifetime
  - 25-50 years
- Structure lifetime
  - 50-100 years