Renewable Energy & Hydroelectric Works

8th semester, School of Civil Engineering

2nd semester, Master's Programme "Water Resources Science & Technology"

Small Hydropower Plants

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Definition and classification of SHPPs

- To define a hydroelectric plant as **small**, the installed power capacity of the turbines must be within a certain limit, determined by the national legislation.
- This limit varies considerably globally, but the most common values are from 10 to 30 MW.
- For example, in Canada, China and New Zealand the limit is **50 MW**, in the USA and several South America countries it is **30 MW**, and in most EU countries and Greece it is **15 MW**.
- SHPPs can be further subdivided into **mini** (0.1-1 MW), **micro** (5-100 kW) and **pico** (<5 kW).

Storage facility

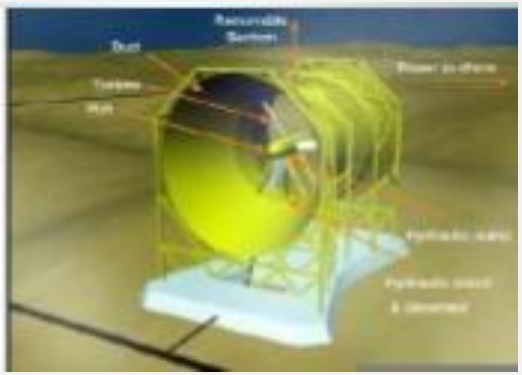
Settled downstream of large dams to take advantage of the environmental flow, which is released from an independent intake (e.g., bottom outlet)

Run-off-river

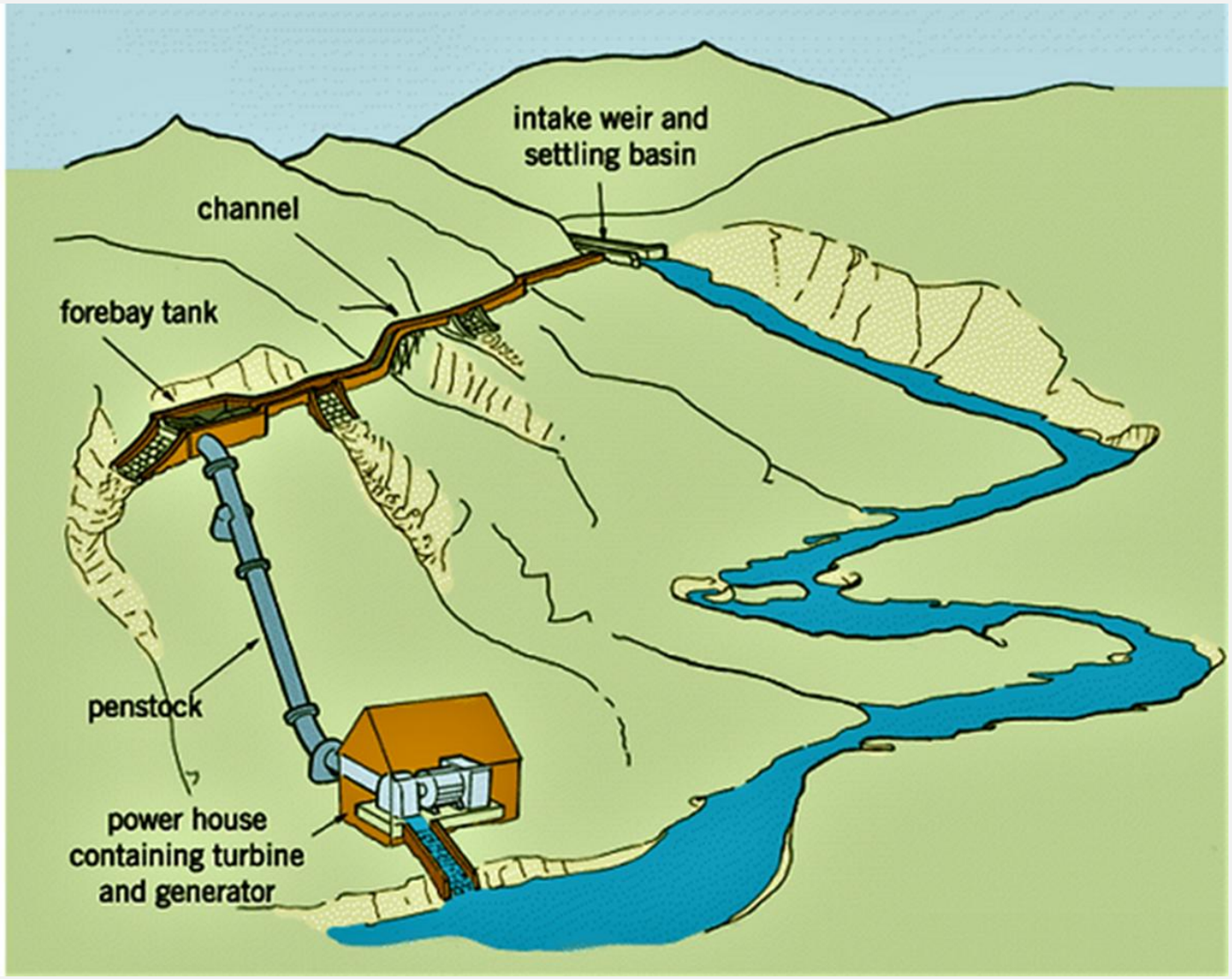
Utilizes the streamflow as it arrives, without the ability to store water. This is the most common type of SHPPs.

In-stream

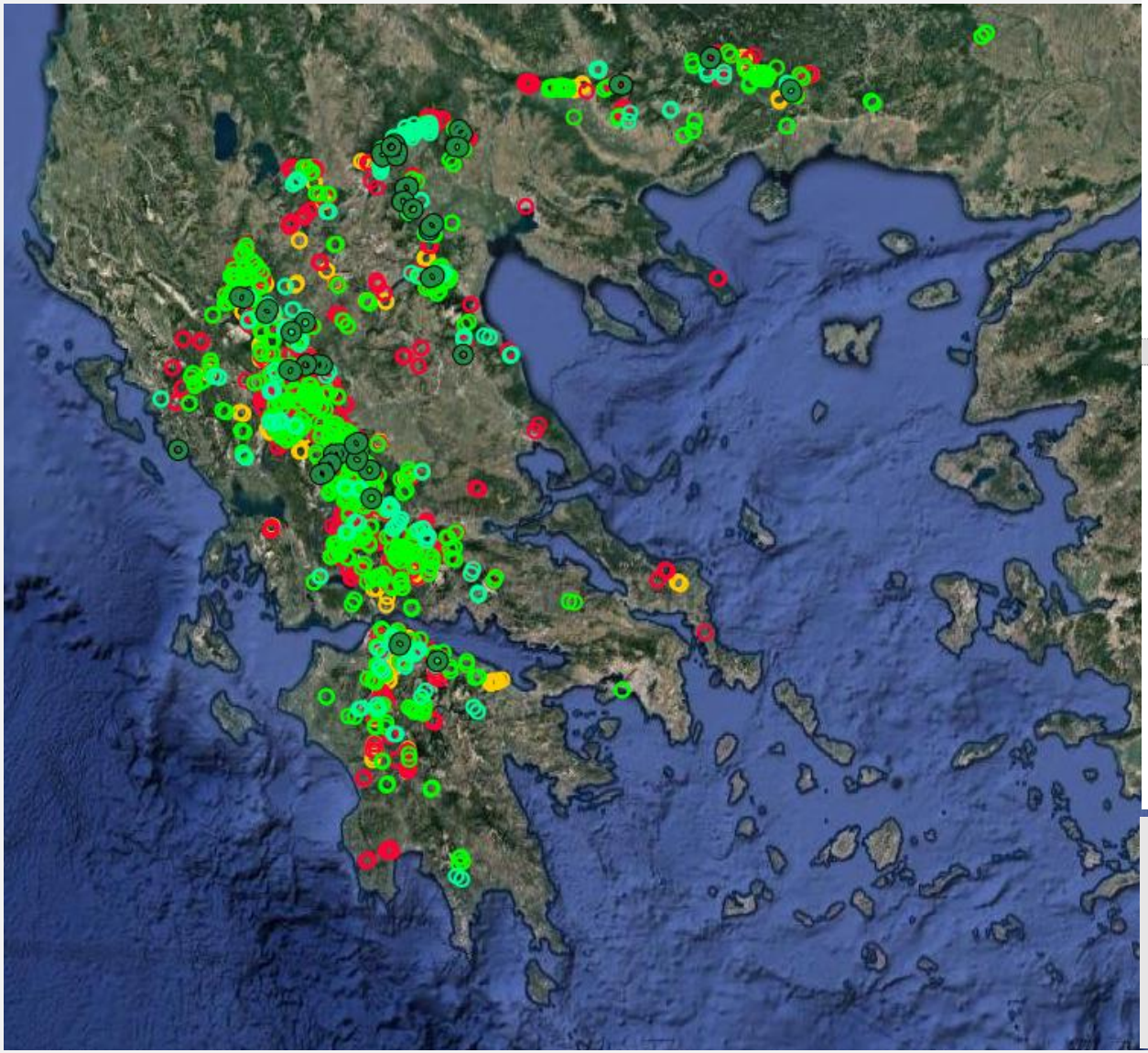
Utilizes the flow velocity to produce electric energy. Very few projects of this type exist.

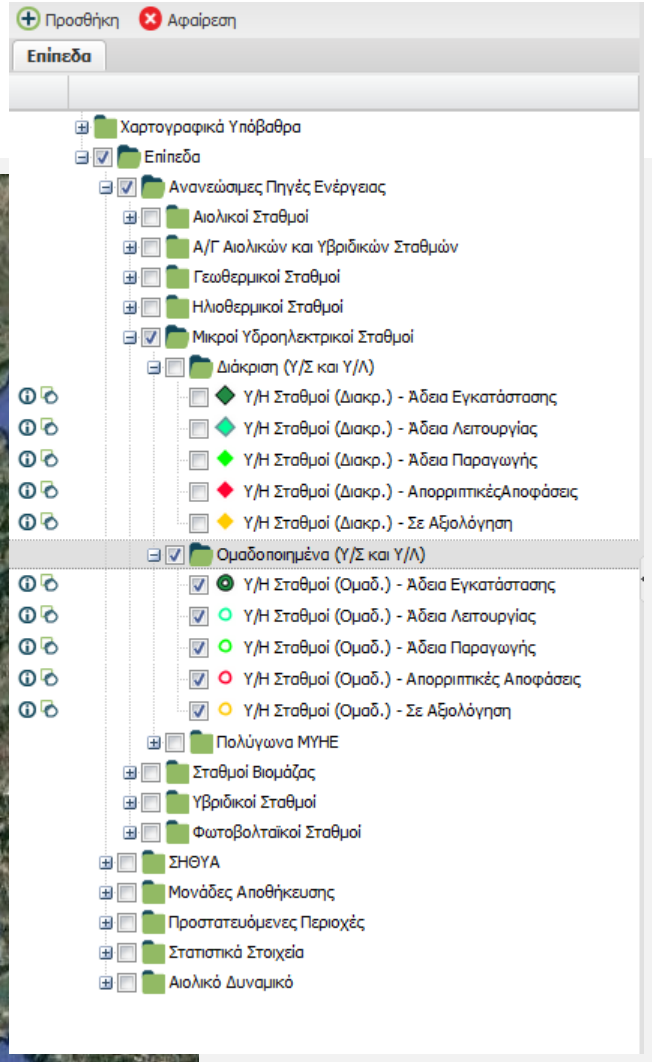


Typical layout of run-off-river plants



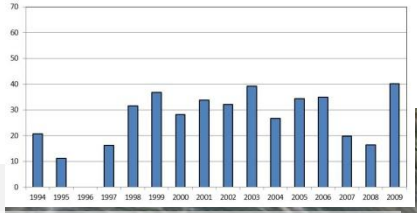
SHPPs in Greece





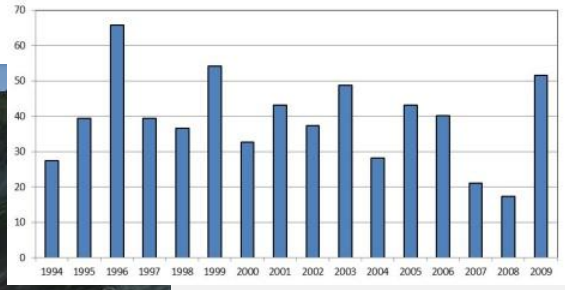
110 plants in operation, of total capacity 281 MW (annual energy production 125 GWh, year 2023), ~85% unexploited

Characteristic examples: Glafkos (Patra)



Mean annual diverted discharge (1998-2009) **31.1 hm³ (0.99 m³/s)**

Mean annual flow (1994-2009) **39.1 hm³ (1.24 m³/s)**



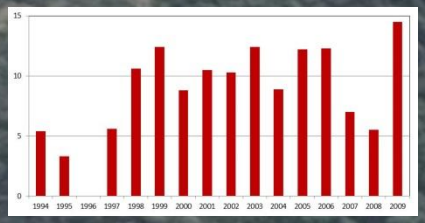
Water intake

River

Penstock
Head: 150 m

Mean annual discharge captured by the turbines (1998-2009): **82%**

Mean annual energy production (1998-2009) **10.4 GWh**



Mean capacity factor (1998-2009): **31%**

Patra's water supply

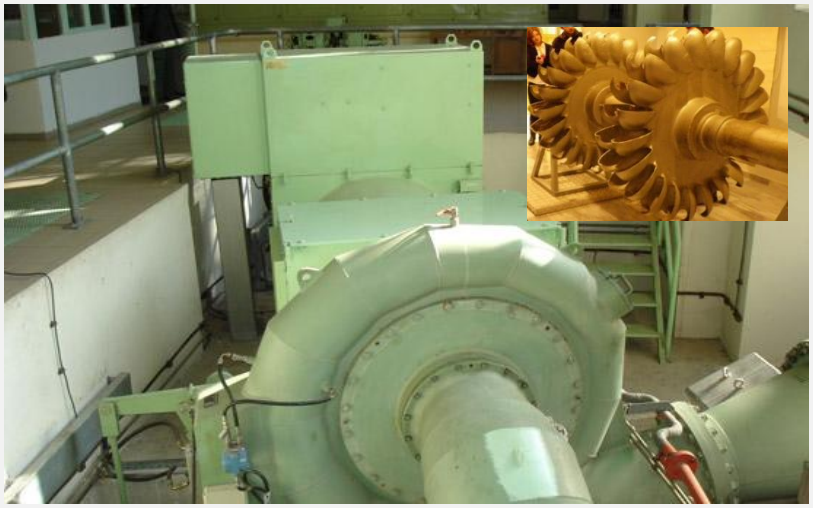
Total capacity: 3.8 MW (2.2 MW Francis, 1.6 MW Pelton)

Dam water intake

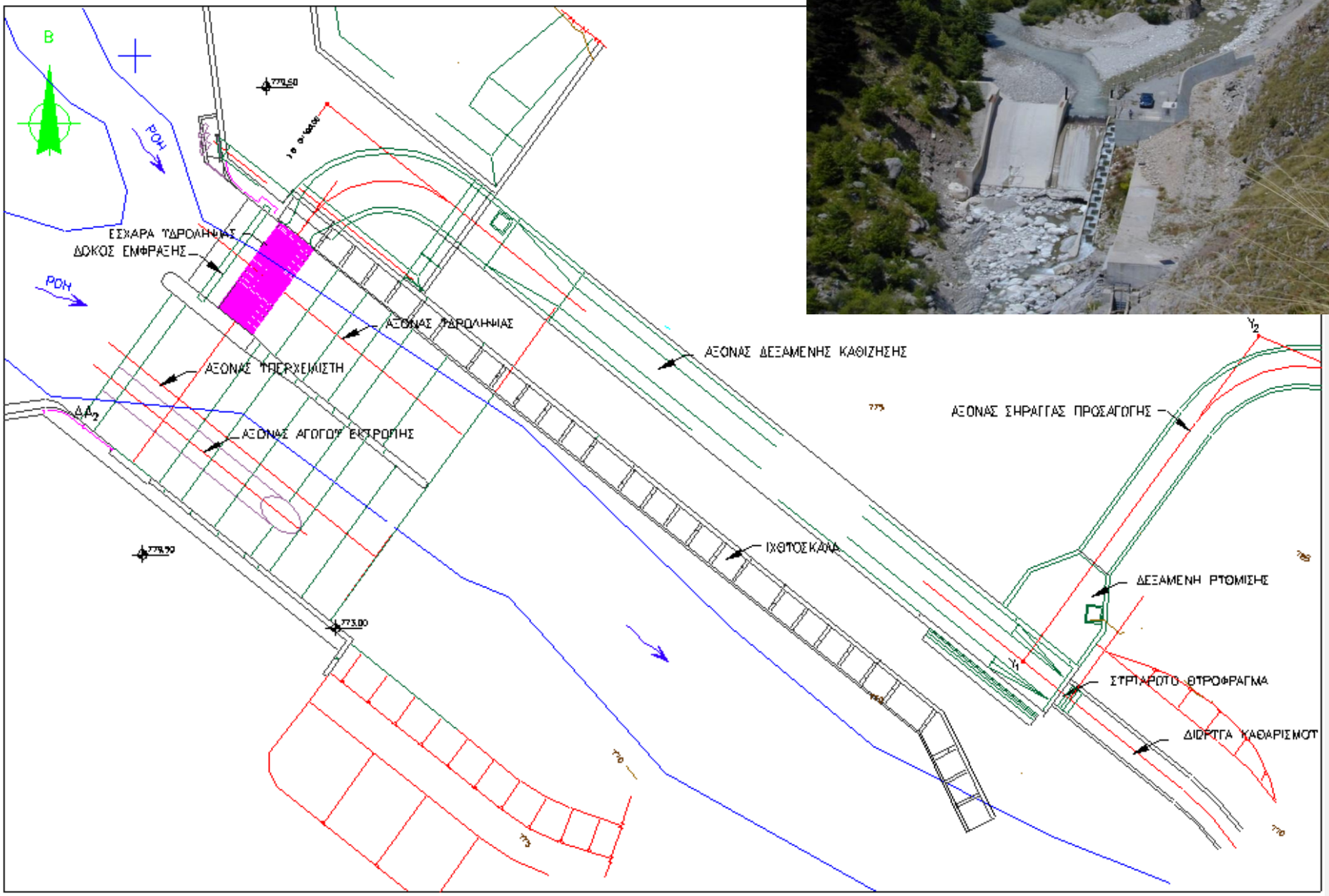
Sand trap – desilter – sedimentation tank

Penstock

Turbines



Characteristic examples: Theodoriana (Epirus)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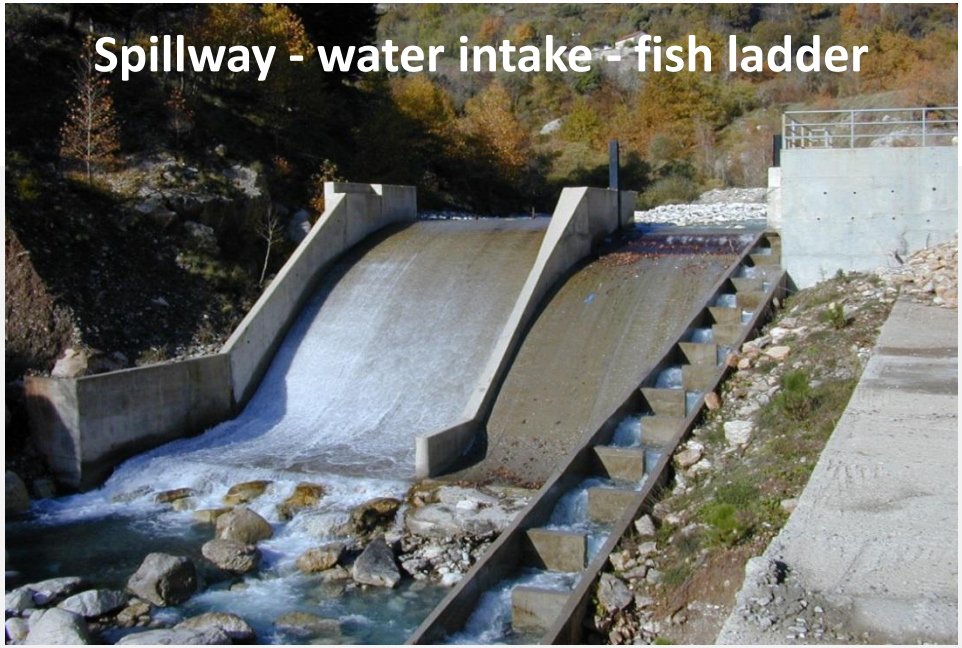
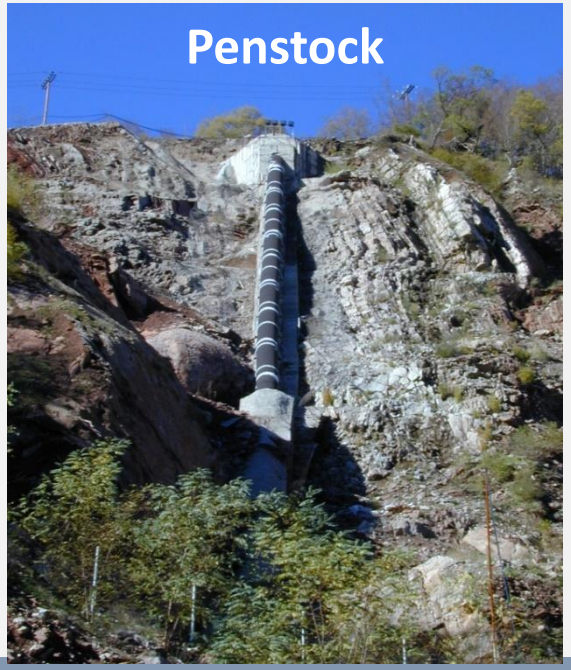

Spillway - water intake - fish ladder

Water intake

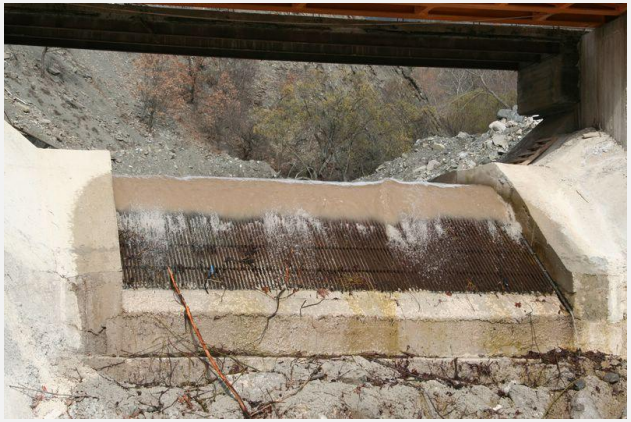

Penstock

Power house

Characteristic examples: Thermorema (Spercheios)

Desilter (sand traps)

Trash rack of water intake



Headwater channel - sand traps

Forebay tank

Penstock

Photos: ΔΕΛΤΑ Project

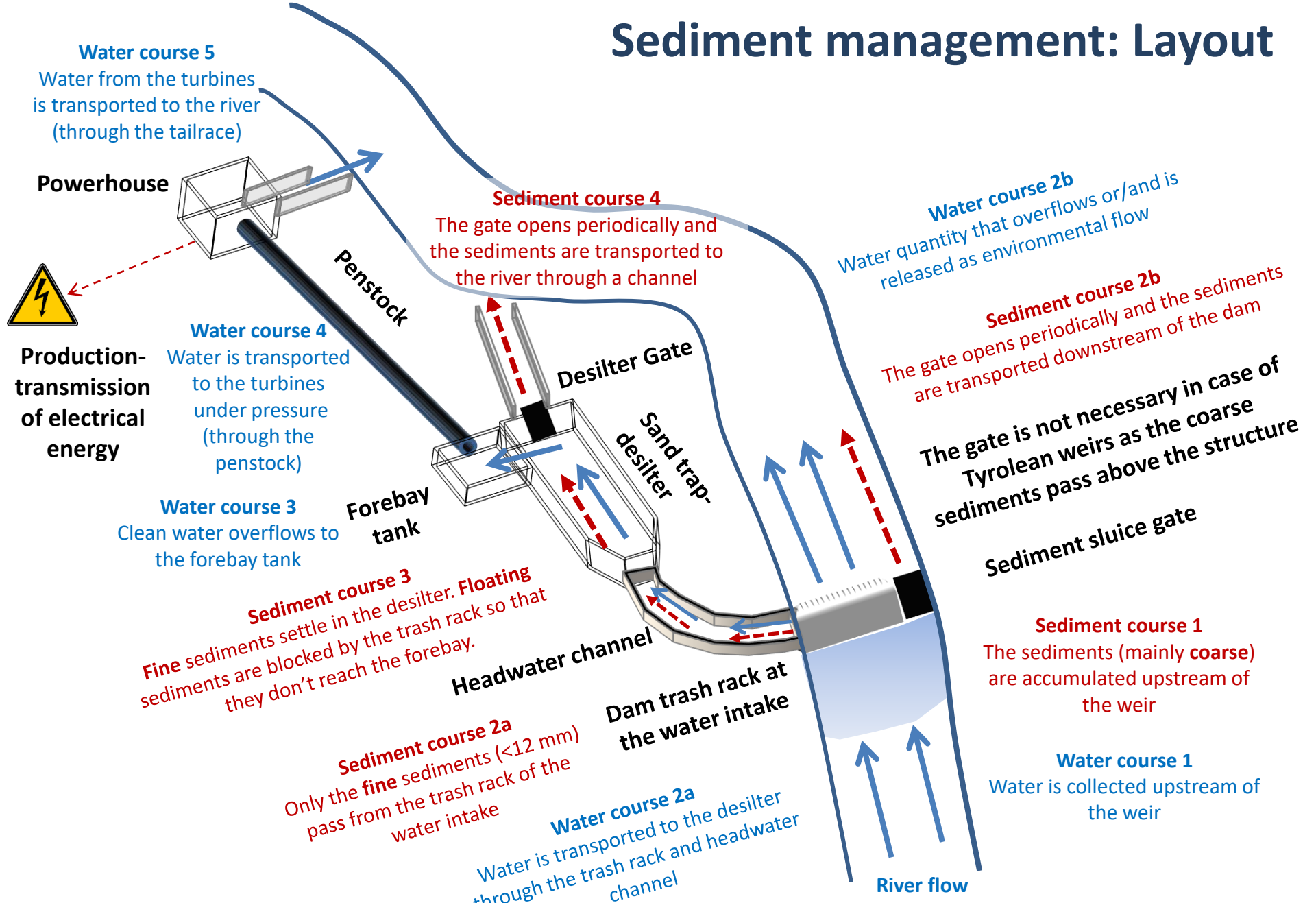
About sedimentation

Bed load: Mainly includes stony material, such as gravel and cobbles. These are transported on or near the bed of the river (continuously or intermittently), with velocities lower than the flow. Main movement mechanisms are sliding, rolling or hopping.

Suspended load: Mainly includes clay, silt (diameter < 6 mm) and sand. These are transported in the water body with the same velocity as the river flow.

Floating sediments: Leaves, branches, debris, garbage etc., that float on the river surface.

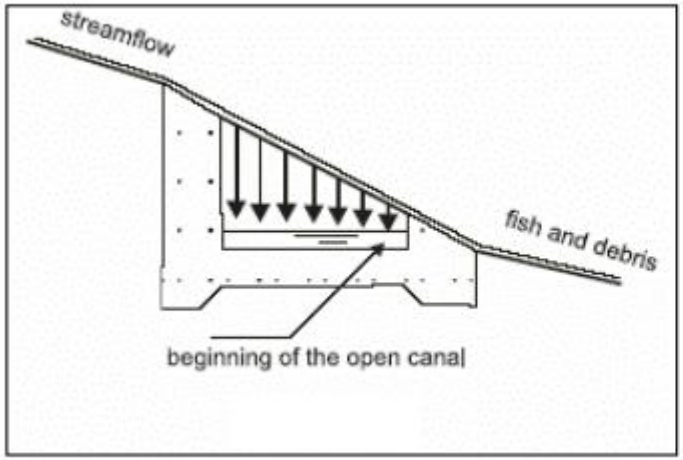
Sediment management: Layout

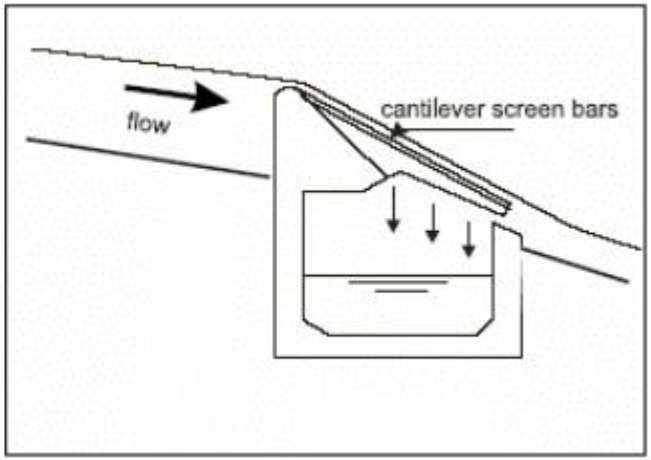


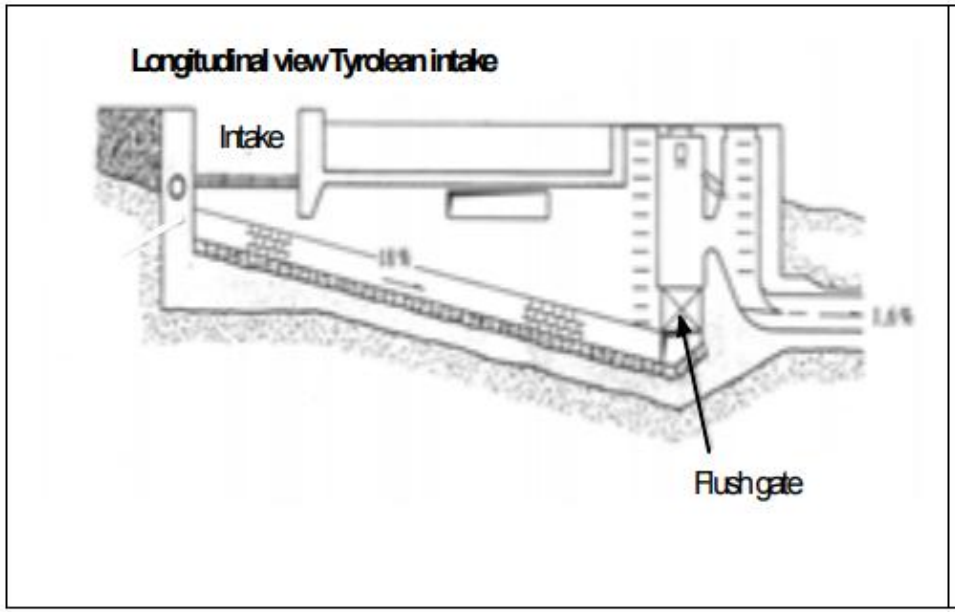
Drop intakes – Tyrolean weirs

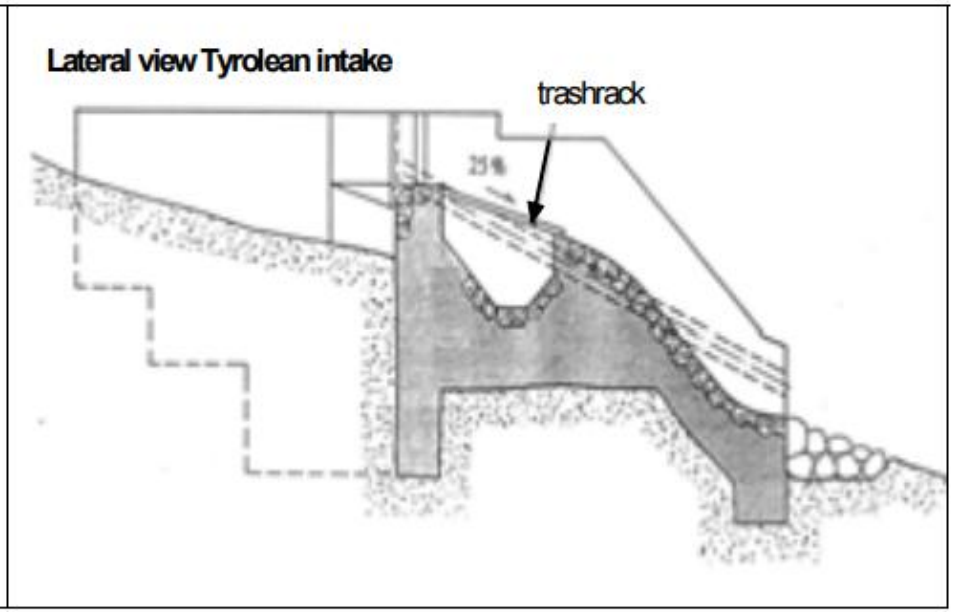
- **Tyrolean weir** is a water intake structure in which water is abstracted from the main flow through a trash rack (screen) over a gutter.
- The gutter is usually made of concrete and built into the river bed.
- The trash rack on the crest should slope downstream (15-30 degrees), to ensure adequate velocity and thus prevent sediment carried by the stream from blocking it.
- Through the gutter, water enters a pipeline, which drains into a sedimentation tank.
- Suitable for mountainous areas

Drop intakes – Tyrolean weirs

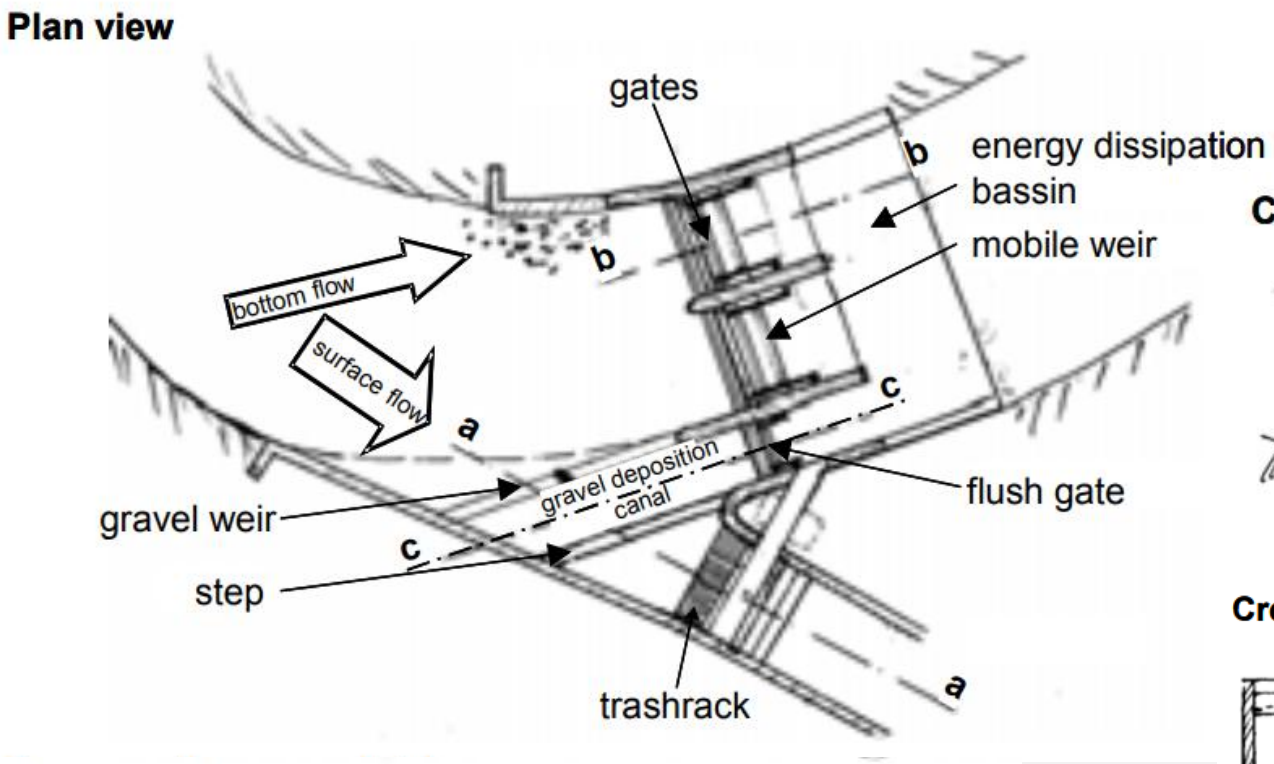


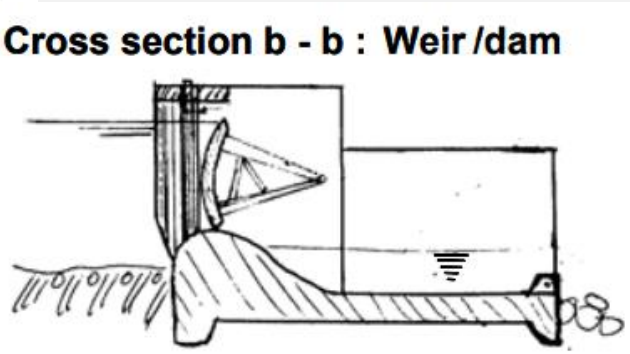


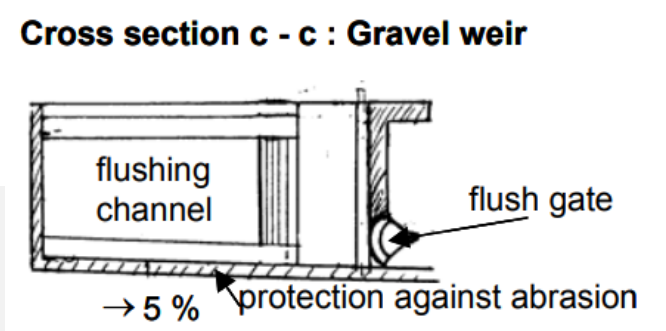


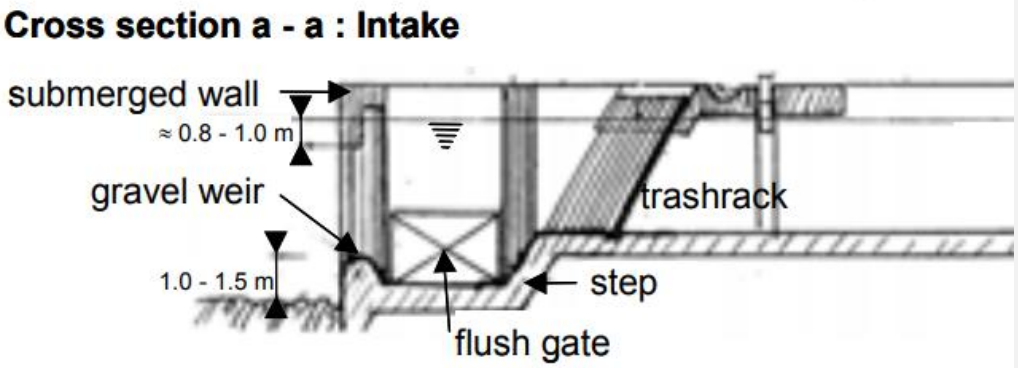


Lateral intakes





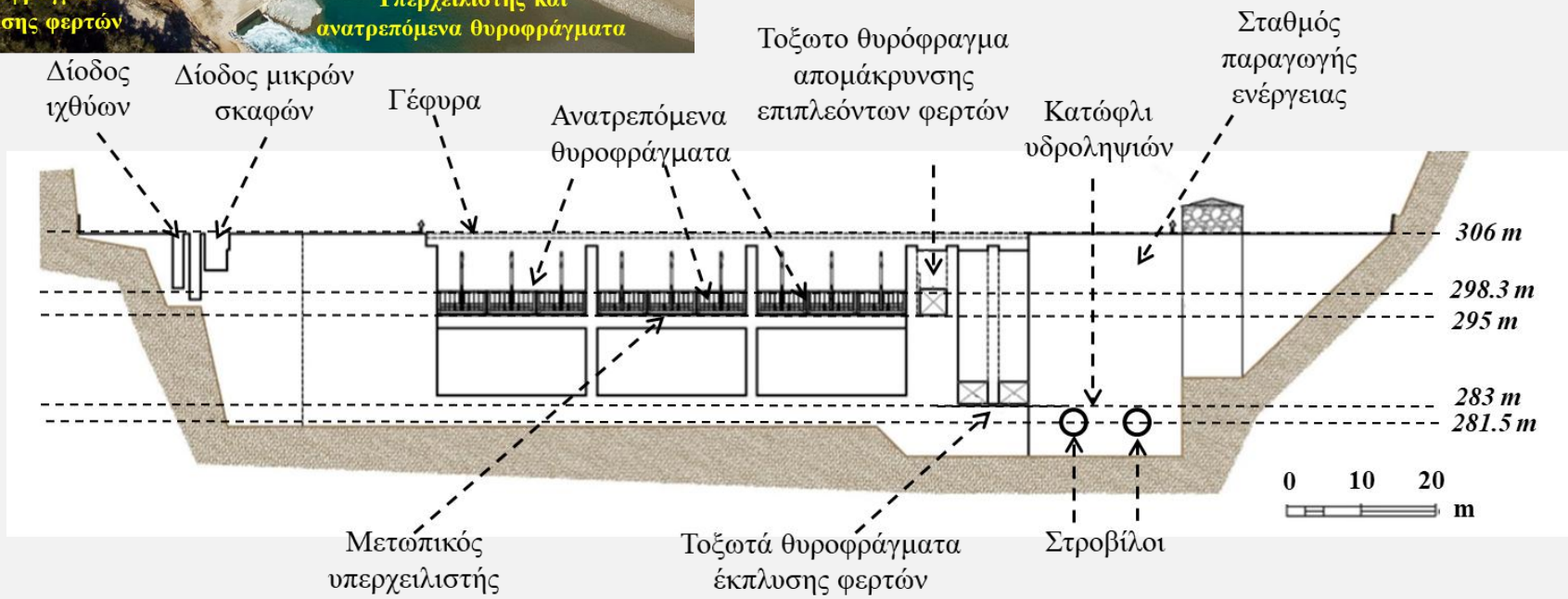




Source: Guide on How to Develop a Small Hydropower Plant, European Small Hydropower Association (ESHA), 2004

Characteristic examples: Dafnozonara (Achelous)

2 turbines Kaplan S-Type, power 5.93 MW (5-40 m^3/s)
Mean annual electric energy production 40 GWh



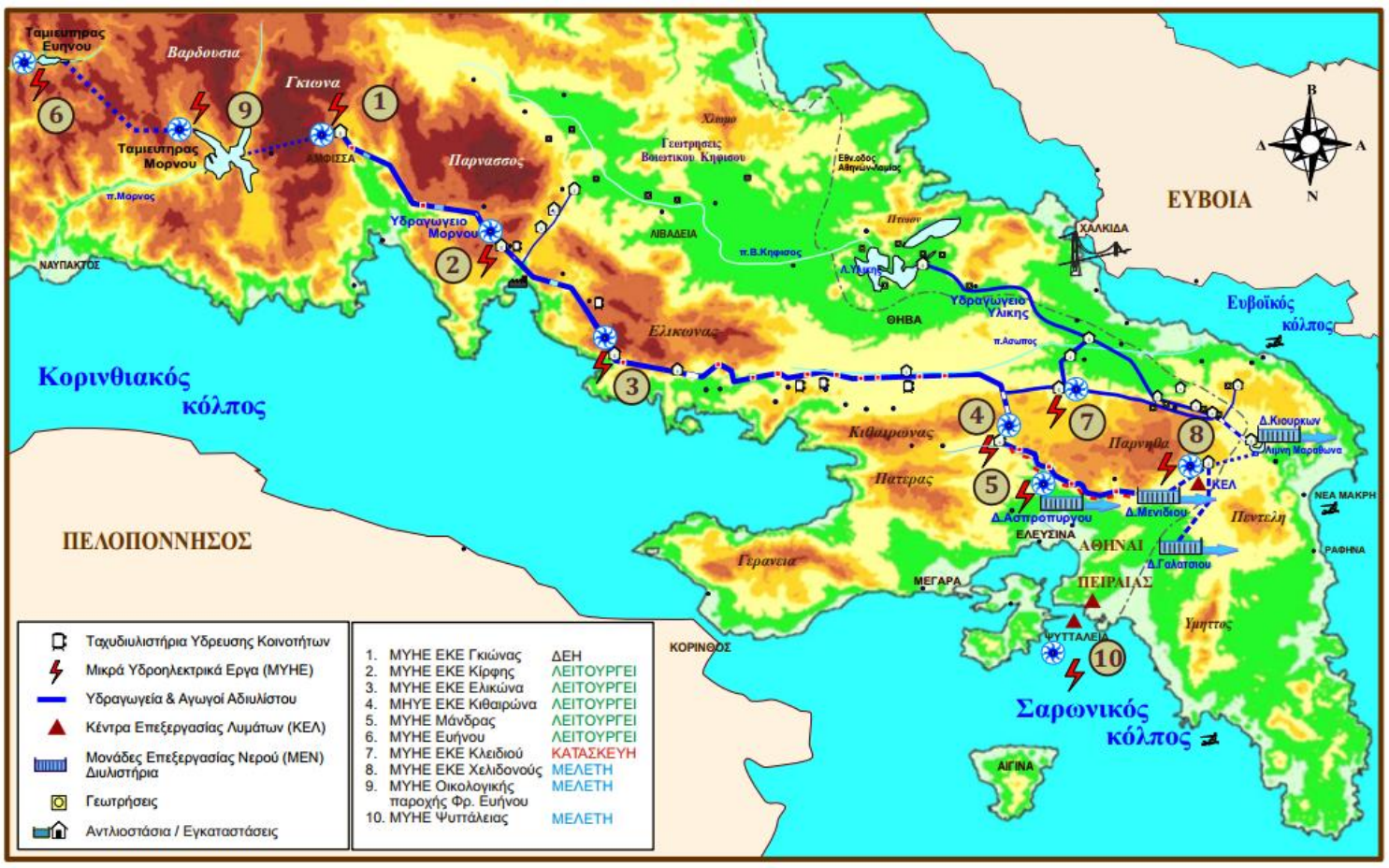
SHPPs as additions: Agia Varvara (Aliakmonas)

Source:
PPC Renewables

Constructed at the foot of the Agia Varvara regulatory dam, in 2008 (downstream of Aliakmon Hydropower Complex, operated by PCC). It exploits the environmental flow of the river (**4.5 m³/s**). It includes a Kaplan S-type horizontal-axis turbine of **23 m** head and **0.92 MW** capacity. The mean annual electricity production is about **4.5 GWh**.

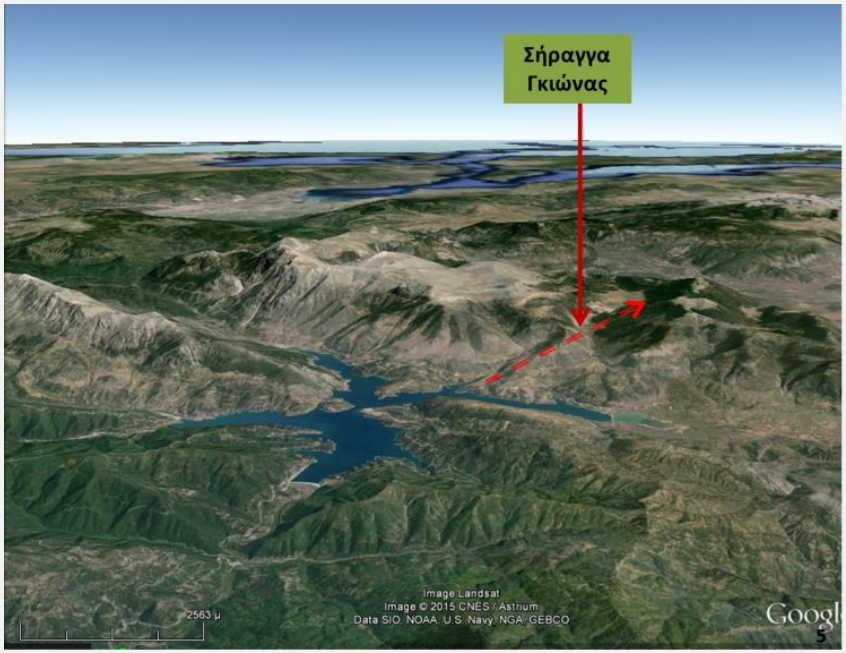
SHPPs as additions: Athens water supply system

EYDAP constructed several SHPPs along the aqueducts that convey the water to Athens. In each SHPP location, the water is diverted to a lateral canal where electrical energy is produced, and the water is then returned to the main canal.



Evinos dam: 820 kW
Kirfi: 760 kW
Elikonas: 650 kW
Kitheronas: 1200 kW
Mandra: 630 kW
Klidi: 590 kW

SHPPs as additions: Giona (Mornos aqueduct)

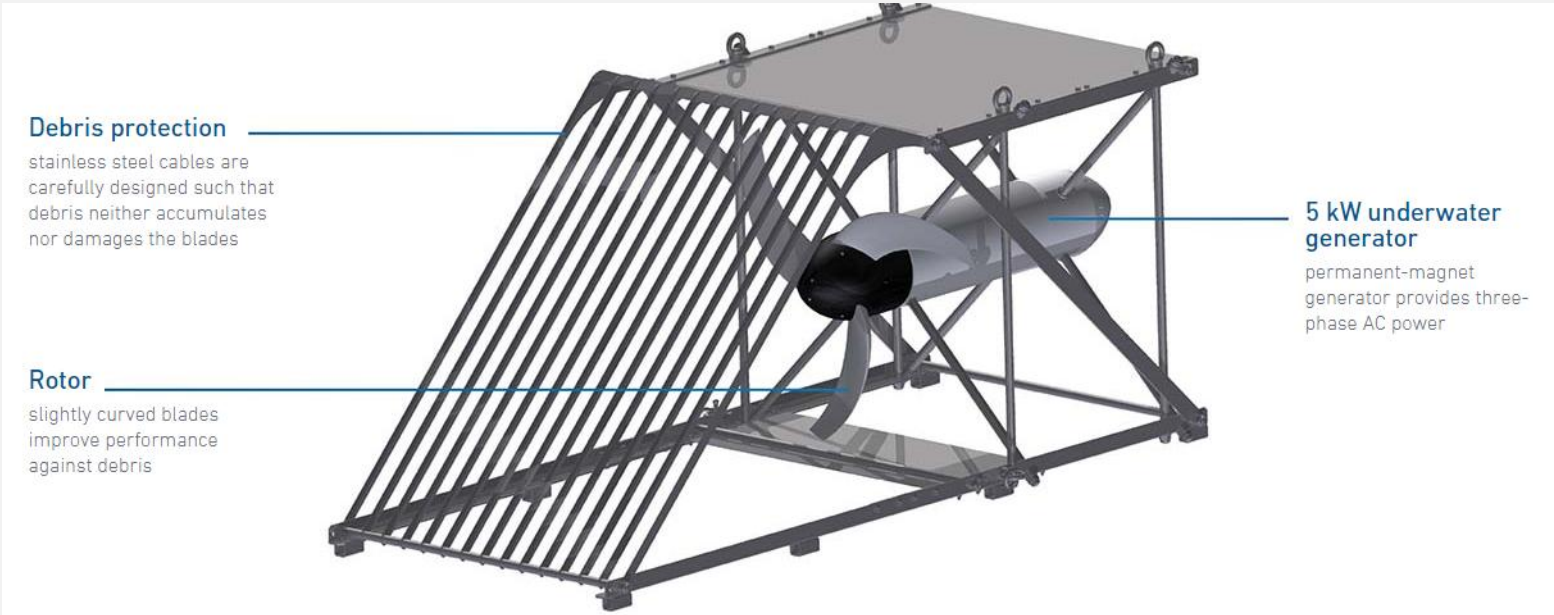


The largest SHPP across Mornos aqueduct is Giona, which operates since 1987. It is located near the city of Amfissa, belongs to the PPC and exploits part of the flow conveyed to Athens. The operational discharge fluctuates from 7.8 to 14.5 m^3/s, and the head from 30.0 to 66.1 m. The installed capacity is 8.67 MW, and the mean annual electrical energy production is about 34 GWh.

Small-scale in-stream projects

Smart free stream: **5 kW**

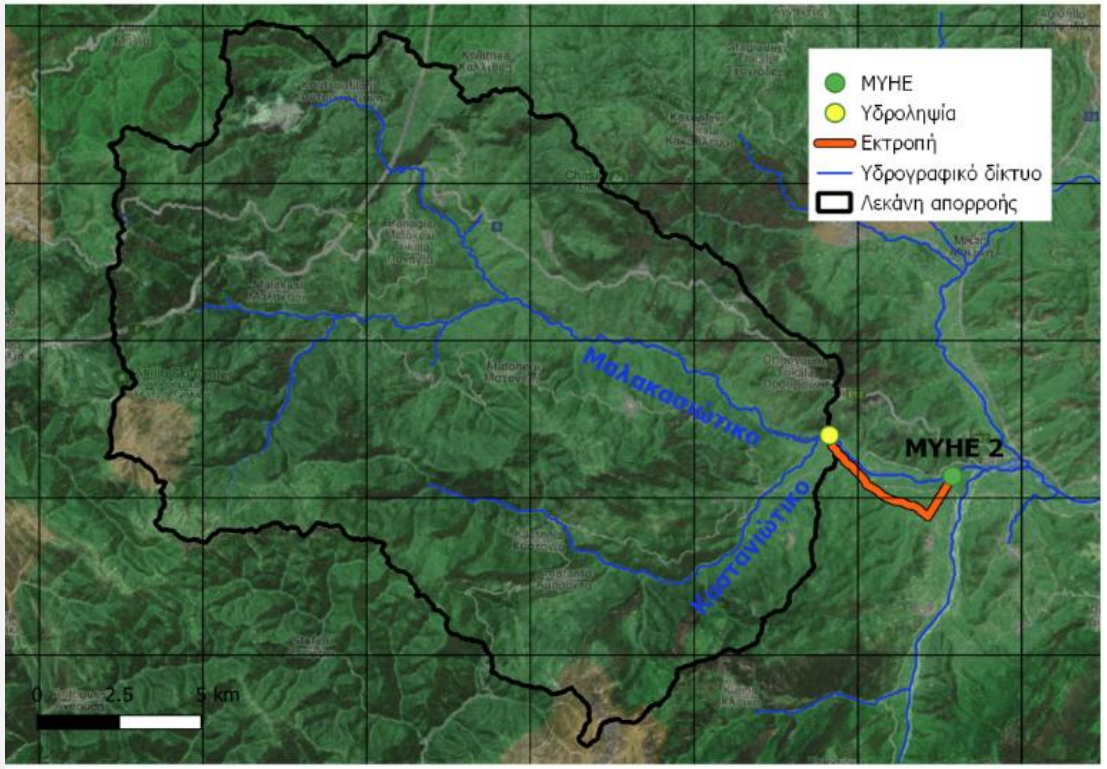
River current turbines



HydroQuest River: **80 kW**, Minimum water head: **4.2 m**, Nominal current flow velocity: **3.1 m/s**

Run-of-river plants: Layout objectives

- Maximization of discharge
  - Depends (but not exclusively) on the extent of the river basin area upstream of the intake
- Maximization of head → elevation difference between the intake and the outflow site
- Minimization of diversion length (part of it may be a free flow channel)
  - hydraulic losses along pressured pipes
  - cost of diversion works
  - impacts to river system
- Under several legal and environmental constraints



Run-of-river plants: Key design challenges

- **Intake systems**
  - Captures part of inflow, which is diverted to the conveyance system
  - Issues to concern: ecological flows, sediments, floods, fish passages
- **Water conveyance system**
  - Single pipe under pressure or combination of open flow channel (or tunnel), forebay and penstock (depends on relief, issue of cost)
  - Minimization of head losses across the penstock (function of length and diameter)
- **Turbines**
  - Usually mixing of two turbines (preferably of different capacity, to exploit as much as possible of inflow arriving at the intake)
  - Power production depends on highly varying flow conditions, also resulting to highly varying efficiency values

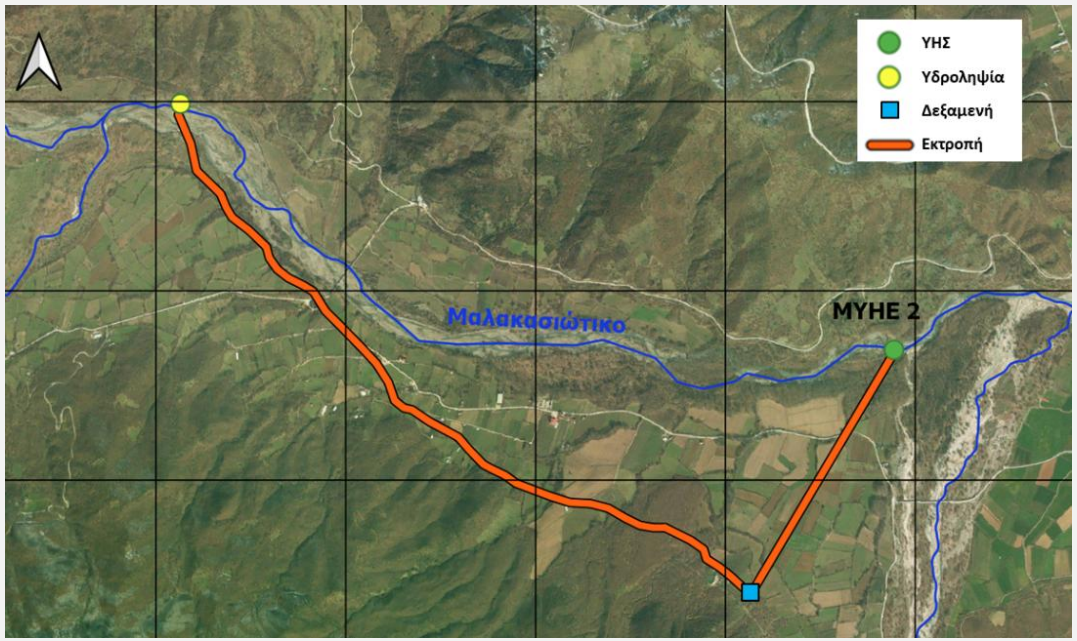
Design issues: Legal framework & constraints

- Minimum allowable distance from upstream SHPPs: 1.0 km
- Maximum allowable length of diversion (for installed capacity $P > 0.30$ MW, older legal status):

$$L_{max} = 0.25 + \left[1.4 - 0.4\left(\frac{q_e}{q_e'}\right)^{0.5}\right]\left[11.2\,\frac{P - 0.30}{5 + (P - 0.30)}\right]$$

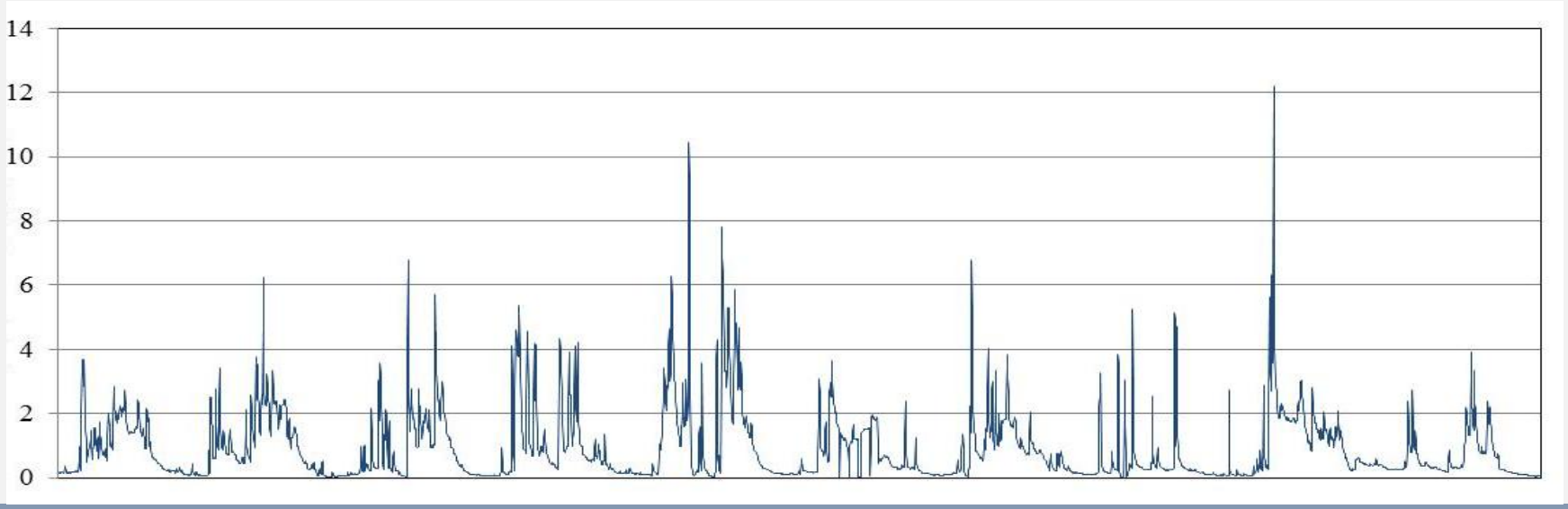
where q_e is the environmental flow and q_e' is the flow allowed to pass from the operator of the project.

- For $P < 0.30$ MW, the length is up to 0.25 km
- **Recent legal status**: 8 km in Natura areas, 15 km in general (ΔΙΠΑ/ΟΙΚ. 37674/ 2016 Β'2471)



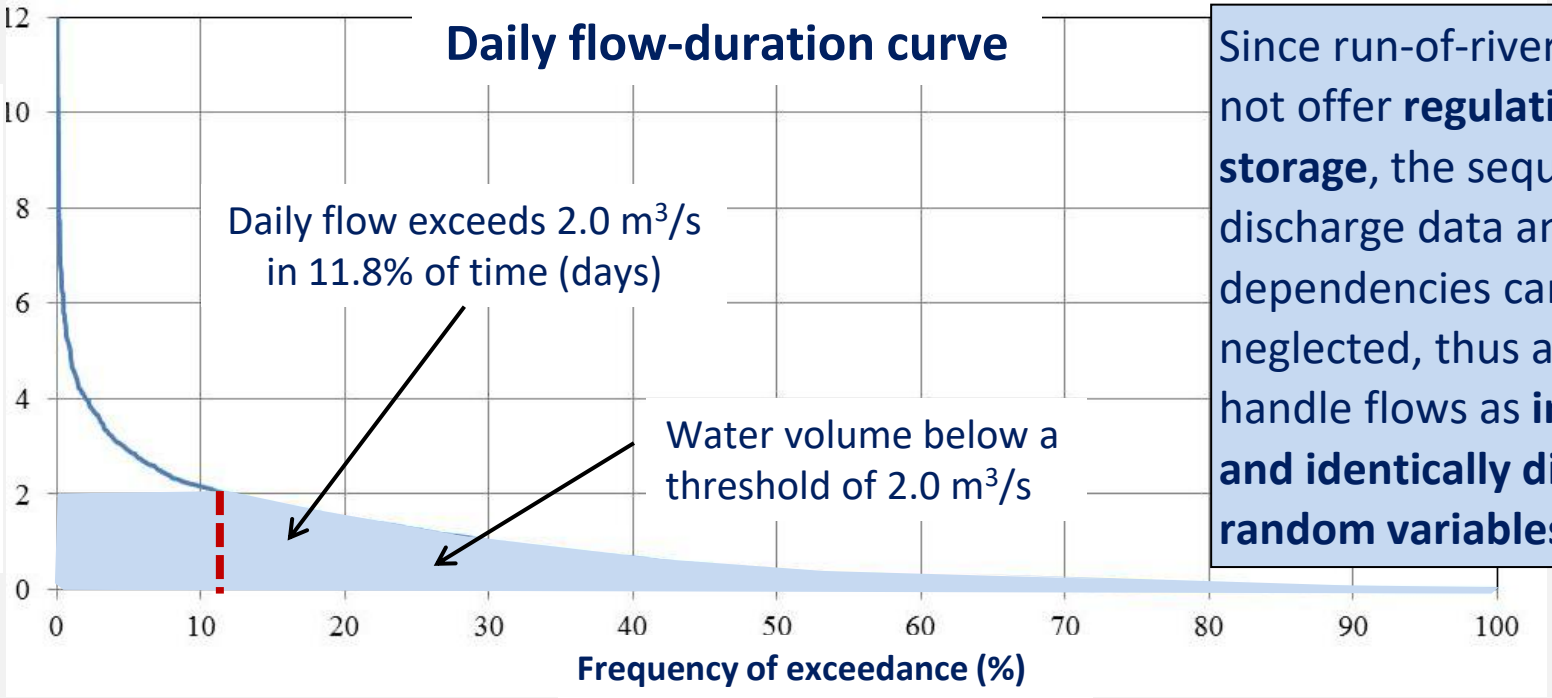
Design issues: Hydrological analysis

- Desirable **length** of streamflow data: at least 10 years
- Desirable **temporal resolution**: daily or finer (calculations with monthly discharge data provide overestimated performance characteristics)
- Typically, the flow at the site of interest (intake) must be estimated from hydrological information provided in the broader study area
- Hydrological analysis, for given streamflow data, $q(t)$
  - Estimation of environmental flow, q_e (typically constant)
  - Estimation of system performance (e.g., power produced) for given design characteristics, by using as input the exploitable discharge, $q'(t) = \max[0, q(t) - q_e]$



Flow-duration curve

- The **flow-duration curve (FDC)** is obtained by sorting the streamflow data in descending order and assigning an empirical exceedance probability to each value.
- If n is the data size, the probability of exceeding the sorted flow value at position i is estimated by using the **Weibull plotting position**, i.e. $p_i = i / (n + 1)$.
- Using the FDC we can estimate the **percentage of time** that streamflow is likely to exceed a specified value of interest or, equivalently, the **minimum flow** ensured for a specific percentage of time (exceedance probability), or the associated **runoff volume** (through integration, by expressing frequencies in time units, i.e. hours per year).



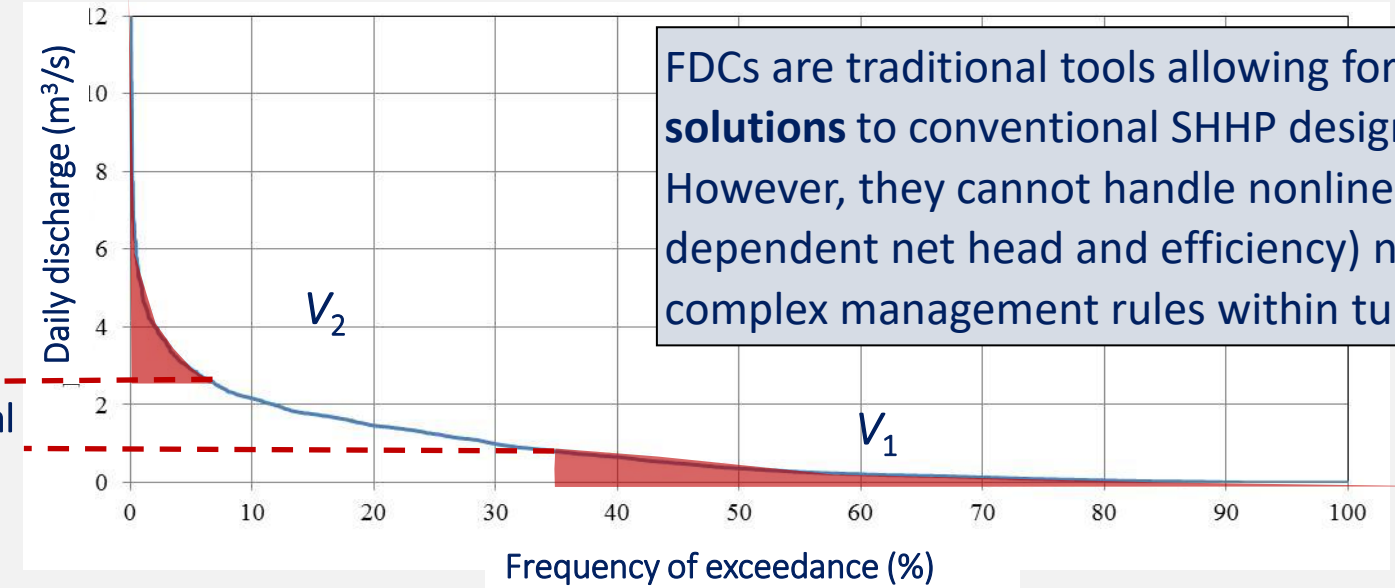
Since run-of-river plants do not offer **regulation through storage**, the sequence of discharge data and their time dependencies can be neglected, thus allowing to handle flows as **independent and identically distributed random variables**

Design issues: Environmental flows

- **Definition**: Quantity, quality and timing of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on them.
- Environmental flow assessment (EFA) has been historically developed as a response to the **degradation of aquatic ecosystems caused by human interventions**.
- Classification of EFA approaches:
  - Hydrological, based on statistical analysis of inflow data per se;
  - Hydraulic rating, involving the estimation of key hydraulic quantities (depth, velocity);
  - Habitat simulation (for representative fish species);
  - Holistic approaches, also accounting for socioeconomic issues.
- Traditionally, EFA implies the preservation of a constant discharge, while the current practices require a flow scheduling that follows the natural variability of streamflow.
- The **Greek legislation** implies the preservation of a time-constant environmental flow downstream of SHPPs, which should be the maximum of the following quantities:
  - 30% of average streamflow during the summer period (June, July, August);
  - 50% of average streamflow of September;
  - 30 L/s, in any case.
- The above value must be increased, in case of an important ecosystem downstream.
- EF is typically released through the fish ladder.

Design issues: Operational flow range

- A small hydropower plant exploits a feasible **flow range** between a minimum and a maximum discharge value; the latter depends on the installed capacity of turbines (it is also referred to as nominal discharge), while the former which depends on their type.
- The volumes V_1 and V_2 are not exploited for energy production. V_1 depends on the minimum flow of the smallest turbine, and V_2 on the maximum flow of all turbines.
- Key design objective is the minimization of V_1 and V_2, which is achieved through the combination of several turbines with varying power capacity (**turbine mixing**).
- According to Greek legislation the design of SHPPs must ensure: **(a) exploitation of at least 75% of the available volume; and (b) time percentage of operation >30%**.



Operational flow range

FDCs are traditional tools allowing for **fast graphical solutions** to conventional SHHP design problems. However, they cannot handle nonlinearities (flow-dependent net head and efficiency) neither complex management rules within turbine mixing.

Turbine selection: Numerical example 1

Data

H = 260 m

η = 0.85

Theoretical power for **various** discharges

Q (m³/s)	I (MW)
0.5	1.1
1	2.2
1.5	3.3
2	4.3
2.5	5.4
3	6.5
4	8.7
5	10.8
10	21.7

Legend

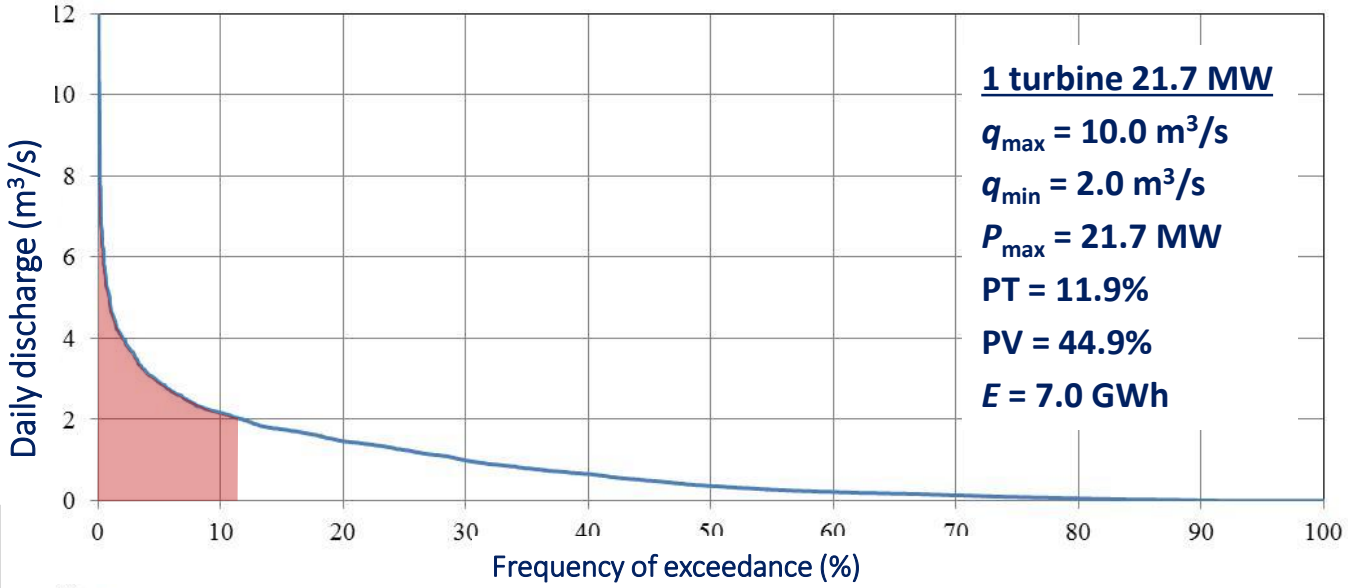
q_{min}, q_{max}: Minimum, maximum exploitation discharge (m³/s)

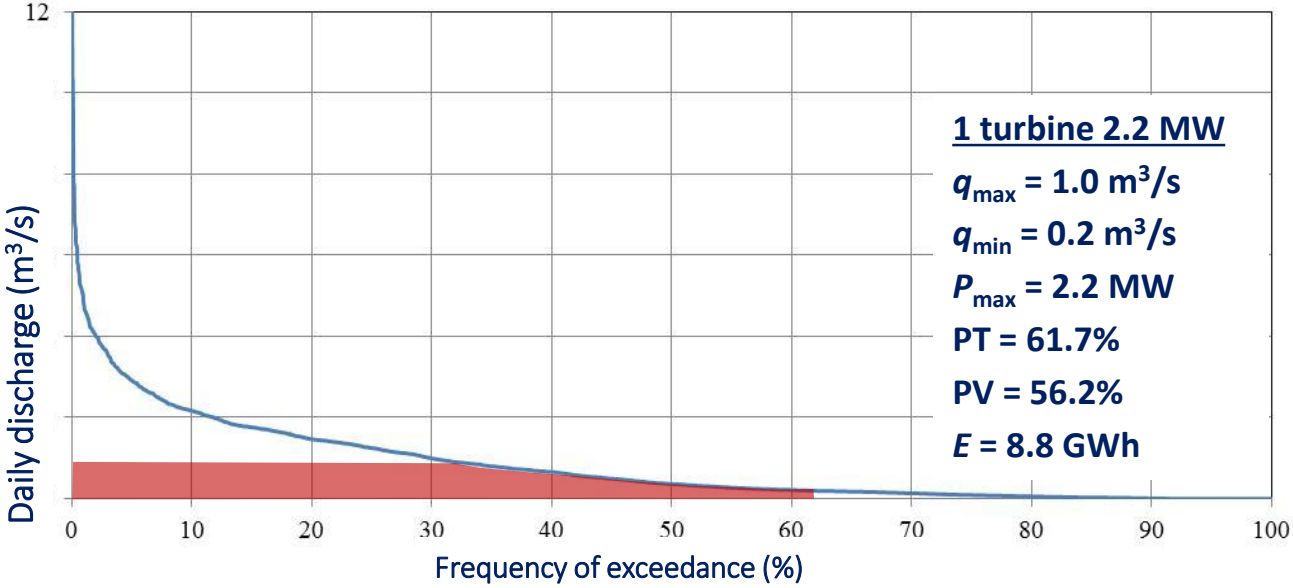
P_{max}: Power in maximum exploitation discharge (MW)

PT: Percentage of operation time in a typical year (%)

PV: Percentage of water volume used (%)

E: Total annual electrical energy produced (GWh/y)





Turbine selection: Numerical example 2

Data

H = 260 m
η = 0.85

Theoretical power for various discharges

Q (m³/s)	I (MW)
0.5	1.1
1	2.2
1.5	3.3
2	4.3
2.5	5.4
3	6.5
4	8.7
5	10.8
10	21.7

Legend

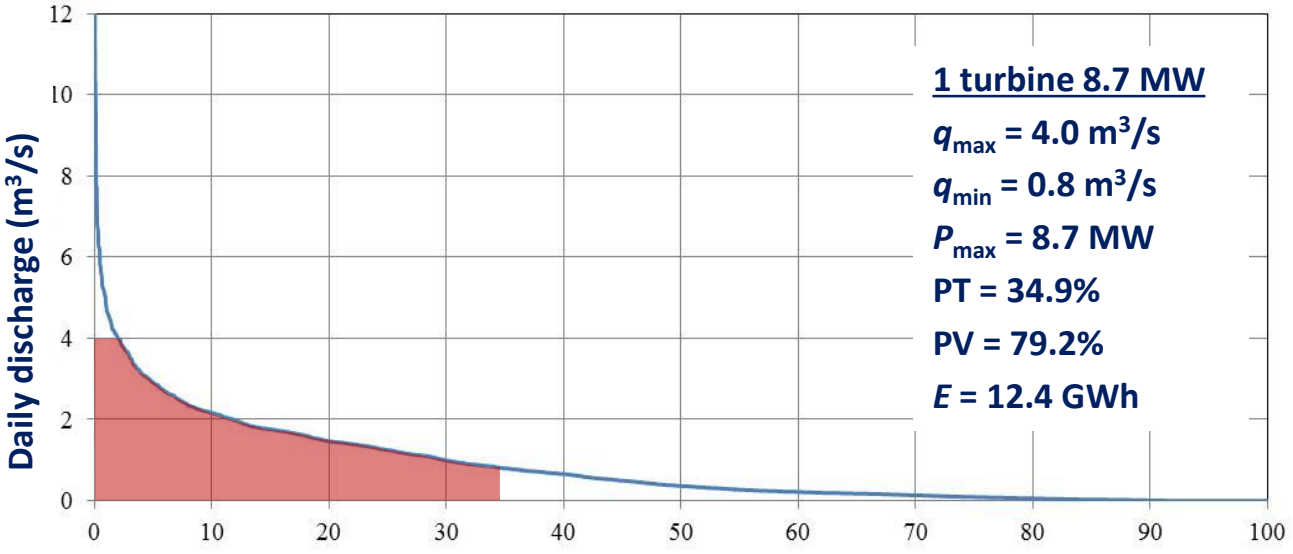
q_{min}, q_{max}: Minimum, maximum exploitation discharge (m³/s)

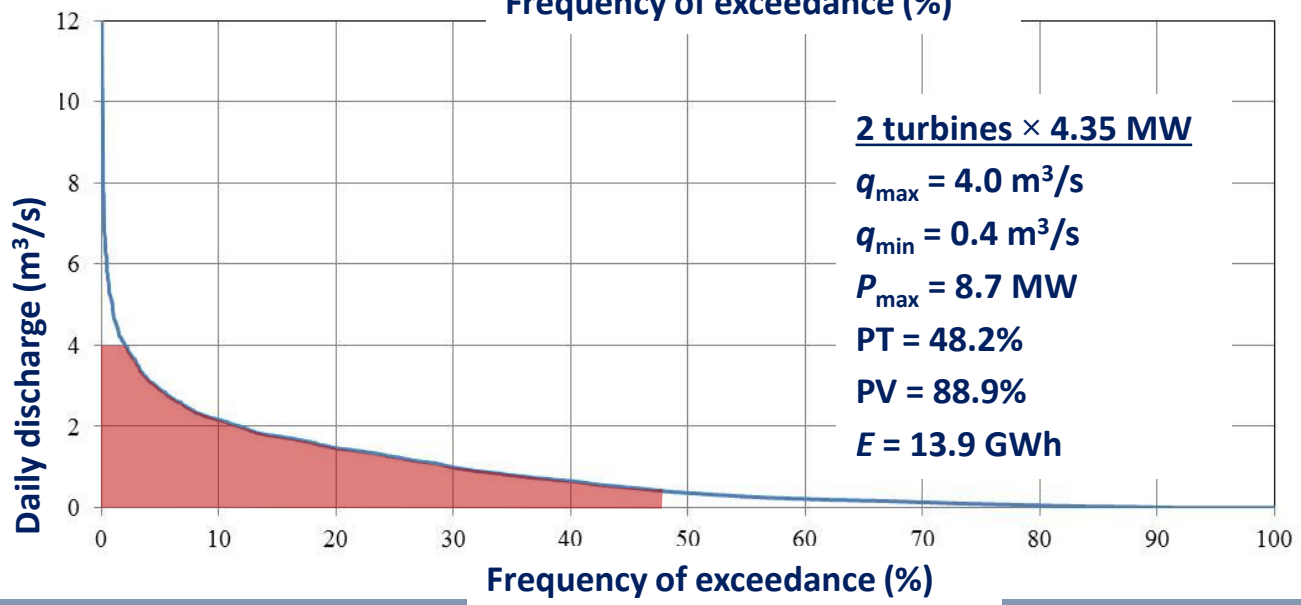
P_{max}: Power in maximum exploitation discharge (MW)

PT: Percentage of operation time in a typical year (%)

PV: Percentage of water volume used (%)

E: Total annual electrical energy produced (GWh/y)





Turbine selection: Numerical example 3

Data

H = 260 m

η = 0.85

Theoretical power for various discharges

Q (m³/s)	I (MW)
0.5	1.1
1	2.2
1.5	3.3
2	4.3
2.5	5.4
3	6.5
4	8.7
5	10.8
10	21.7

Legend

q_{min}, q_{max}: Minimum, maximum exploitation discharge (m³/s)

P_{max}: Power in maximum exploitation discharge (MW)

PT: Percentage of operation time in a typical year (%)

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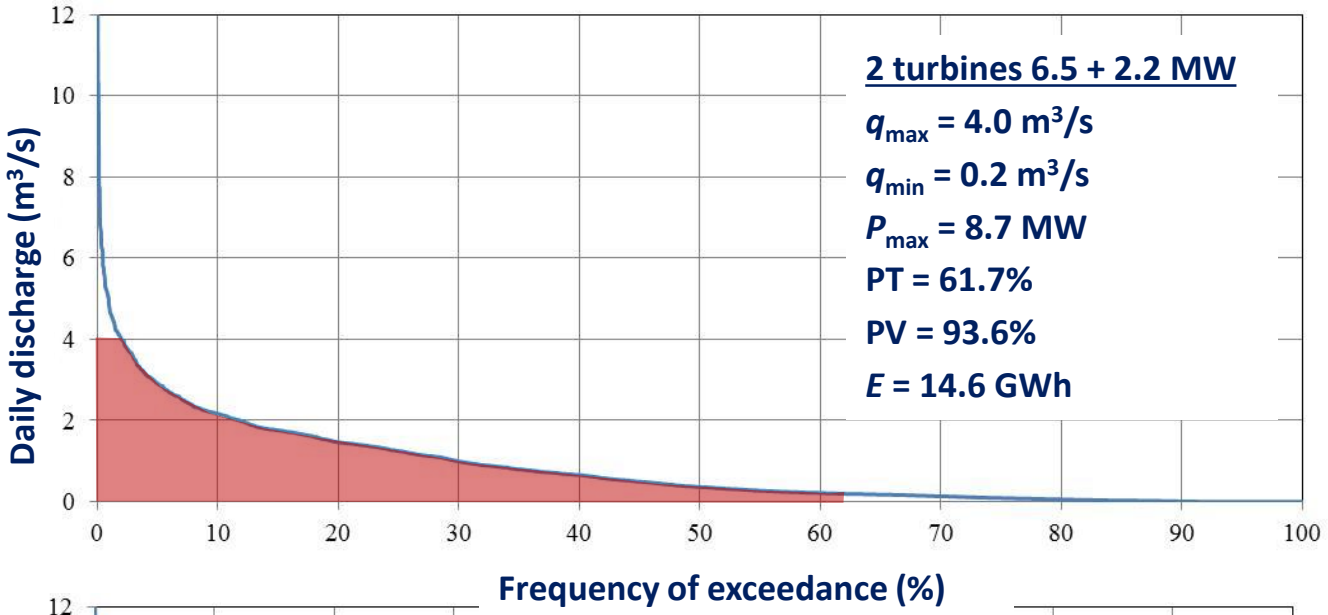
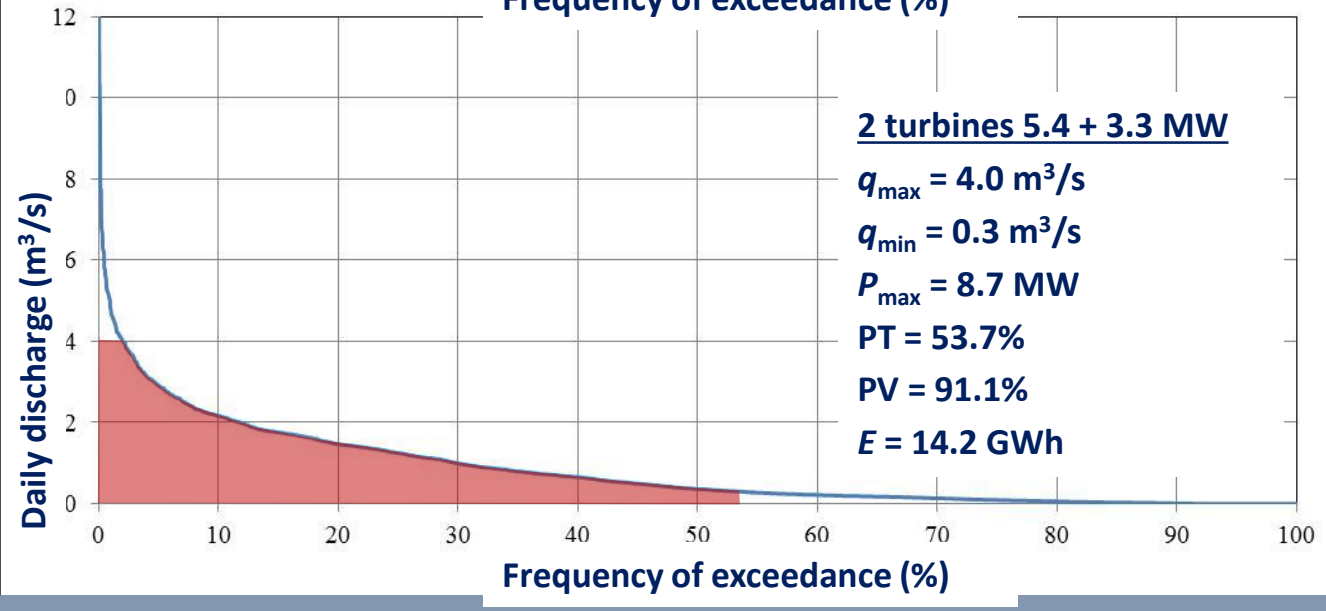
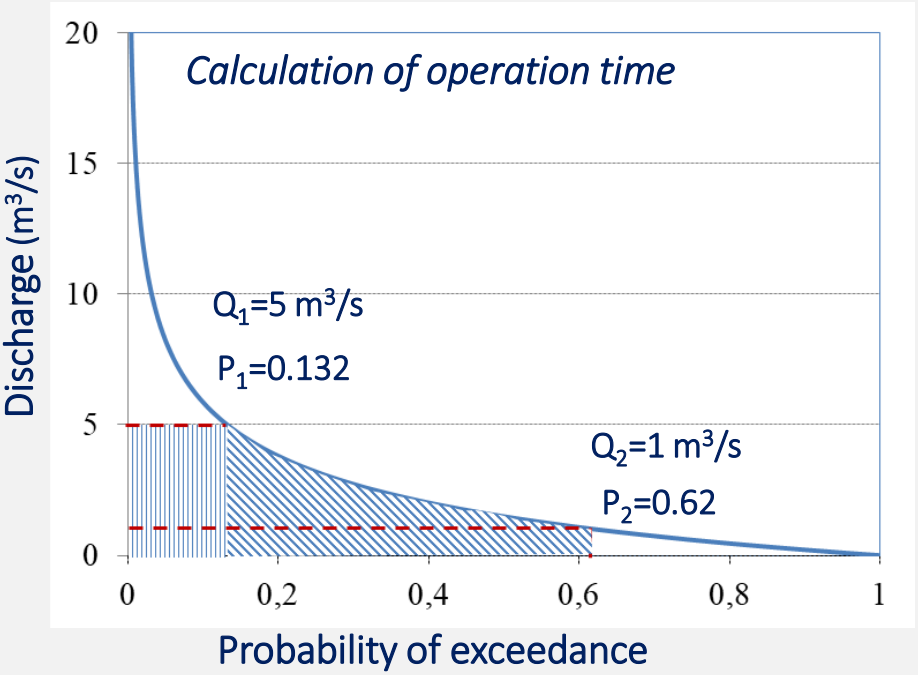




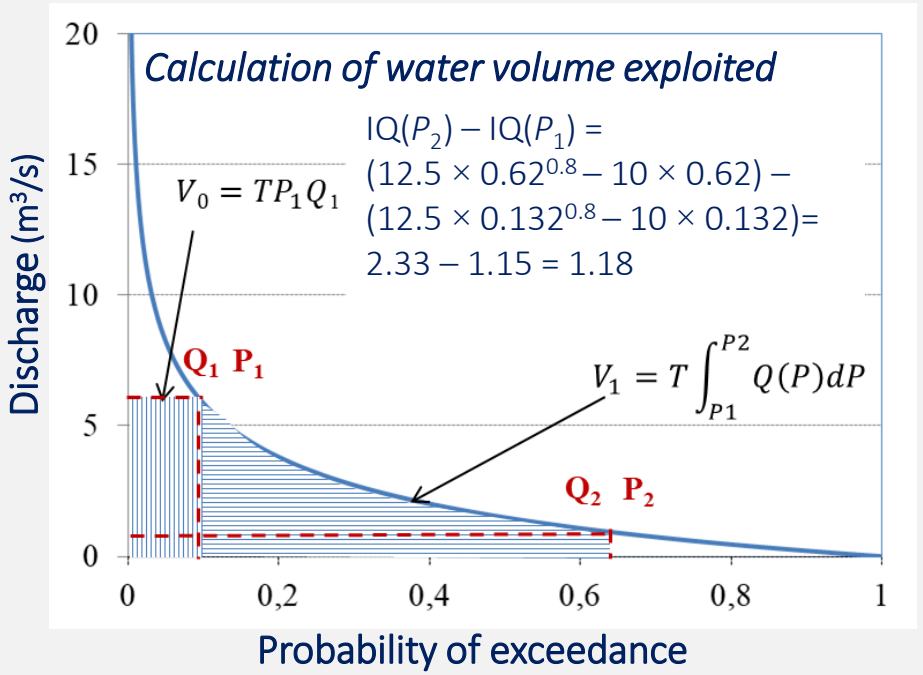
Estimations based on analytical expressions of FDCs

- Problem assumptions and key calculations:
  - Single turbine, operating within the range 1.0 to 5.0 m^3/s
  - Analytical FDC formula (q discharge, P probability): $P(q) = 1 - F(q) = (1 + q/10)^{-5}$
  - Inverse FDC function (= cumulative distribution function of Q): $q(P) = 10\,(1/P^{0.2} - 1)$
  - Integral of FDC: $\mathrm{IQ} := \int q(P)\mathrm{d}P = 12.5P^{0.8} - 10P$



Operational time: **62%**

Operational time at max discharge: **13.2%**



For one-year operation, $T = 31.56 \times 10^6$ s

$V_0 = 31.56 \times 0.132 \times 5 =$ **20.8 hm³**

$V_1 = 31.56 \times 1.18 =$ **37.1 hm³**

Design through simulation: Model inputs

- Let consider two turbines of power capacity, P_1 and P_2, of specific type.
- Input data:
  - Streamflow time series at the intake, q, after subtracting environmental flows;
  - Gross head, h (practically constant);
  - Total efficiency, $\eta(q/q_{max})$, expressed as function of rated discharge;
  - Maximum discharge that can pass from the turbines (nominal flow), $q_{i,max}$
  - Minimum discharge for energy production, $q_{i,min}$ (typically, 10-30% of $q_{i,max}$)
- The **maximum (nominal) discharge** of each turbine is given by:

$$q_{i,max} = \frac{P_i}{\gamma\, \eta_{i,max}\, h_n}$$

where $\eta_{i,max}$ is the total efficiency at the maximum discharge, which depends on the turbine type, γ is the specific weight of water (9.81 KN/m^3) and h_n is the net head, i.e. the gross head, h, after subtracting hydraulic losses, h_L.

- Hydraulic losses include friction and local ones, which are function of discharge and the penstock properties (roughness, length, diameter, geometrical transitions).
- The **minimum discharge** of each turbine is expressed as ratio of the maximum one, i.e.:

$$q_{i,min} = \theta_i\, q_{i,max}$$

Design through simulation: Calculations

- Let q be the streamflow arriving at the intake after subtracting the environmental flow, q_e. The flow passing from the first turbine is given by:

$$q_{T1} = \min(q,\ q_{1,max})$$

- If $q > q_{1,max}$ then the surplus flow passing from the second turbine is:

$$q_{T2} = \min(q - q_{T1},\ q_{2,max})$$

- The hydraulic losses and thus the net head, h_n, are estimated as function of the total discharge, $q_{T1} + q_{T2}$, which is diverted to the turbines.
- For $q_{Ti} < q_{i,min}$ the turbine is set out of operation, while for $q_{Ti} > q_{i,min}$ the energy produced by each turbine is:

$$E_i = \eta(q_{Ti})\ \gamma\ q_{Ti}\ h_n\ \Delta t$$

where Δt is the time interval of calculations and $\eta(q_{Ti})$ the flow-dependent total efficiency of each turbine, which is either expressed analytically or given by nomographs.

- The volume exploited by each turbine is given by:

$$V_i = \begin{cases} 0 & Q_{Ti} < Q_{i,min} \\ Q_{Ti}\,\Delta t & Q_{Ti} \geq Q_{i,min} \end{cases}$$

- The total energy produced by the system is $E = E_1 + E_2$.

Design through simulation: Performance metrics

- **Capacity factor**, expressed on mean annual basis:

$$CF = \frac{E_\alpha}{(P_1 + P_2)\, T_\alpha}$$

where E_α is the mean annual energy production and T_α are the hours per year (= 8760).

- **Percentage of operational time**, estimated as the probability of producing energy over the entire simulation period:

$$OT = P(E_1 + E_2 > 0)$$

- **Percentage of water volume used by the turbines for power production**:

$$OV = \frac{E[V_1 + V_2]}{E[Q]\, \Delta t}$$

where $E[X]$ denotes the mean value of a random variable X.

The mean annual energy, E_α, is associated with the anticipated revenues from the operation of the power system, while the total installed capacity, $P_1 + P_2$, is associated with investment costs for the electromechanical equipment (turbines, generator, etc.), also affecting the design discharge and thus the cost of the water transfer system. **In an optimization context, E_α and CF are the two major contrasting objectives to maximize within SHPP design**.

Analytical formula for turbine efficiency

- Large hydroelectric reservoirs allow for controlling outflows, thus their turbines are normally working with the nominal flow (which maximizes η).
- In contrast, SHPPs are operating under varying discharge conditions, thus η is strongly varying across the feasible flow range (q_{min}, q_{max}).
- Generalized formula for turbine efficiency, n_{T}, as function of **rated discharge**, q/q_{max}:

$$n_{\mathrm{T}} = n_{min} + \left(1 - \left(1 - \left(\frac{q/q_{max} - \theta}{1 - \theta}\right)^{a}\right)^{b}\right)(n_{max} - n_{min})$$

  where n_{max}, n_{min} are the upper and lower efficiency values within the feasible flow range, $\theta = q_{min}/q_{max}$, and a and b are shape parameters.

- Typical values for two common turbine types that are applied in SHPPs:
  - **Pelton**: $\theta = 0.10$, $n_{min} = 0.78$, $n_{max} = 0.89$, $a = 1.0$, $b = 8.0$
  - **Francis**: $\theta = 0.15$, $n_{min} = 0.33$, $n_{max} = 0.93$, $a = 0.78$, $b = 3.11$
- The total efficiency should by multiplied by a reduction coefficient, e.g. 0.95, to account for **electromechanical losses** in the generator, the transformer and the transmission lines.
- The variability of efficiency with respect to discharge plays key role in the design and operation of SHPPs and should not be neglected!

Retro small hydro (Theodoriana, 10 kW, ~1930)