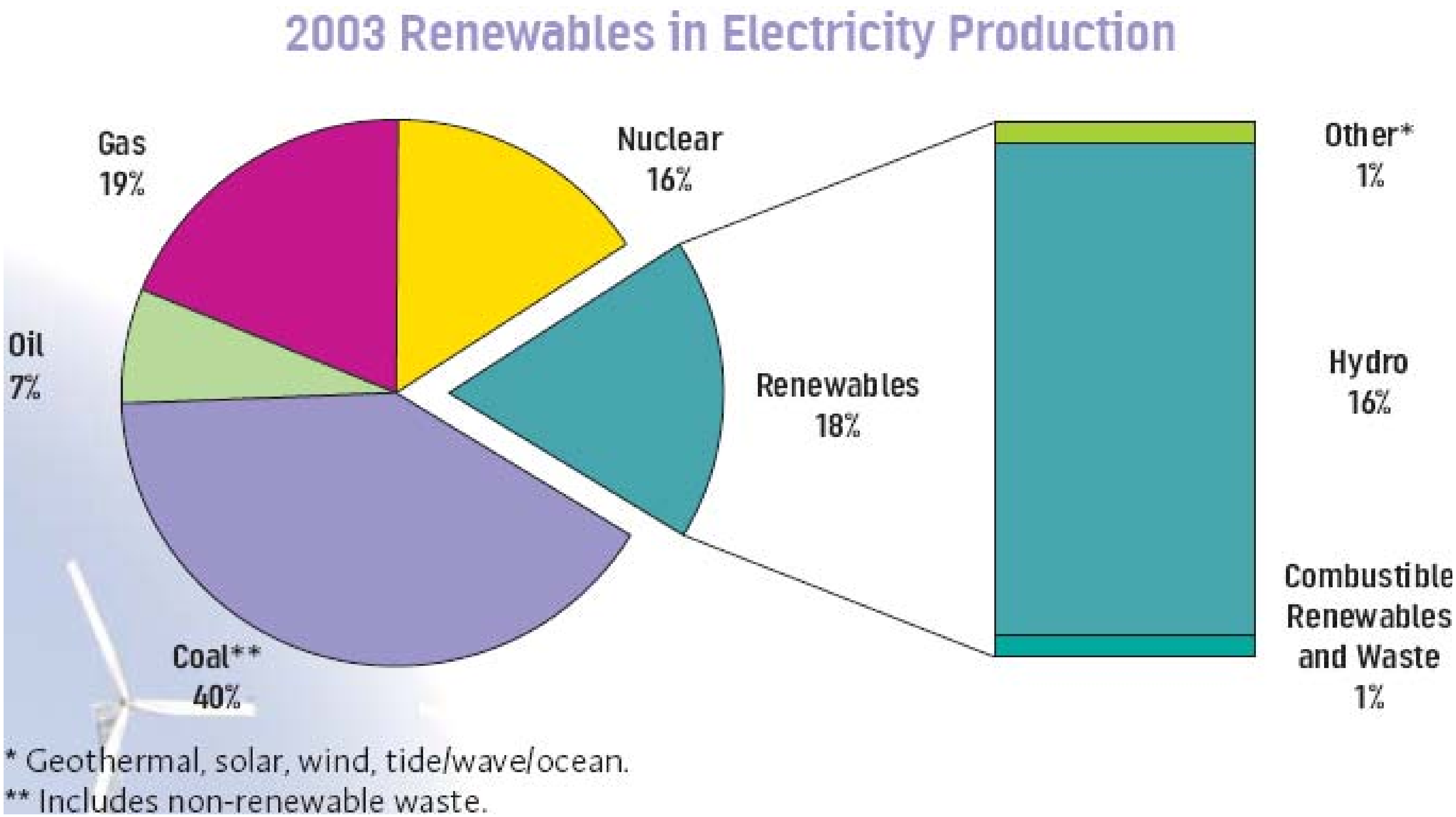
Hydropower

See the notes in Compedu

http://www.energy.kth.se/compedu/webcompedu/index.html

Source: Marianne Salomon @ KTH

Global Renewable Energy



Source: IEA

Worldwide Hydropower

Producers	TWh	% of World total
People's Rep. of China	354	12.6
Canada	341	12.1
Brazil	321	11.4
United States	271	9.7
Russia	176	6.3
Norway	109	3.9
Japan	94	3.3
India	85	3.0
Venezuela	70	2.5
Sweden	60	2.1
Rest of the World	927	33.1
World	**2 808**	**100.0**

2004 data

Installed Capacity (based on production)	GW
United States	99
People's Rep. of China	86
Canada	67
Brazil	59
Japan	46
Russia	44
India	30
Norway	28
France	25
Sweden	16
Rest of the World	307
World	**807**

2003 data

Country (based on first 10 producers)	% of hydro in total domestic electricity generation
Norway	98.8
Brazil	82.8
Venezuela	71.0
Canada	57.0
Sweden	39.6
Russia	18.9
People's Rep. of China	16.1
India	12.7
Japan	8.8
United States	6.5
Rest of the World*	14.2
World	**16.1**

2004 data

Source IEA

Hydropower - History

- For many centuries, hydropower had been used to produced mechanical power to perform a range of activities, including grain milling, textile processing and other light industrial operations.
- A great part of the industrial revolution in the 18th century was "fueled" by access to hydropower

Hydropower Basics

- P (W) = ρ g H Q η_t

ρ = water density = 1000 kg/m^3

g = gravitational const. = 9,81 m/s^2

H = head (m)

Q = water flow (m^3/s)

η_t = turbine efficiency

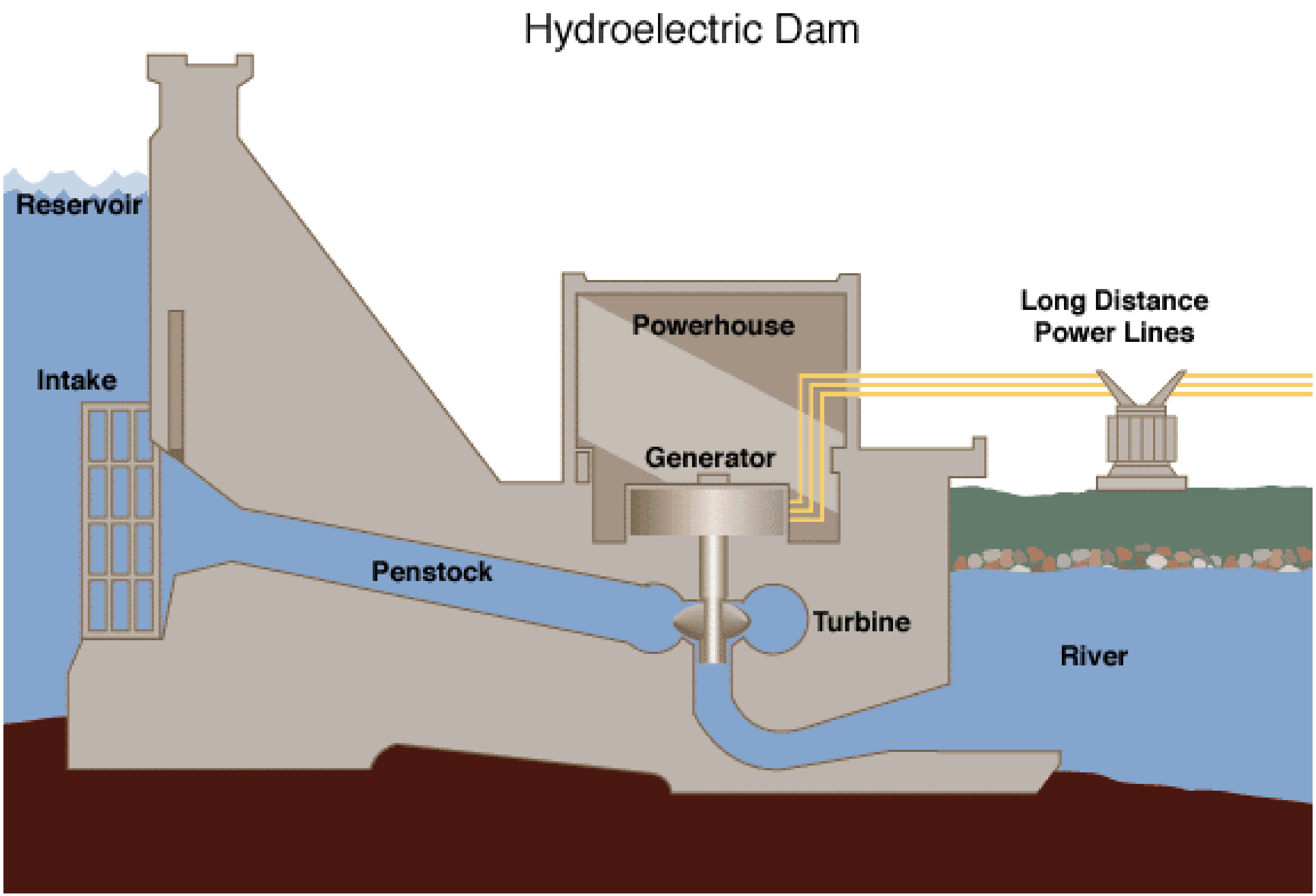
Hydropower Advantages

- A big advantage of hydroelectric power is the ability to quickly and readily vary the amount of power generated, depending on the load presented at that moment.
- It utilizes a renewable energy source as “fuel” (water)
- Generation process is environmentally clean
- High reliability

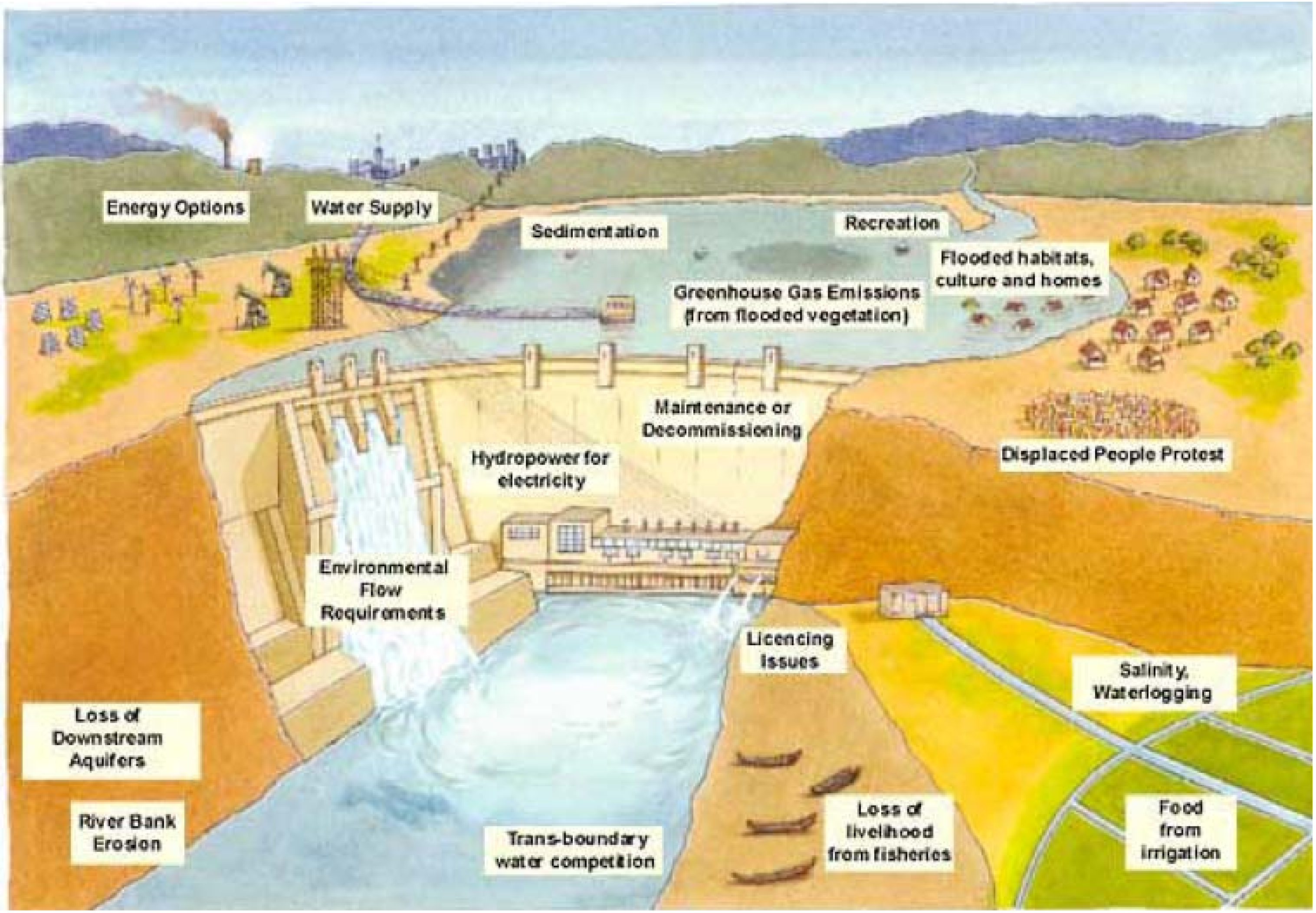
Hydropower Disadvantages

- It requires large initial investments
- Long transmission lines
- Social and environmental impacts for large-scale schemes

Hydropower Plant



Dams


Energy Options
Water Supply
Sedimentation
Recreation
Flooded habitats, culture and homes
Greenhouse Gas Emissions (from flooded vegetation)
Maintenance or Decommissioning
Hydropower for electricity
Displaced People Protest
Environmental Flow Requirements
Licencing issues
Salinity, Waterlogging
Loss of Downstream Aquifers
River Bank Erosion
Trans-boundary water competition
Loss of livelihood from fisheries
Food from irrigation

Hydropower Plant

- Dam
- Penstock
- Spillway
- Turbine
- Powerhouse
- Generator
- Transformer
- Transmission lines

Dams

- Today there are over 45,000 dams (h>15 m, or V > 3 x 10^6 m^3) in > 150 nations.
- About one fifth of the world's agricultural land is irrigated, and irrigated agriculture accounts for about 40% of the world's agricultural production.
- One third of the countries in water-stressed regions of the world are expected to face severe water shortages this century. By 2025 there will be approximately 6.5 times as many people - a total of 3.5 billion - living in water-stressed countries.
- Half the world's large dams were built exclusively or primarily for irrigation, and an estimated 30 to 40% of the 271 million hectares of irrigated lands worldwide rely on dams.
- Dams are estimated to contribute to 12-16% of world food production.
- Hydropower currently provides 16% of the world's total electricity supply, and is used in over 150 countries with 24 of these countries depending on it for 90% of their supply.

Dam Types

- Gravity Dams
- Arch Dams
- Buttress Dams
- Embankment Dams
  - Earthfill dams
  - Rockfill dams

Primary Embankment Dam Performance

- Freeboard
- Erosion protection
- Filter system
- Dam foundation
- Compaction
- Drainage system
- Geotechnical stability
- Spillway function
- Interaction dam body – dam foundation

Dam Failures

TABLE 3.16 Earth Dam Failures

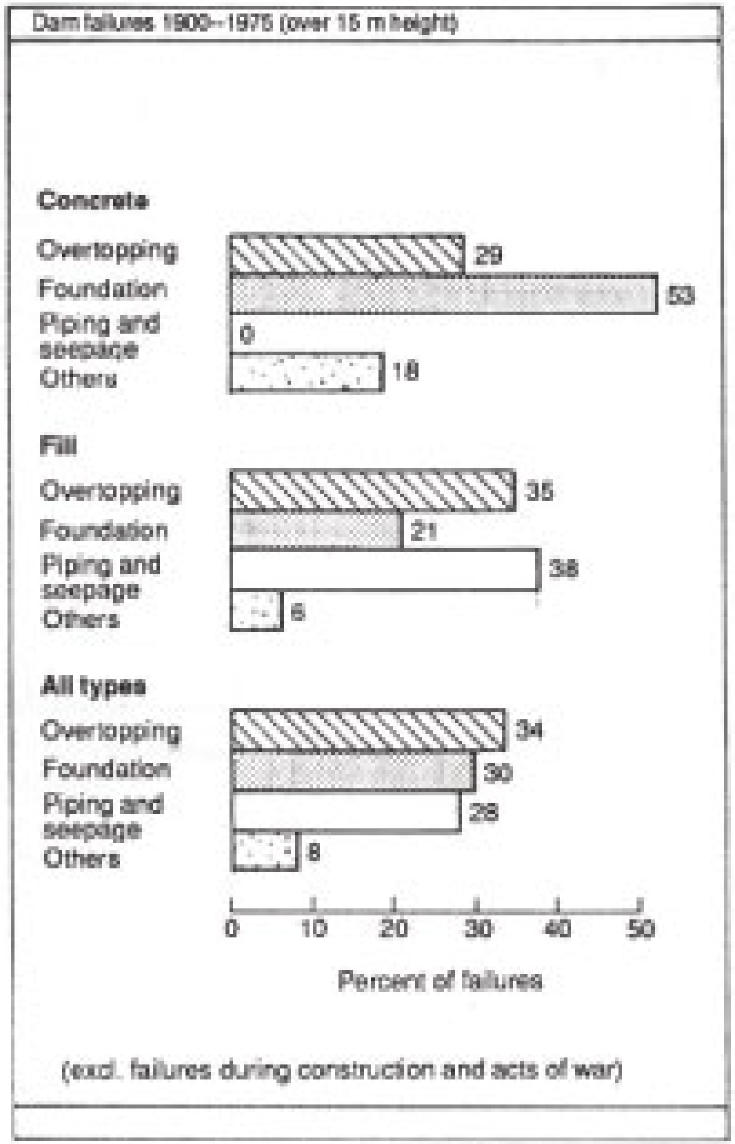
Form	General characteristics	Causes	Preventive or corrective measures
Overtopping	Flow over embankment, washing out dam.	*Hydraulic Failures (30% of all failures)* Inadequate spillway capacity. Clogging of spillway with debris. Insufficient freeboard due to settlement, skimpy design.	Spillway designed for maximum flood. Maintenance: trash booms, clean design. Allowance for freeboard and settlement in design: increase crest height or add flood parapet.
Wave erosion	Notching of upstream face by waves, currents.	Lack of riprap, too small riprap.	Properly designed riprap.
Toe erosion	Erosion of toe by outlet discharge.	Spillway too close to dam. Inadequate riprap.	Training walls. Properly designed riprap.
Gullying	Rainfall erosion of dam face.	Lack of sod or poor surface drainage. *Seepage Failures (40% of all failures)*	Sod, fine riprap: surface drains.
Loss of water	Excessive loss of water from reservoir and/or occasionally increased seepage or increased groundwater levels near reservoir.	Pervious reservoir rim or bottom. Pervious dam foundation. Pervious dam. Leaking conduits.	Banket reservoir with compacted clay or chemical admix: grout seams, cavities. Use foundation cutoff: grout upstream blanket. Impervious core. Watertight joints: waterstops: grouting.
	Settlement cracks in dam.	Remove compressible foundation, avoid sharp changes in abutment slope, compact soils at high moisture.	
	Shrinkage cracks in dam.	Use low-plasticity clays for core, adequate compaction.	
Seepage erosion or piping	Progressive internal erosion of soil from downstream side of dam or foundation backward toward the upstream side to form an open conduit or "pipe." Often leads to a washout of a section of the dam.	Settlement cracks in dam.	Remove compressible foundation, avoid sharp changes, internal drainage with protective filters.

Dam Failures

Form	General characteristics	Causes	Preventive or corrective measures
	Shrinkage cracks in dam.	Low-plasticity soil: adequate compaction; internal drainage with protective filters.	
	Pervious seams in foundation.	Foundation relief drain with filter: cutoff.	
	Pervious seams, roots, etc., in dam.	Construction control: core; internal drainage with protective filter.	
	Concentration of seepage at face.	Toe drain: internal drainage with filter.	
	Boundary seepage along conduits, walls.	Stub cutoff walls, collars: good soil compaction.	
	Leaking conduits.	Watertight joints: water stops; materials.	
	Animal burrows.	Riprap, wire mesh.	
Foundation slide	Sliding of entire dam, one face, or both faces in opposite directions, with bulging of foundation in the direction of movement.	*Structural Failures (30% of all failures)* Soft or weak foundation. Excess water pressure in confined sand or silt seams.	Flatten slope: employ broad berms; remove weak material; stabilize soil. Drainage by deep drain trenches with protective filters: relief wells.
Upstream slope	Slide in upstream face with little or no bulging in foundation below toe.	Steep slope. Weak embankment soil. Sudden drawdown of pond.	Increased compaction; better soil. Flatten slope, rock berms: operating rules.
Downstream slope	Slide in downstream face.	Steep slope. Weak soil. Loss of soil strength by seepage pressure or saturation by seepage or rainfall.	Flatten slope or employ berm at toe. Increased compaction: better soil. Core: internal drainage with protective filters: surface drainage.
Flow side	Collapse and flow of soil in either upstream or downstream direction.	Loose embankment soil at low cohesion, triggered by shock, vibration, seepage, or foundation movements.	Adequate compaction.

Source: From National Research Council [13].

Dam Failures



Overtopping

Dam Failure

A large section of the upper reservoir failed, draining over 4 million m^3 of water in twelve minutes

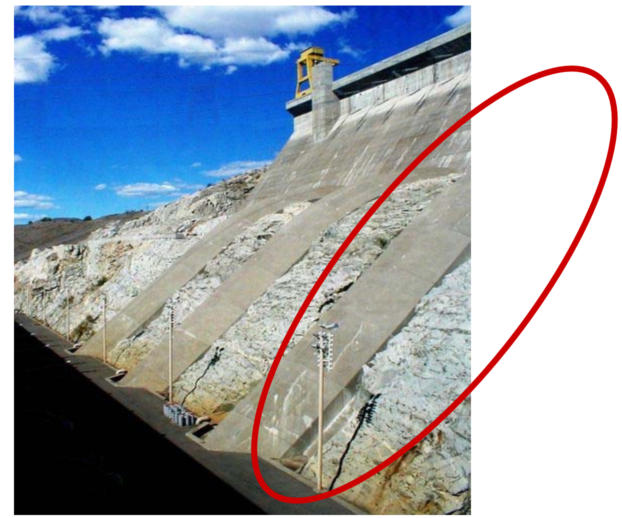
Source: Federal Energy Regulatory Commission

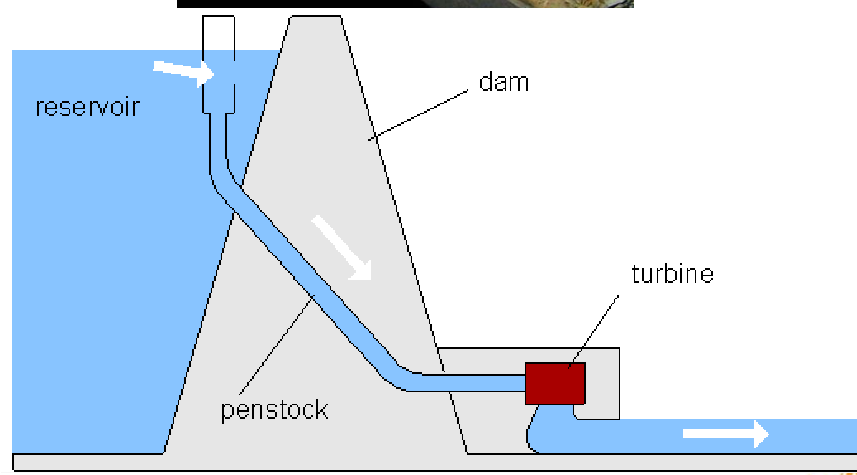
The reservoir behind the Teton Dam (Idaho, USA) was emptied within hours of the initial breach (1976)

Source: U.S. Department of the Interior, Bureau of Reclamation

Penstock

- The penstock is a pressurized-water conductor that extends from the free water surface at the reservoir, canal, or surge tank to the powerhouse.





Trash Racks

- A trash rack is required to protect the turbine runner from impinging objects.
- It is an structure made up of one or more panels, each generally fabricated of a series of evenly spaced parallel metal bars.

N.C. Department of Environment & Natural Resources, Division of Water Resources - Instream Flow Web Page

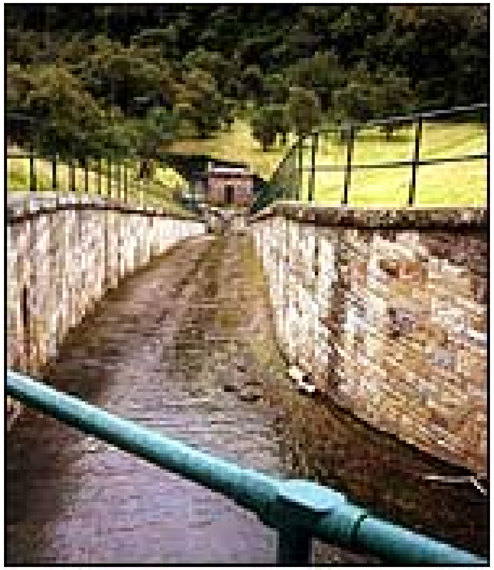
Carbonton Hydropower Project, Deep River
Lee County, N.C.

Spillways Types

- The overflow type of spillway is the most common and is usually the most economical for passing large flows.

- Side channel spillways are used mainly with embankment dams. They are located just upstream and to the side of the dam.

Overflow spillway: Source: British Dam Society.



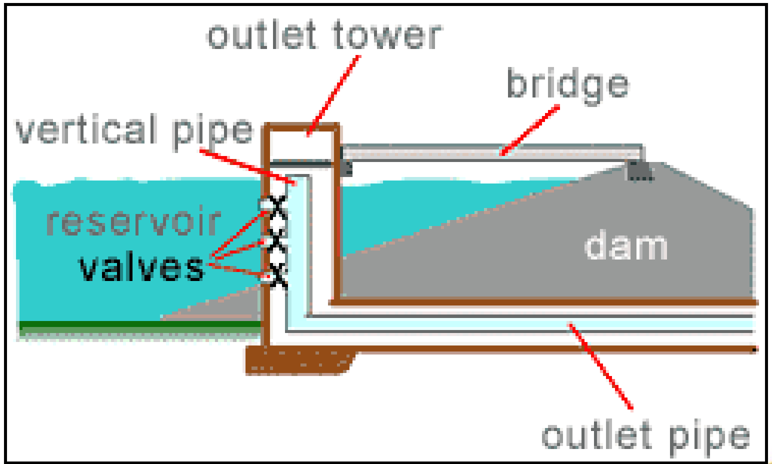
spillway chute from side channel to river

Source: British Dam Society.

Spillway Types

- A shaft spillway is sometimes called a "morning glory" spillway. It is a hollow tower or shaft, usually circular, which has a funnel at its top. The tower sits in the reservoir near the dam.
- The tower sits above an outlet pipe or tunnel used to transport water out of the reservoir. It is built to house controls for opening and closing valves or gates that control the flow of water through the outlet.

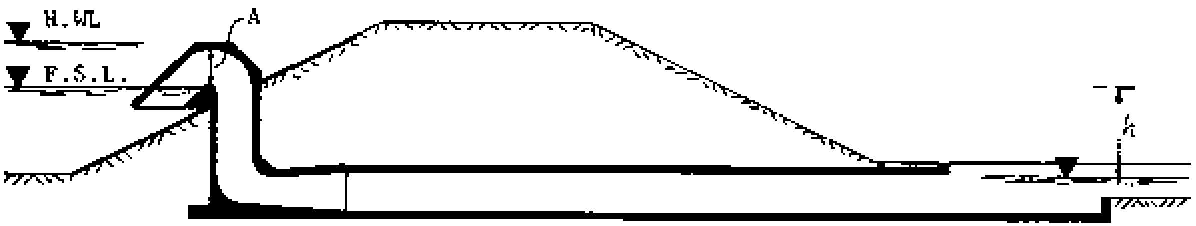
The top of the shaft spillway at Llyn Pontsticill in Wales



Source: British Dam Society.

Spillways Types

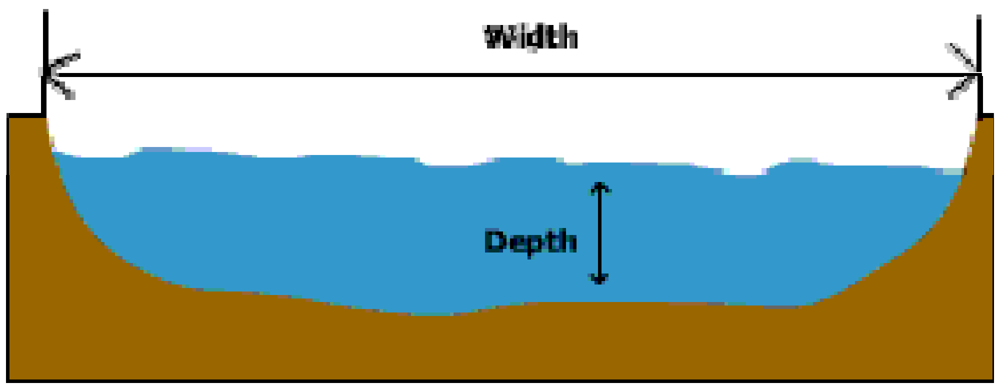
- The siphon spillway is a closed conduit for discharging water over or through the dam. This type of spillway can also provide automatic surface-level regulation.
- The entrance to a siphon spillway is usually submerged below the normal water level, to prevent the entrance of air and reduce the potential for clogging with debris or ice.



Source: Food and Agriculture Organization of the United Nations

Canals

- A power canal conveys water from the reservoir to the turbine intake structure. In some cases, the canal conveys water to a forebay upstream of the turbine intake.



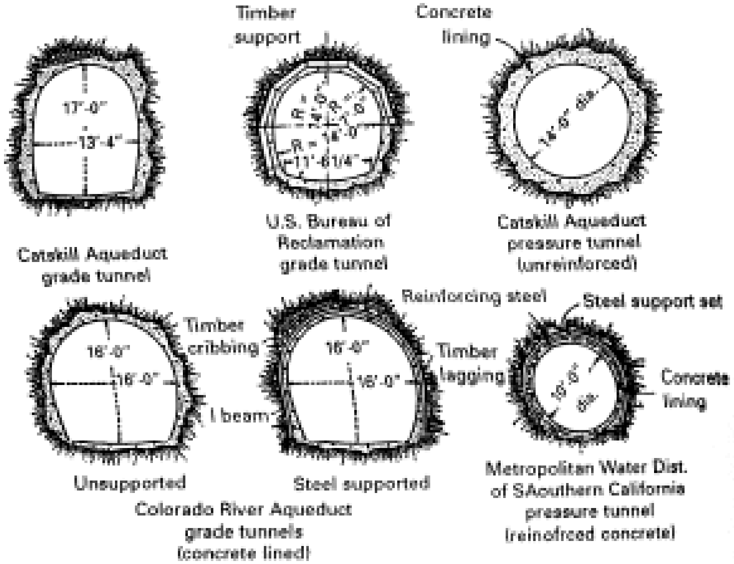
Source: Ritter, Michael E. The Physical Environment: an Introduction to Physical Geography. 2006

Tunnels

- The layout of a hydroelectric plant sometimes requires carrying the water through mountains, requiring the use of tunnels. These tunnels may operate under pressure or flow partly full.

Kárahnjúkar power station (Iceland)

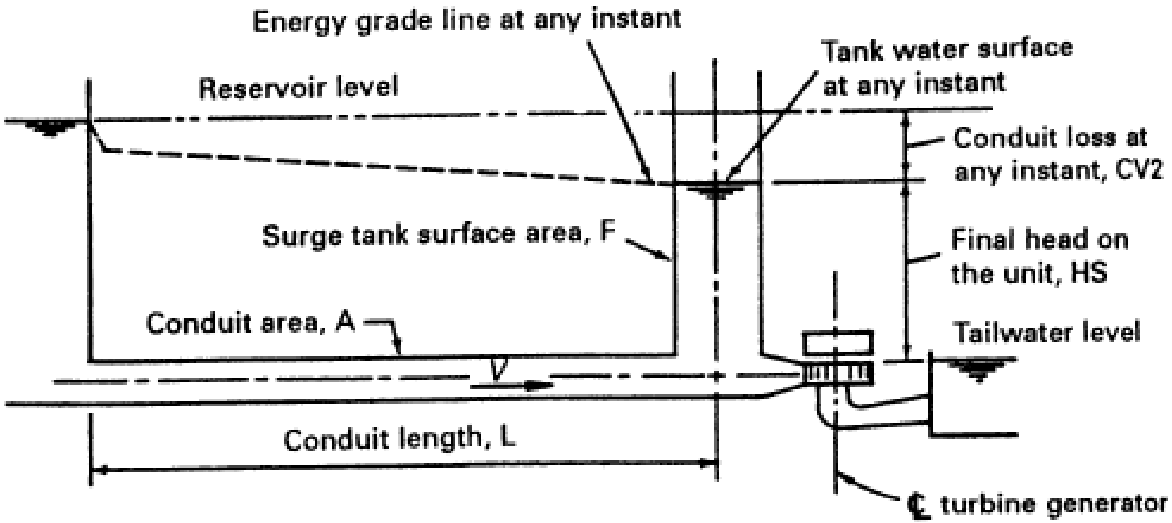
Source: www.tunnels.mottmac.com/



Source: Standard Handbook of Powerplant Engineering. Elliot, T. et al. 1997

Surge Tanks

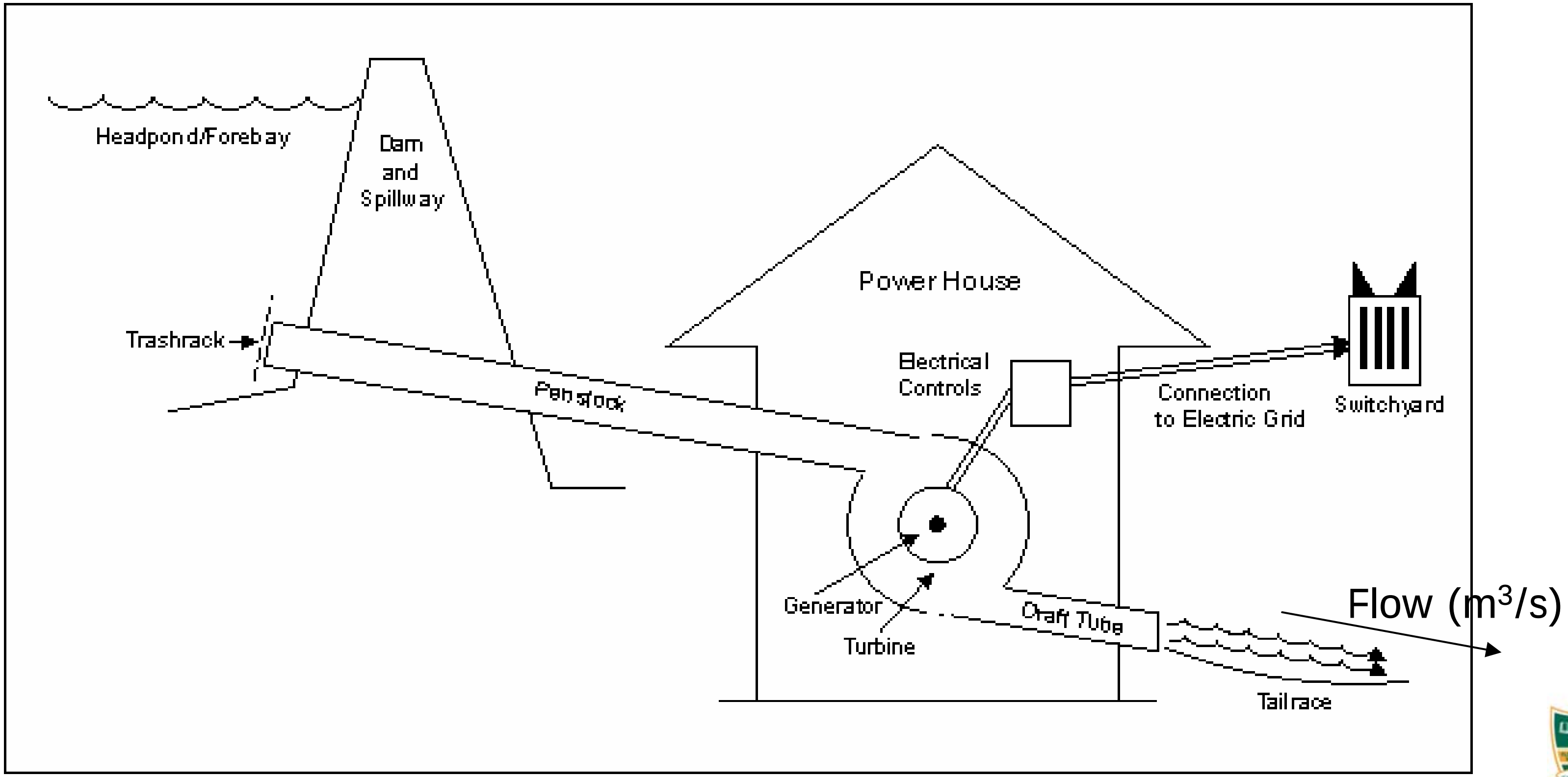
- Its purpose is to relieve the excessive pressures resulting from the manipulation of the turbine gates as the load on the generating unit varies, and to supply initial water for an increasing load while the water in the tunnel is being accelerated.



Source: Standard Handbook of Powerplant Engineering. Elliot, T. et al. 1997

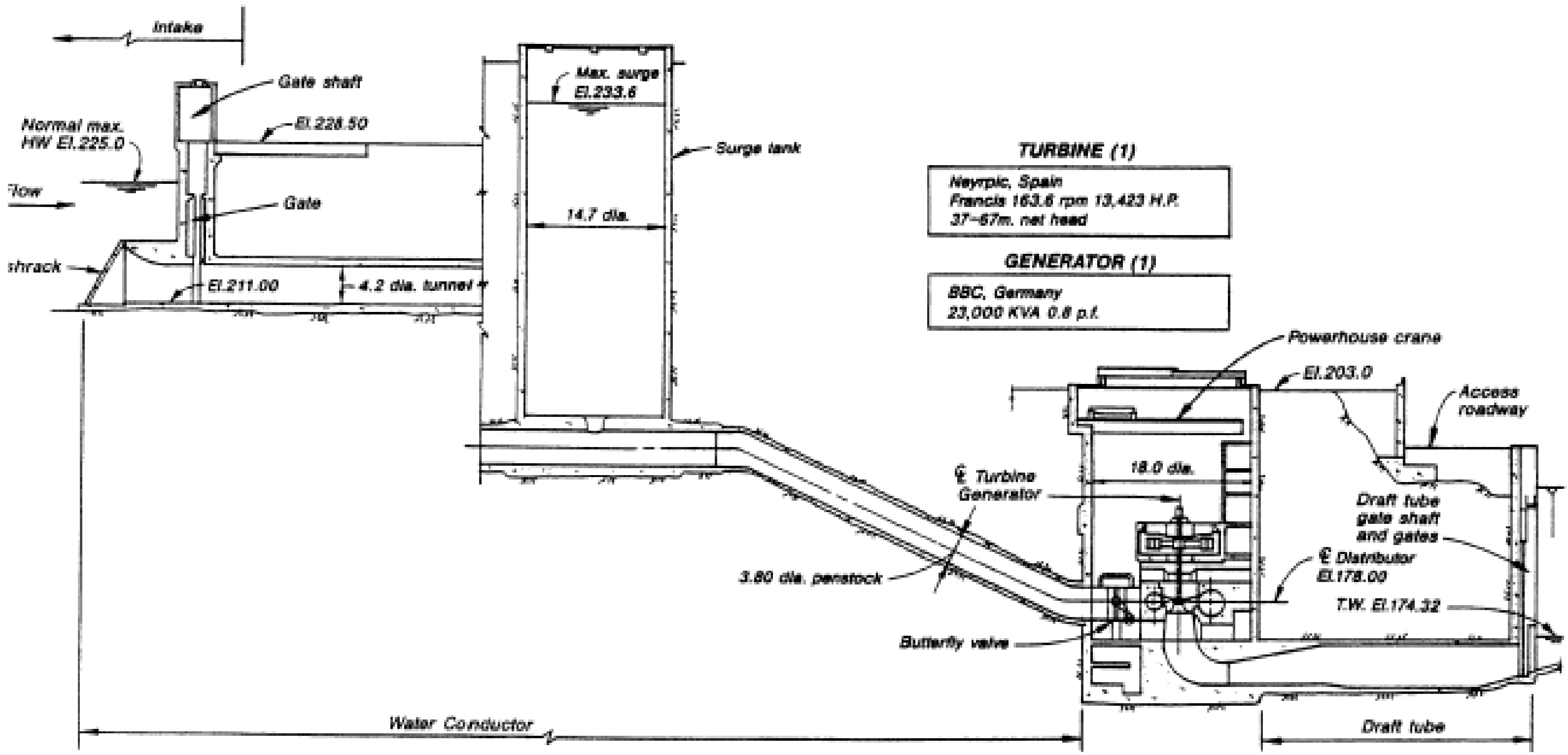
Tailrace

- The tailrace is channel or canal that carries water away from a dam. Also sometimes called an afterbay.



Draft Tube

- A water conduit which carries water from a reaction turbine runner to the tailrace. It is designed to maximize head utilization by the turbine.



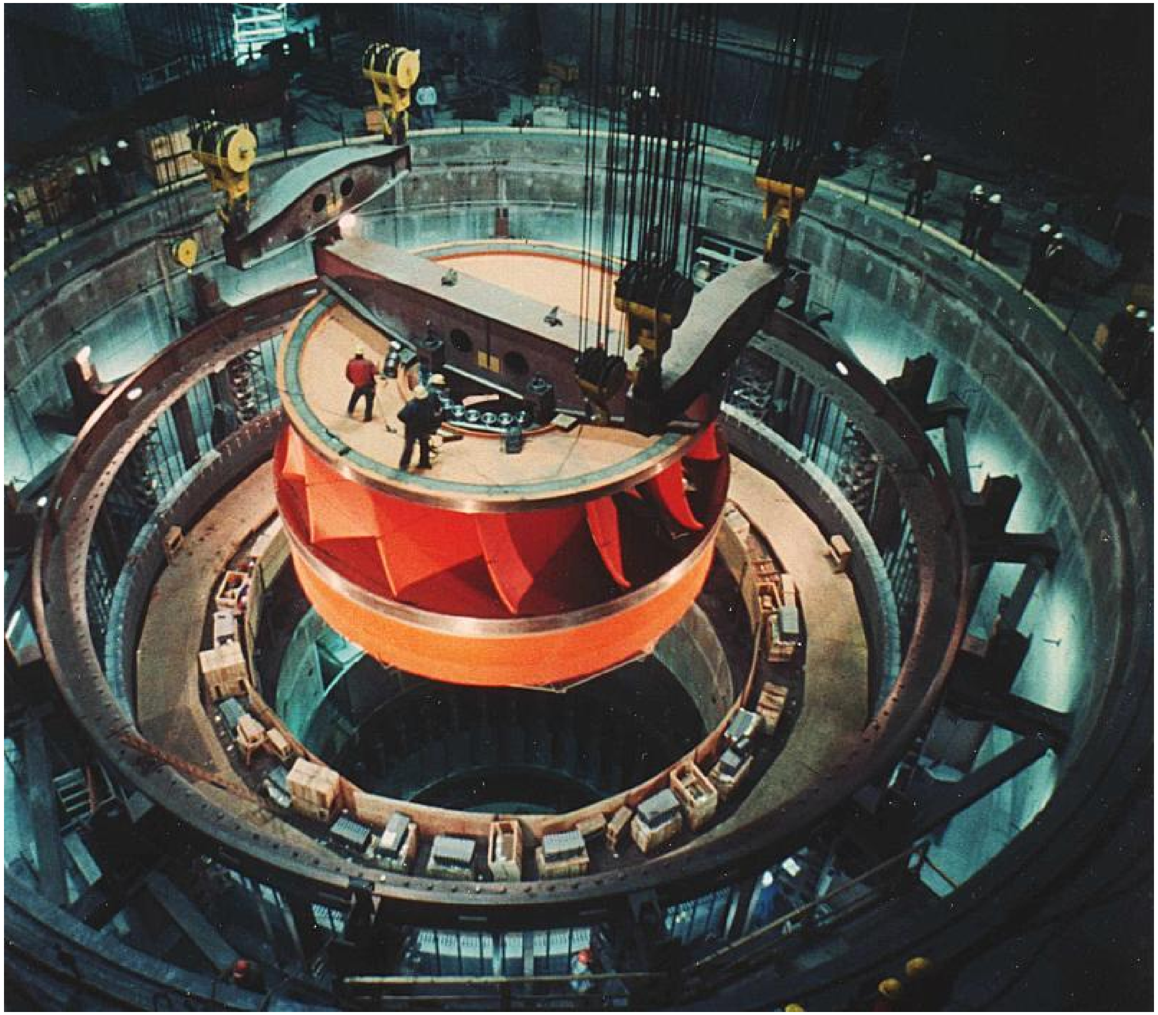
Fish Passages

- It is an structure consisting e.g. of a series of overflow weirs which are arranged in steps that rise about 30 cm (width varies from 1.2 m to 2.4 m and lengths varying between 1.8 and 3.0 m) and serve as a means for allowing migrant fish to travel upstream past a dam or weir.

John Day Dam fish ladder, Columbia River

Source: United States Army Corps of Engineers.

Turbines



Water Wheels

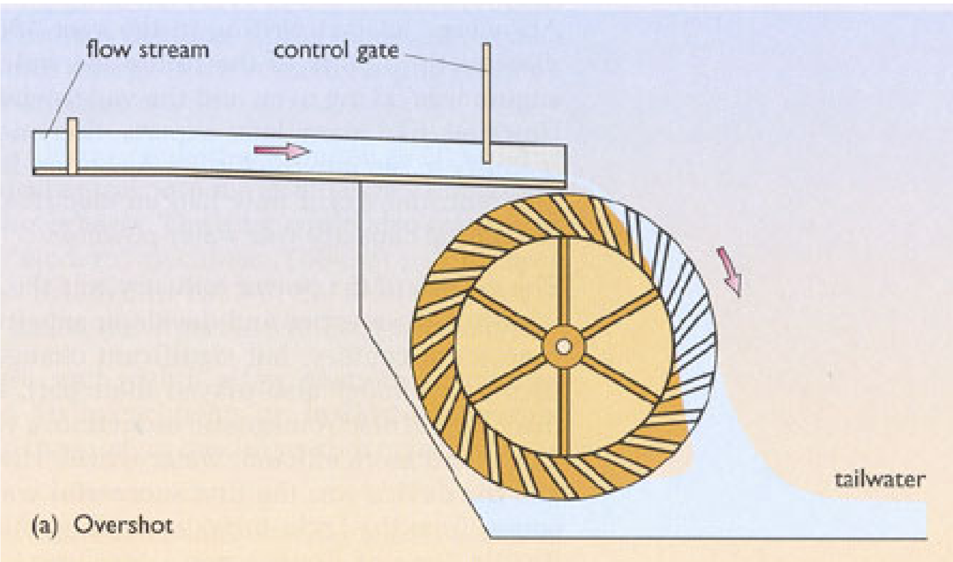
- Water wheels have been used for thousands of years for industrial power. Their main shortcoming is size, which limits the flow rate and head that can be harnessed.
- The migration from water wheels to modern turbines occurred during the Industrial revolution

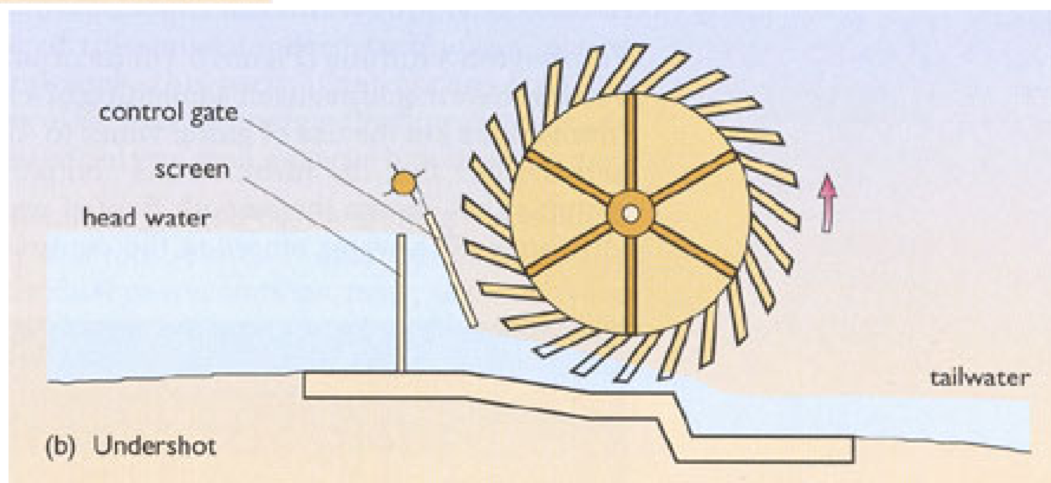
Water Wheels

- The main difference between early water turbines and water wheels is a swirl component of the water which passes energy to a spinning rotor.

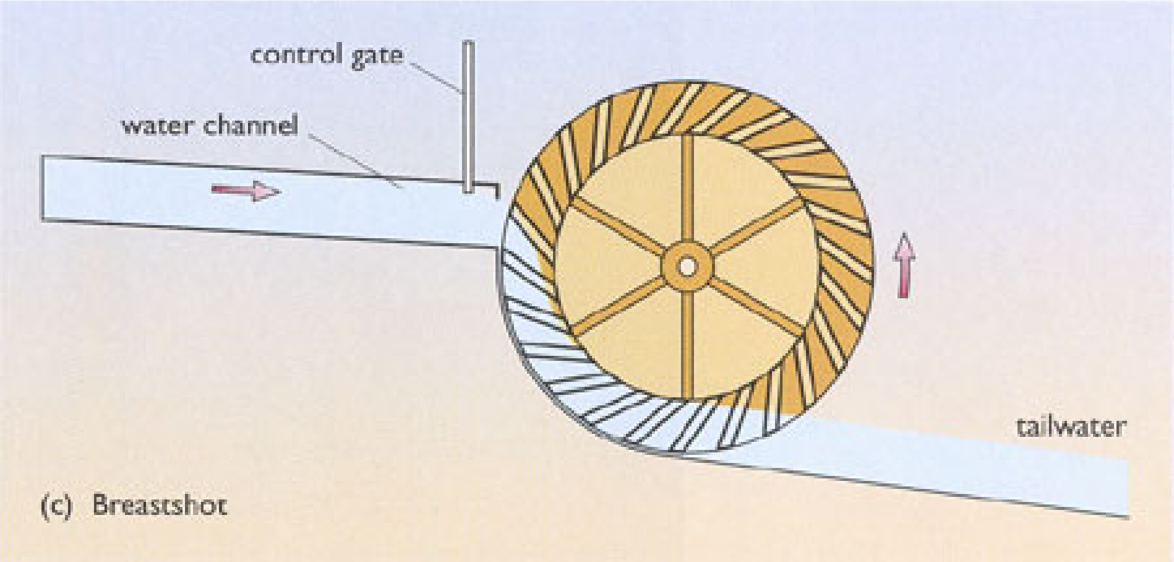
The Orontes River water wheels in Hama, Syria

Water Wheel Types



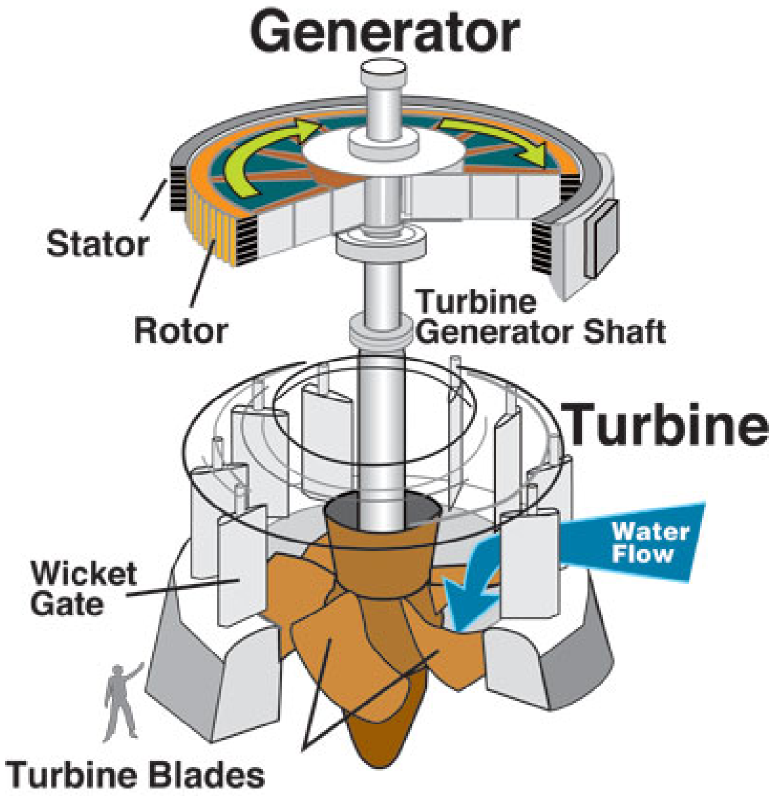


Water Wheel Types



Water Turbines

- Water turbines were developed in the nineteenth century and were widely used for industrial power prior to electrical grids

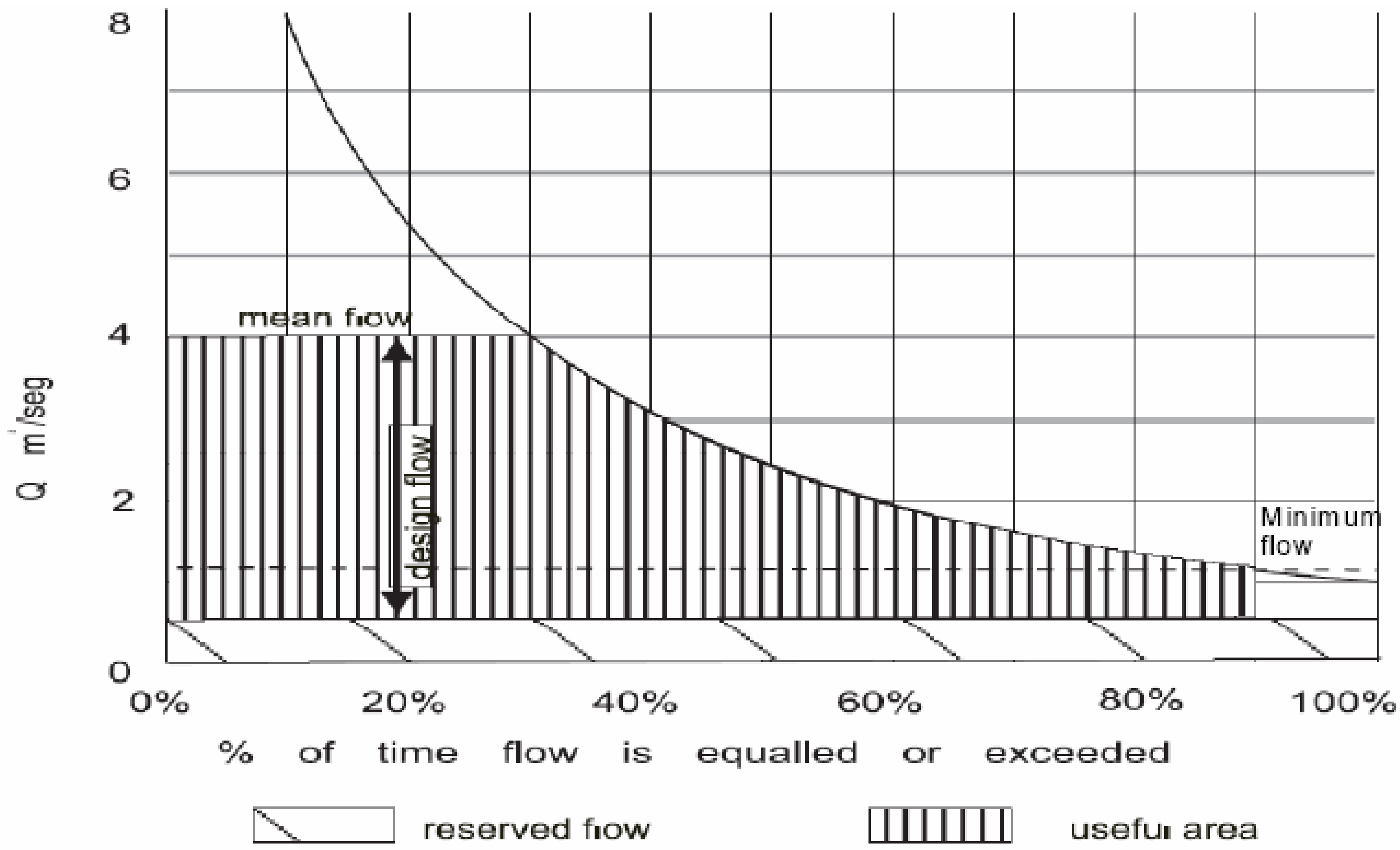


Source: United States Army Corps of Engineers.

Main Design Parameters

- The power capacity of a hydropower plant is primarily a function of two main variables of the water:
  - water flow
  - the hydraulic head

Flow Duration Curve



Source: European Small Hydropower Association

Design Flow

- Design flow is the maximum flow for which your hydro system is designed.

- It will likely be less than the maximum flow of the stream (especially during the rainy season), more than the minimum flow, and a compromise between potential electrical output and system cost.

Design Flow

- If a system is to be independent of any other energy or utility backup, the design flow should be the flow that is available 95 percent of the time or more.
- Therefore, a stand-alone system such as a micro-hydropower system should be designed according to the flow that is available year-round; this is usually the flow during the dry season.

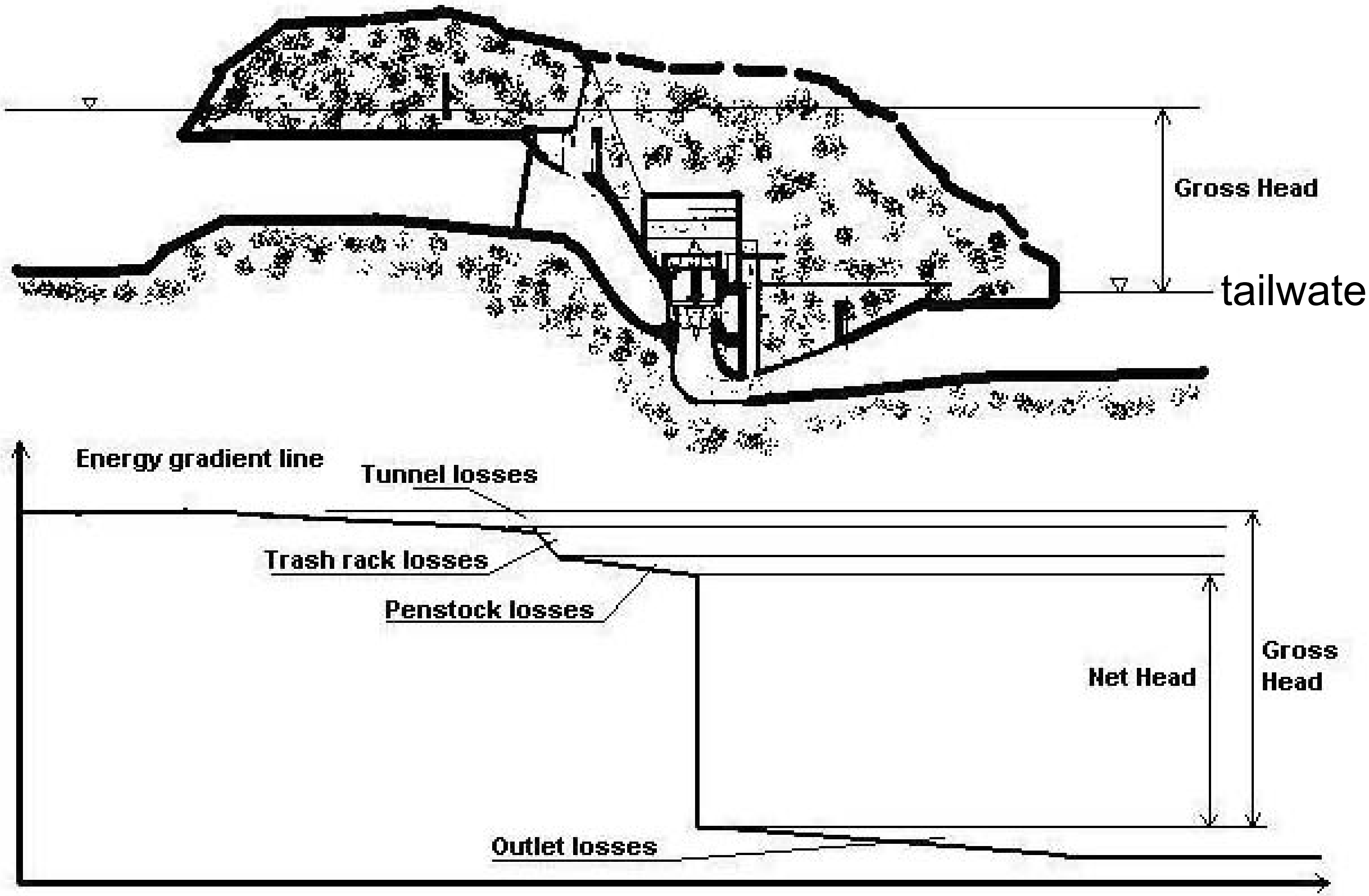
Some flow definitions

- **Reserved flow:** it is the minimum flow required to avoid aquatic life damage in the water stream
- **Firm flow:** The firm flow is defined as the flow being available X % of the time, where X is a percentage specified by the user and usually equal to 95%.

Hydraulic Head

- **GROSS HEAD** of a hydropower facility is the difference between headwater elevation and tailwater elevation.
- **NET HEAD** is the effective head on the turbine and is equal to the gross head minus the hydraulic losses before entrance to the turbine and outlet losses

Net Head


Gross Head
tailwater
Energy gradient line
Tunnel losses
Trash rack losses
Penstock losses
Net Head
Gross Head
Outlet losses

Hydraulic Losses

- Friction losses
- Intake losses
- Trash racks losses
- Transitions losses

Friction Head Losses – Closed Pipe

$$S = \frac{10.29 \cdot n^2 \cdot Q^2}{D^{5.333}}$$

- Where:
  - S is the hydraulic gradient or head loss by linear meter (hf/L).
  - Q is the channel discharge (m^3/s)
  - n is the Manning roughness coefficient

Kind of pipe	n
Welded steel	0.012
Polyethylene (PE)	0.009
PVC	0.009
Asbestos cement	0.011
Ductile iron	0.015
Cast iron	0.014
Wood-stave (new)	0.012
Concrete (steel forms smooth finish)	0.014

Friction Head Losses – Open Channel

$$Q = \frac{1}{n} \cdot \frac{A^{5/3} S^{1/2}}{P^{2/3}}$$

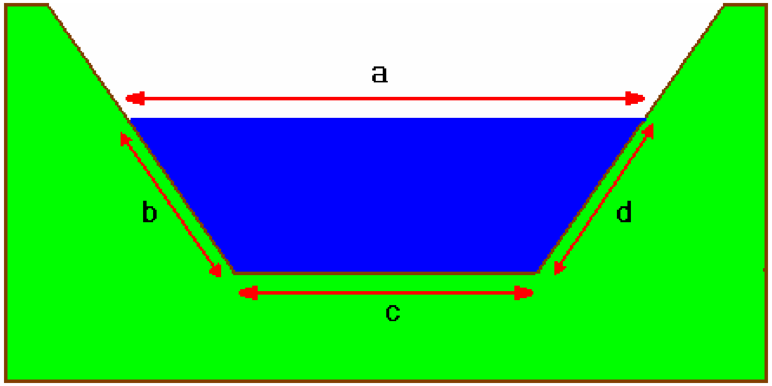
- Where:
  - S is the hydraulic gradient or head loss by linear meter (hf/L).
  - Q is the channel discharge (m^3/s)
  - P is the wetted perimeter (m)
  - A is cross-sectional area of the pipe (m^2), and
  - n is the Manning roughness coefficient

Kind of pipe	n
Welded steel	0.012
Polyethylene (PE)	0.009
PVC	0.009
Asbestos cement	0.011
Ductile iron	0.015
Cast iron	0.014
Wood-stave (new)	0.012
Concrete (steel forms smooth finish)	0.014

Wetted Perimeter

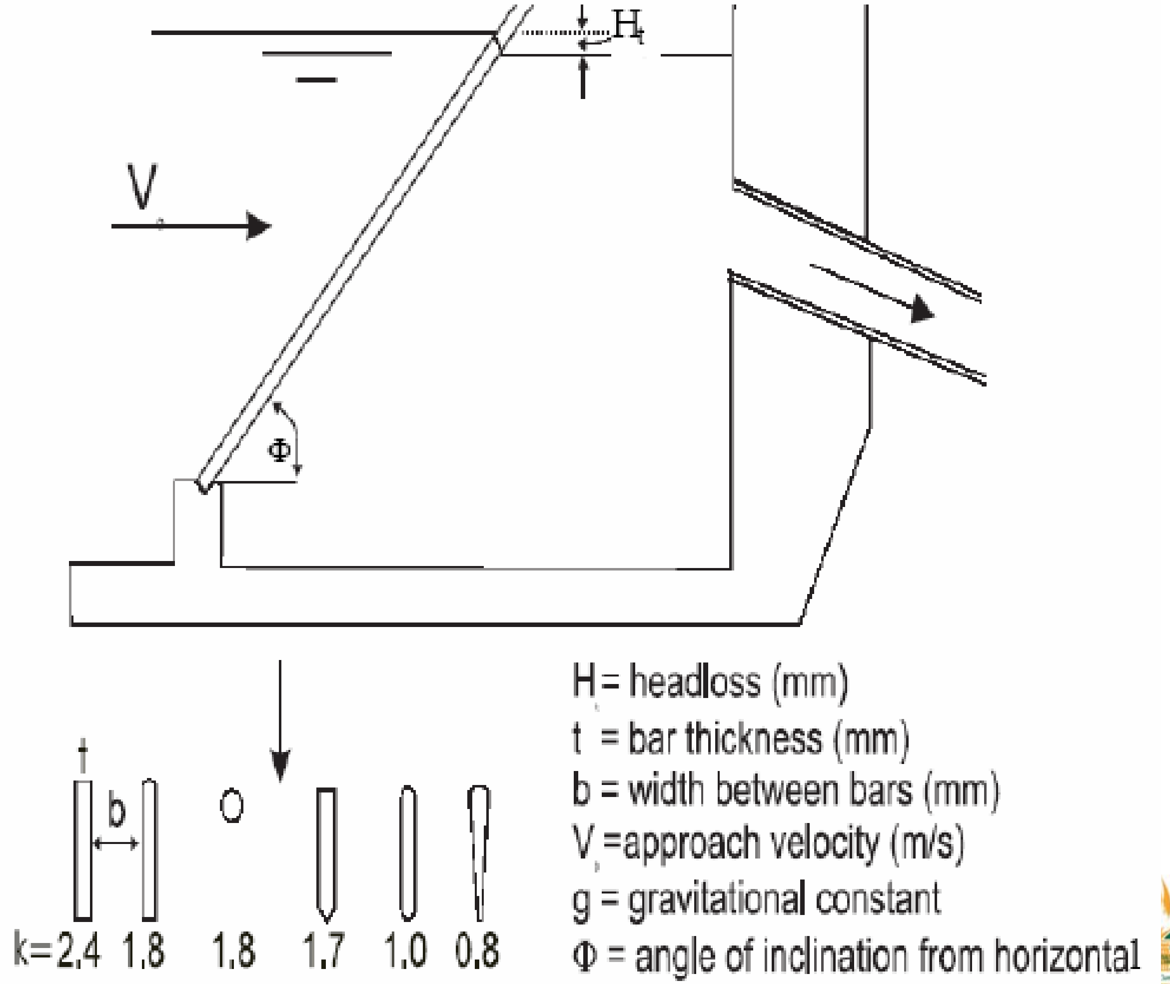
- The wet perimeter is as it sounds, the perimeter of the cross sectional area that is "wet".

- For the figure shown P= a+b+c+d



Trash rack losses

$$h_t = Kt\left(\frac{t}{b}\right)^{4/3}\left(\frac{V_0^2}{2g}\right)\sin\Phi$$

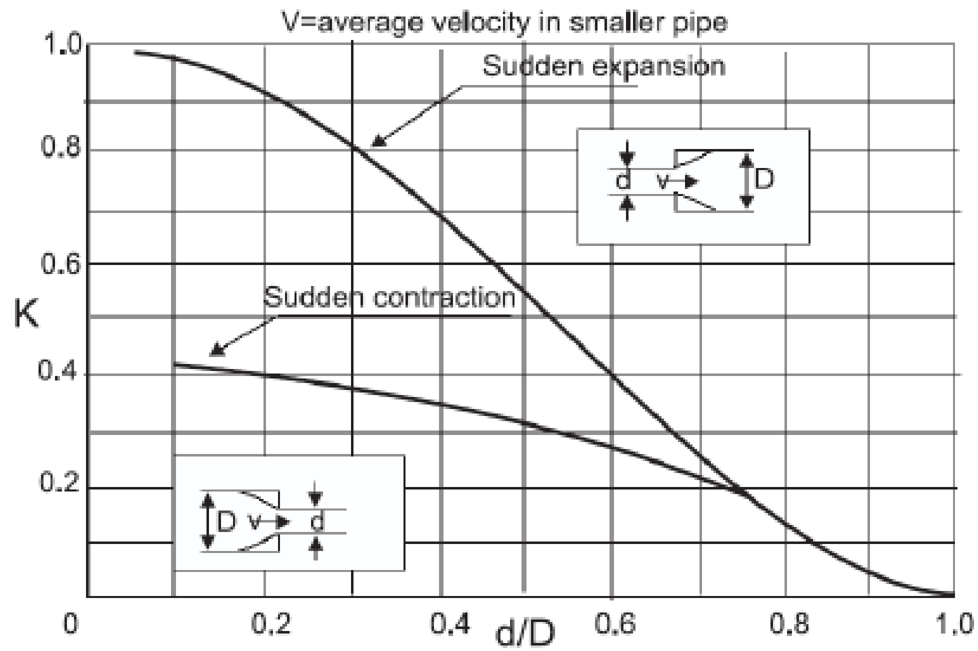


Source: European Small Hydropower Association

Head Loss by Sudden Contraction or Expansion

$$h_c = K_c \cdot \left(\frac{V_2^2}{2g}\right)$$

$$h_{ex} = \frac{(V_1 - V_2)^2}{2g} = \left(1 - \frac{V_2}{V_1}\right)^2 \frac{V_1^2}{2g} = \left(1 - \frac{A_1}{A_2}\right)^2 \frac{V_1^2}{2g} = \left(1 - \frac{d^2}{D^2}\right)\frac{V_1^2}{2g}$$

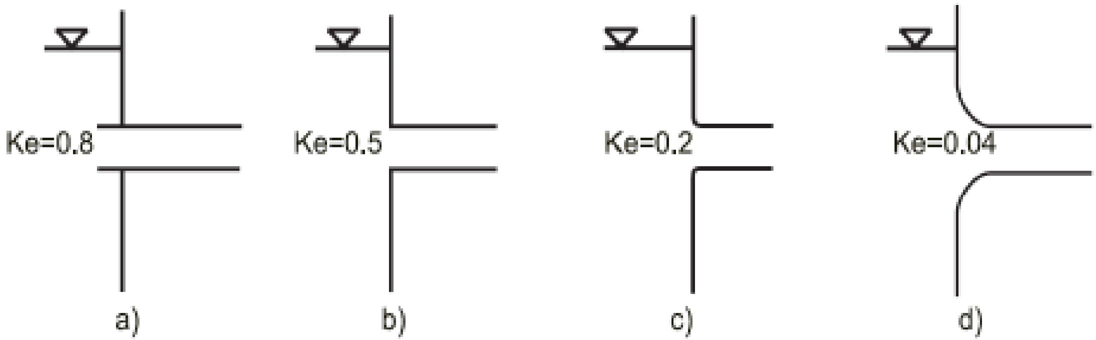


Source: European Small Hydropower Association

Head Loss in/out reservoir

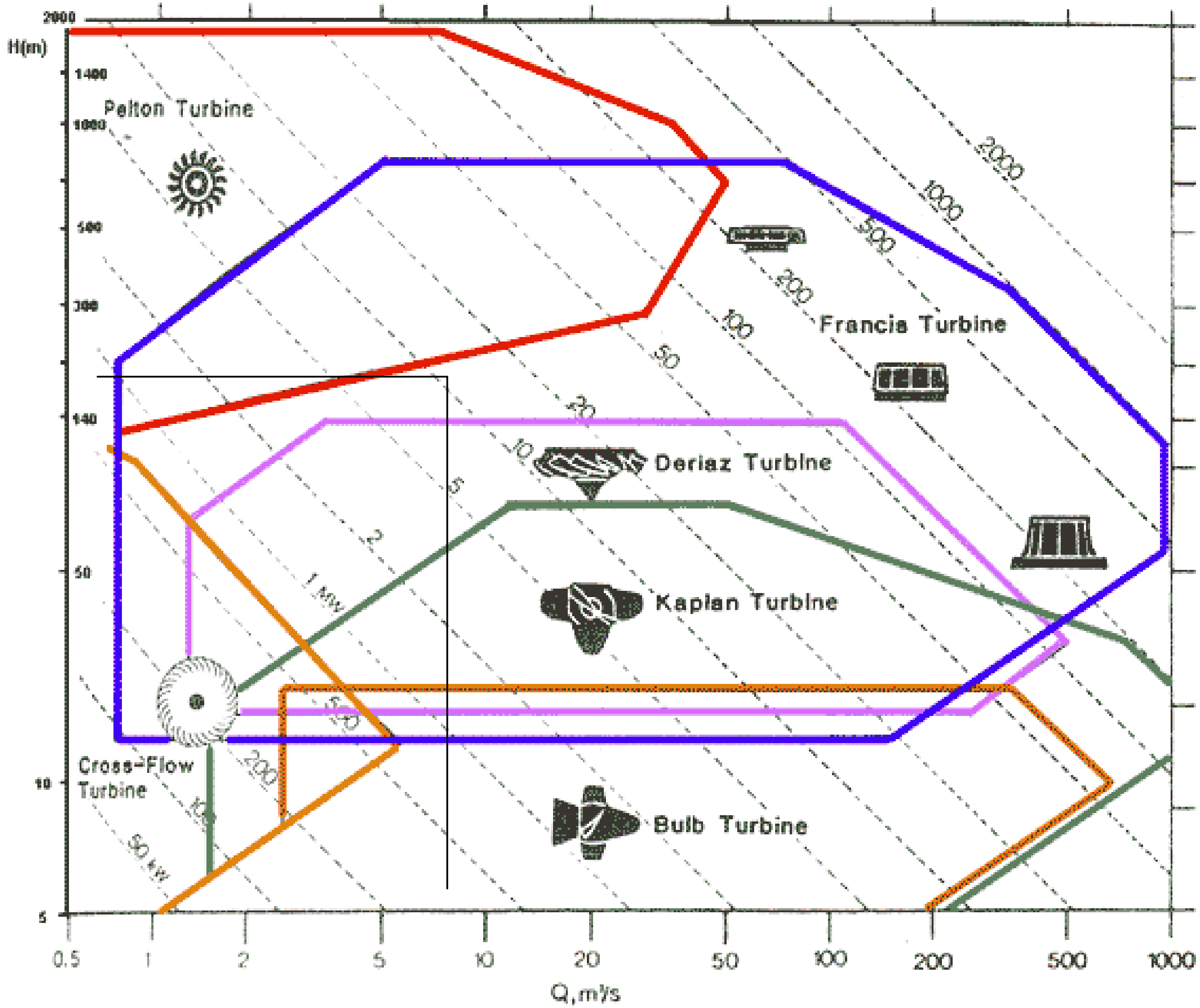
$$h'_{ex} = K'_{ex} \frac{V_1^2 - V_2^2}{2g}$$

- For a submerged pipe discharging in a reservoir –> $V_2=0$
- For the entrance from a reservoir to a pipe -> $V_1=0$

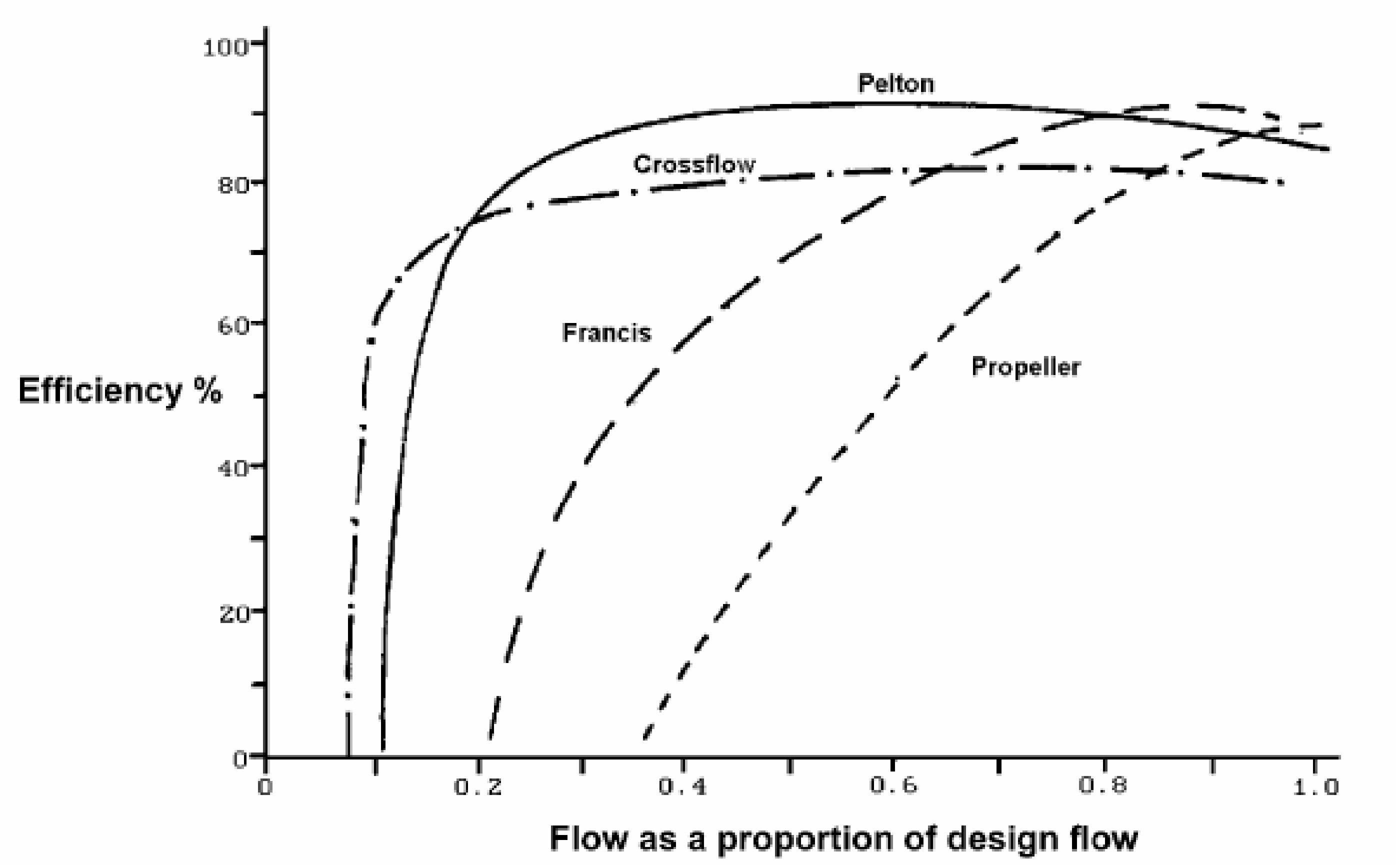


Source: European Small Hydropower Association

Turbine Selection



Turbine Efficiency

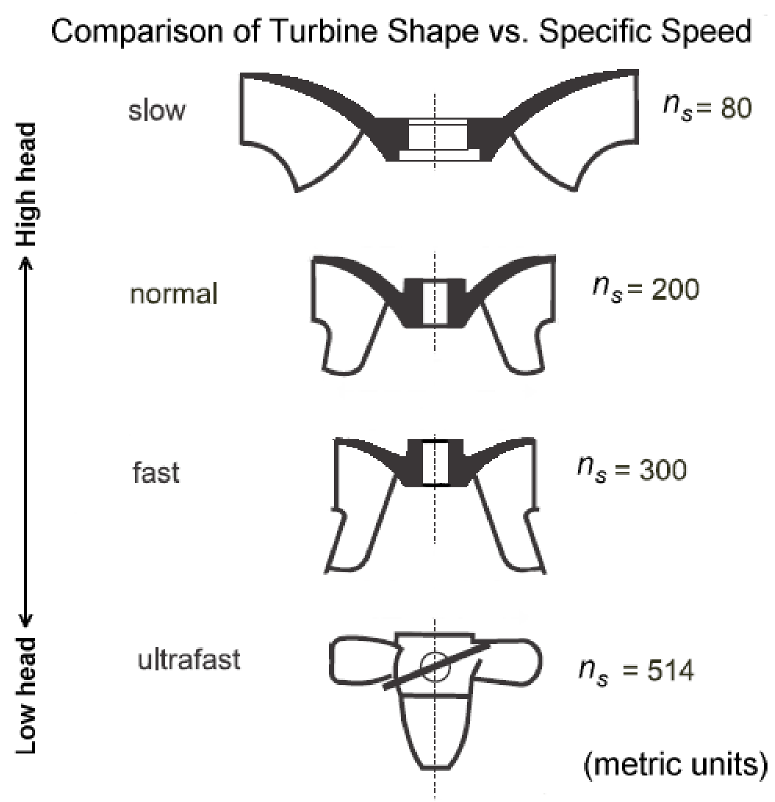


Source: Paish, O.;2002. Small hydro power: technology and current status. Renewable and Sustainable Energy Reviews, Vol 6 pp. 537–556

Turbines: Specific Speed

- The specific speed of a turbine (n_s) can be defined as the speed of an ideal, geometrically similar turbine, which yields one unit of power for one unit of head

- The specific speed of a turbine is given by the manufacturer and will always refer to the point of maximum efficiency



Source: Layman's Guidbook on how to develop a small hydro site

Specific Speed vs. Head

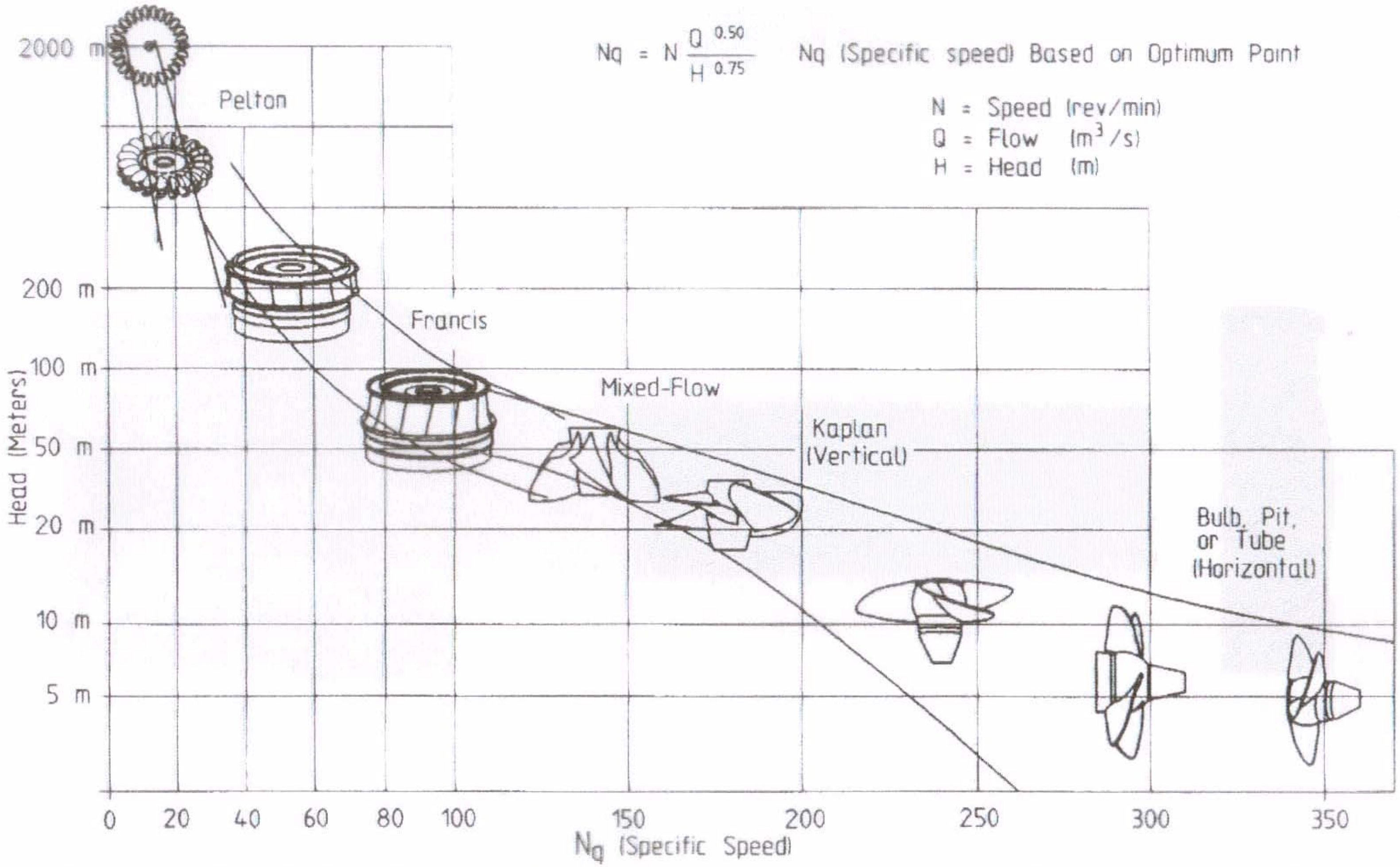
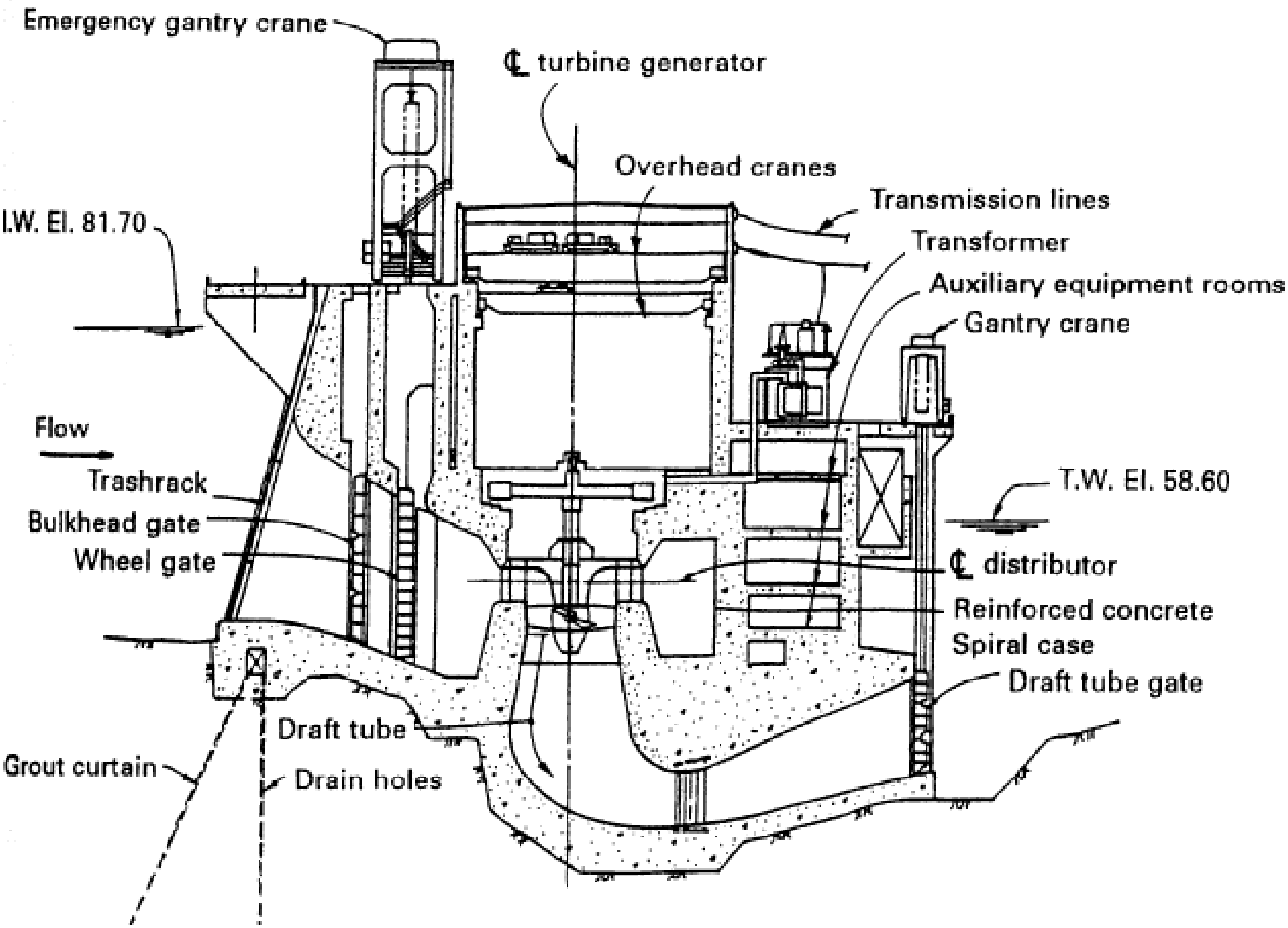


FIGURE 3-2: *Nq versus Head. This figure shows the various turbine types as a function of specific speed (Nq) and head. This figure should be used as a guideline, as there is overlap between the various turbine types with respect to their operating ranges*

Powerhouses

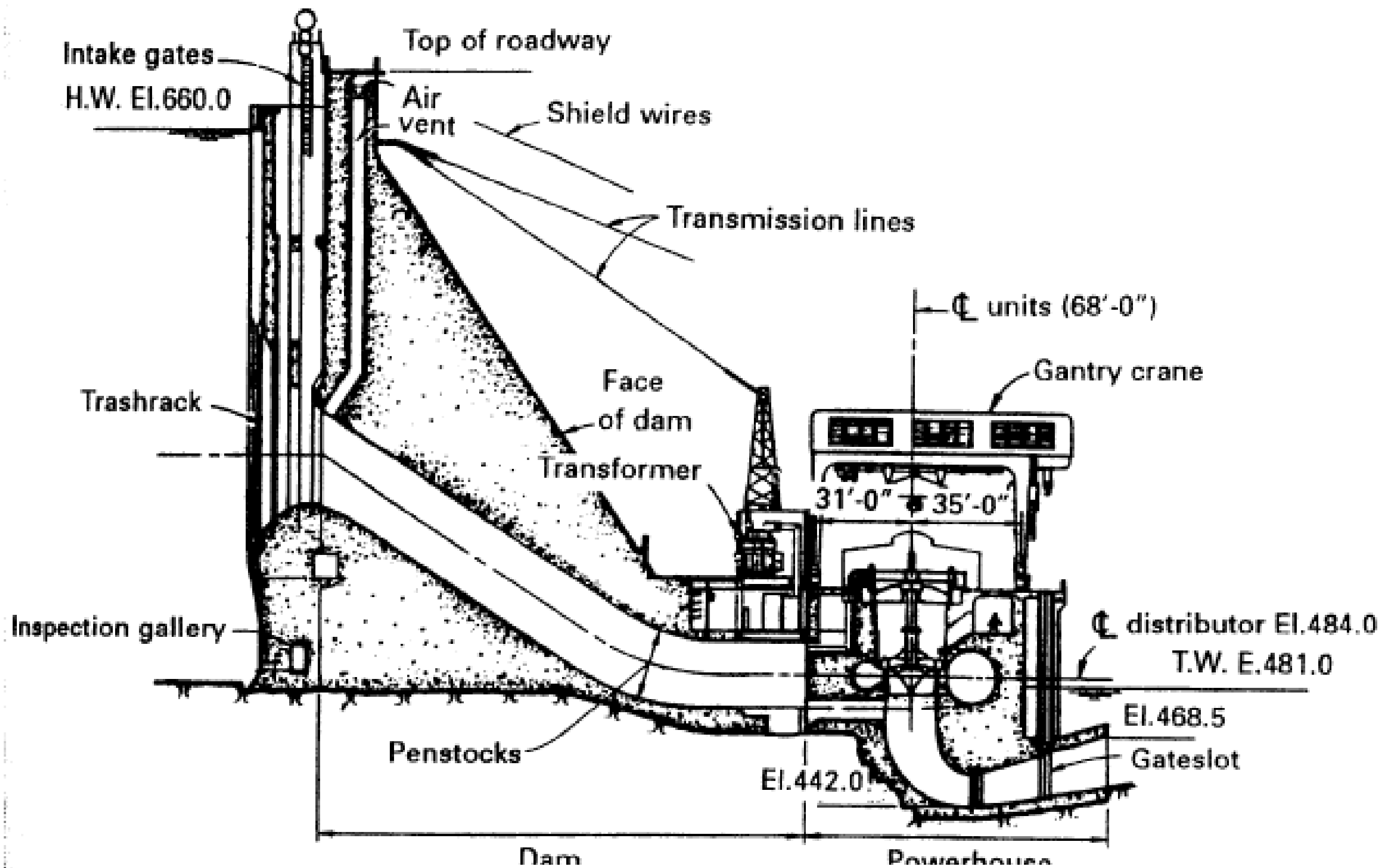
- The powerhouses contain the turbine, generator, control equipment, transformers and supporting auxiliary equipment.
- Below the turbines are the draft tubes and their gates
- Types of powerhouses:
  - Integral intake powerhouse
  - Conventional surface powerhouse
  - Underground powerhouse

Integral Intake Powerhouse



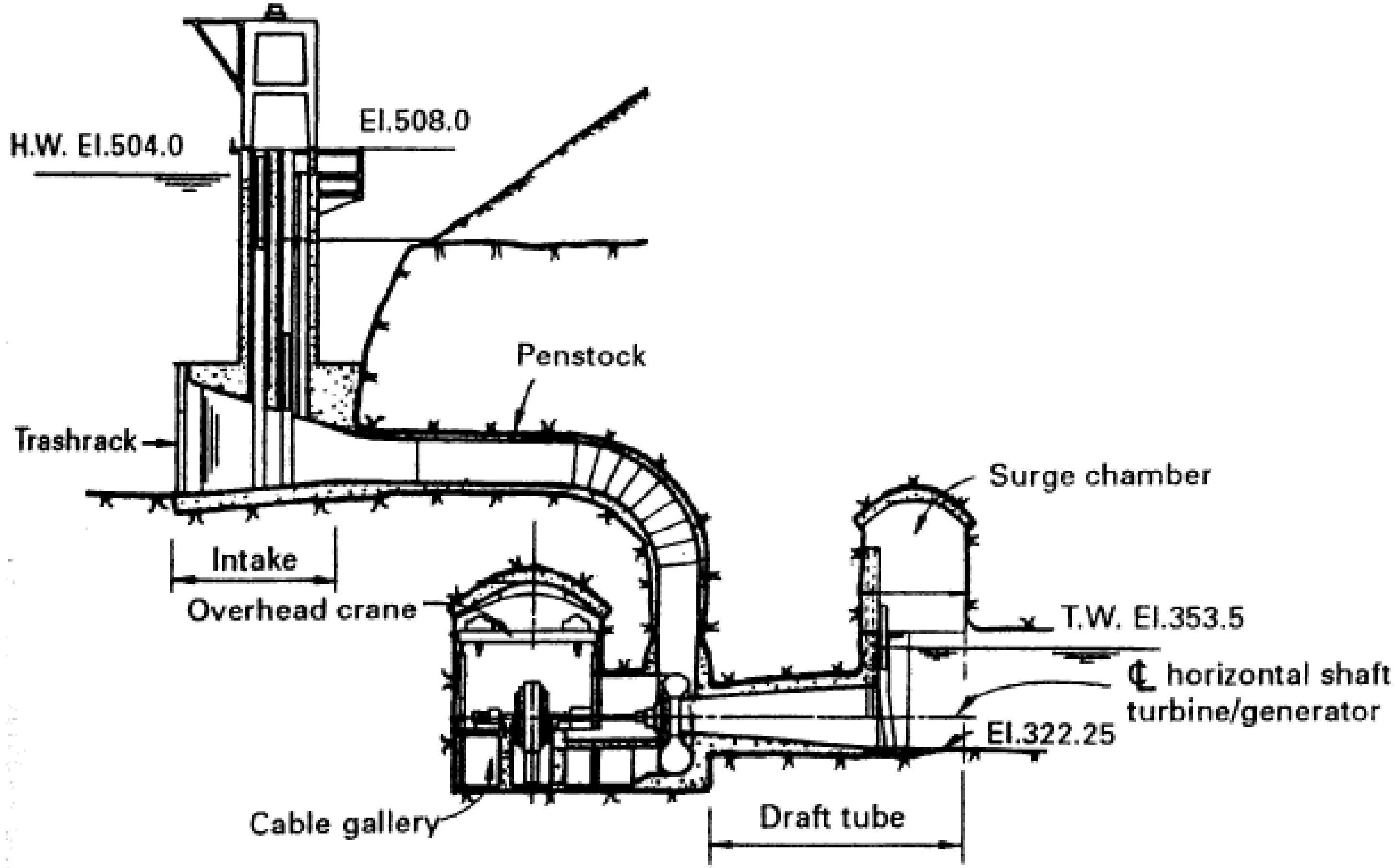
Source: Standard Handbook of Powerplant Engineering. Elliot, T. et al. 1997

Conventional Surface Powerhouse



Source: Standard Handbook of Powerplant Engineering. Elliot, T. et al. 1997

Underground Powerhouses



Source: Standard Handbook of Powerplant Engineering. Elliot, T. et al. 1997

Electrical Components

- Generator
- Transformer
- Transmission Lines

Small–Scale Hydropower Plants

- $P \leq 10$ MW (is the most widely accepted value worldwide)
- More environmental friendly
- Contribute to development of rural and poor regions.
- Reduction of greenhouse gas emissions (1 GWh electricity = reduction 480 tons of CO_2)

Small-Scale Hydropower Plants

- Small hydro (≤10 MW) contributed with over 40 GW of world capacity (2002)
  - Installed capacity of about 8 GW (2002) in Europe*.
  - In China**, the estimated installed capacity is over 26 GW (2002)
- Global small hydro potential is believed to be in excess of 100 GW.

*Defined as ≤ 10 MW

** Defined as ≤ 25 MW

Social & Environmental Impacts

- Population displacement
- Loss of social networks and changing way of living
- Noise pollution is negligible
- CO_2 free electricity production (for the power generation process only)
- Provision of water and sanitation services
- Dams can facilitate development of diseases

Environmental Impacts

- Visual impact
- Diversion of mountain streams
- Blockage of fish passage both upstream and downstream
- Storing water in reservoir may reduce the final flow as a result of evaporation
- Reduction in the flow of soil and nutrients

Environmental Impacts

- Pollution is stored in the reservoir
- Possible dam failure
- Loss of cultural heritage
- local increase in water vapor and some temperature effects
- Vegetation rotting under water produces methane -> emissions from northern reservoirs are typically about 5% of conventional power plants, while emissions from tropical reservoirs are typically 25%

Environmental Impacts

- High levels of total dissolved gas causes bubble disease in aquatic organisms and can lead to their death
- Erosion of riverbed
- Water turbidity
- Eutrophication
- Supersaturation

Environmental Impacts

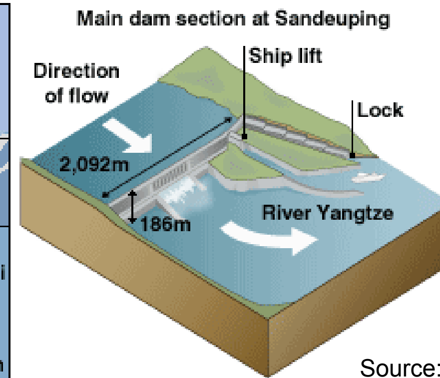
Events during construction	Persons or things affected	Impact	Priority
Geological Surveys	Wildlife	Noise	Low
Existing Vegetation Cutting	Forestry	Alteration of habitat	Medium
Enlargement of Existing Roads	General public	Creation of opportunities, alteration of habitat	Medium
Earth Moving	Site geology	Slope stability	Low
Tunnels Excavation	Site hydro-geology	Alteration of groundwater circulation	Low
Permanent Filling Material on Slopes	Site geology	Slope stability	Low
Embankment Realisation	Aquatic life, site hydro-morphology	Alteration of river hydraulic	Medium
Creation of Temporary Earth Accumulations	Site geology	Slope stability	Low
Temporary Displacement of Persons, Roads, Electric Lines	General public		Negligible
Realisation of Roads and Sheds for the Yard	Wildlife, general public	Visual intrusion, wildlife disturbance	Low
Water Courses Dredging	Aquatic ecosystem	Alteration of habitat	Medium
Temporary Diversion of Rivers	Aquatic ecosystem	Alteration of habitat	High
Use of Excavators, Trucks, Helicopters, Cars for the Personnel, Blondins	Wildlife, general public	Noise	High
Human Presence During the Works on Site	Wildlife, general public	Noise	Low

Environmental Impacts

Events during operation	Persons or things affected	Impact	Priority
Renewable Energy Production	General public	Reduction of Pollutants	High
Watercourses Damming	Aquatic ecosystem	Modification of habitat	High
Permanent Works in the Riverbed	Aquatic ecosystem	Modification of habitat	High
Diversion of Watercourses	Aquatic ecosystem	Modification of habitat	High
Penstocks	Wildlife	Visual intrusion	Medium
New Electric Lines	General public, wildlife	Visual intrusion	Low
Ripraps	Aquatic ecosystem, general public	Modification of habitat, visual intrusion	Low
Levees	Aquatic ecosystem, general public	Modification of habitat, visual intrusion	Low
Flow Rate modification	Fish	Modification of habitat	High
	Plants	Modification of habitat	Medium
	General public	Modification of recreational activities	
Noise from electromechanical equipment	General public	Alteration of life quality	Low
Removal of material from streambed	Aquatic life, General public	Improvement of water quality	high

Three Gorges Dam

- **Type:** Concrete Gravity Dam
- **Cost:** Official cost $25bn - actual cost believed to be much higher
- **Work began:** 1993
- **Due for completion:** 2009
- **Power generation:** 26 turbines on left and right sides of dam. Six underground turbines planned for 2010
- **Power capacity:** 18 GW
- **Reservoir:** 660km long, submerging 632 sq km of land. When fully flooded, water will be 175m above sea level
- **Navigation:** Two-way lock system became operational in 2004. One-step ship elevator due to open in 2009.
- **Dam:**185m high, 2,309m
- **Electricity production:** 3% of the electricity production capacity in 2006



Source: BBC, 2006

Three Gorges Dam

- 18 GW of electricity capacity installed that will generate the equivalent of roughly 18 coal power stations or 11,000 barrels of oil per hour
- The dam could potentially reduce China's annual coal consumption by 40 to 50 million tons
  - This will reduce the discharge of 2 million tons of sulfur dioxide and 10,000 tons of carbon monoxide per year

Three Gorges Dam example

- The primary aims of the dam are to alleviate flooding on the Yangtze River and generate power.
- At least 1 million people are being relocated to make way for the project.
- More than 1,200 towns and villages will disappear under its rising waters
- Those made homeless by the dam are being moved to new townships.

Source: BBC, 2006

Three Gorges Dam

- The 600 km long reservoir will inundate some 1,300 archeological sites and alter the legendary beauty of the Three Gorges

- Despite the amount of effort that has gone into the dam, critics are sceptical that it will adequately control flooding and say silting may eventually clog up its turbines.

Source: BBC, 2006

A billboard in the port of Wushan shows the height that the water will reach, ultimately submerging all of its wharf facilities.

Three Gorges Dam

- The reservoir behind the dam is already polluted
- There are two hazards uniquely identified with the dam:
    - sedimentation modeling is unverified
    - the dam sits on a seismic fault