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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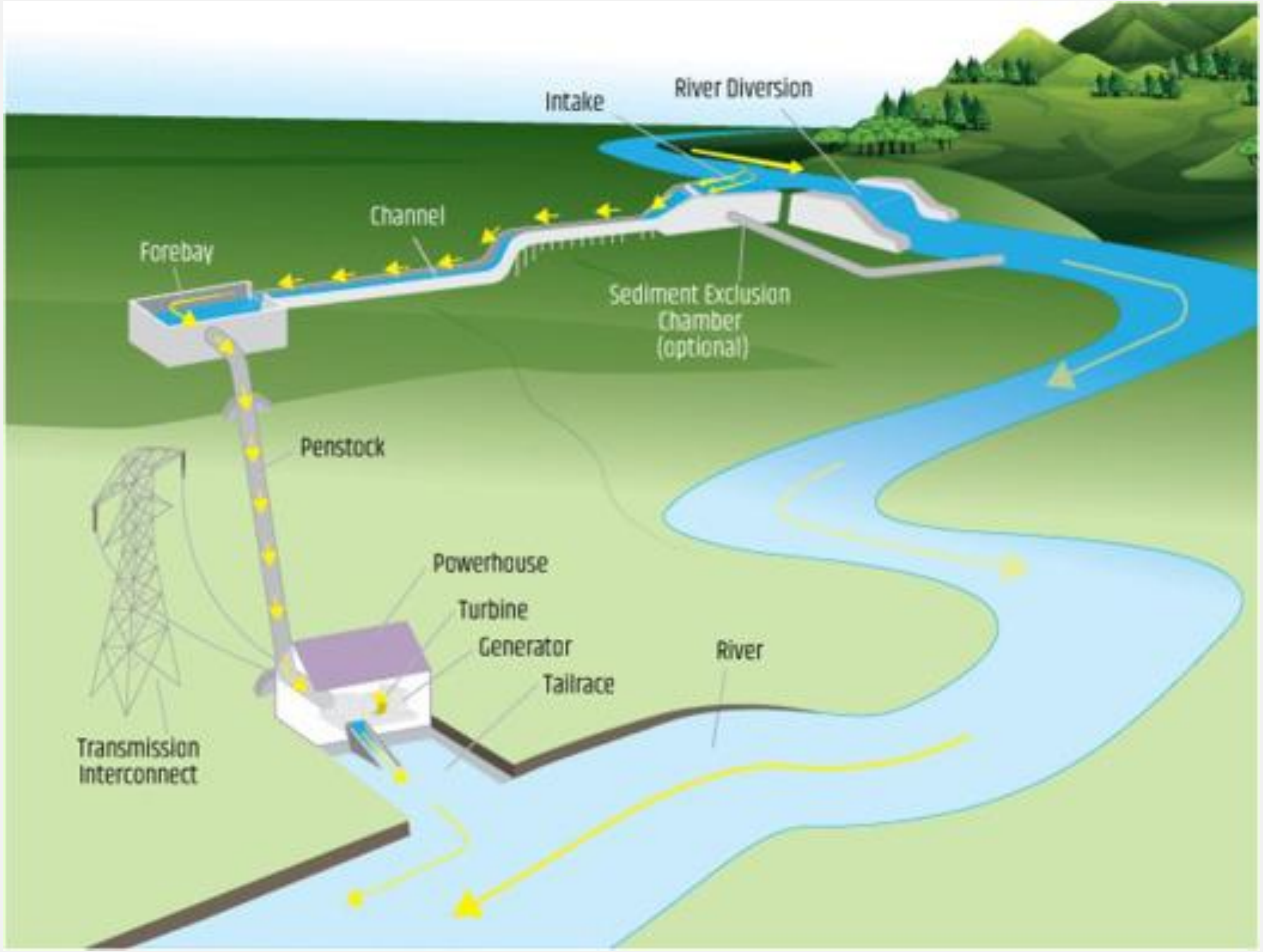
Definition of SHPPs

- To classify 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).
- From a design and water-energy management perspective, the key characteristic is the existence or not of **storage capacity**, not the power capacity per se.

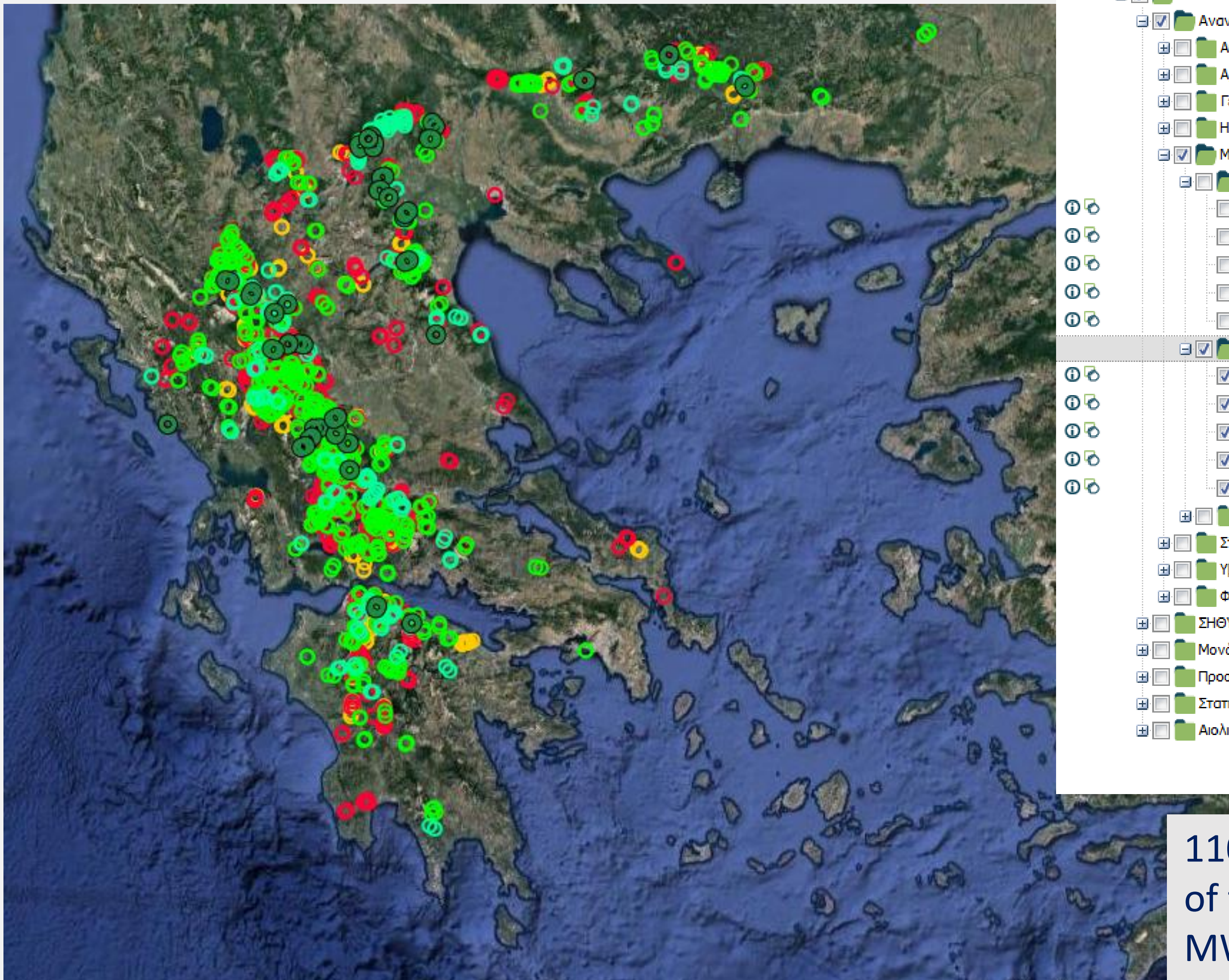
Classification of SHPPs

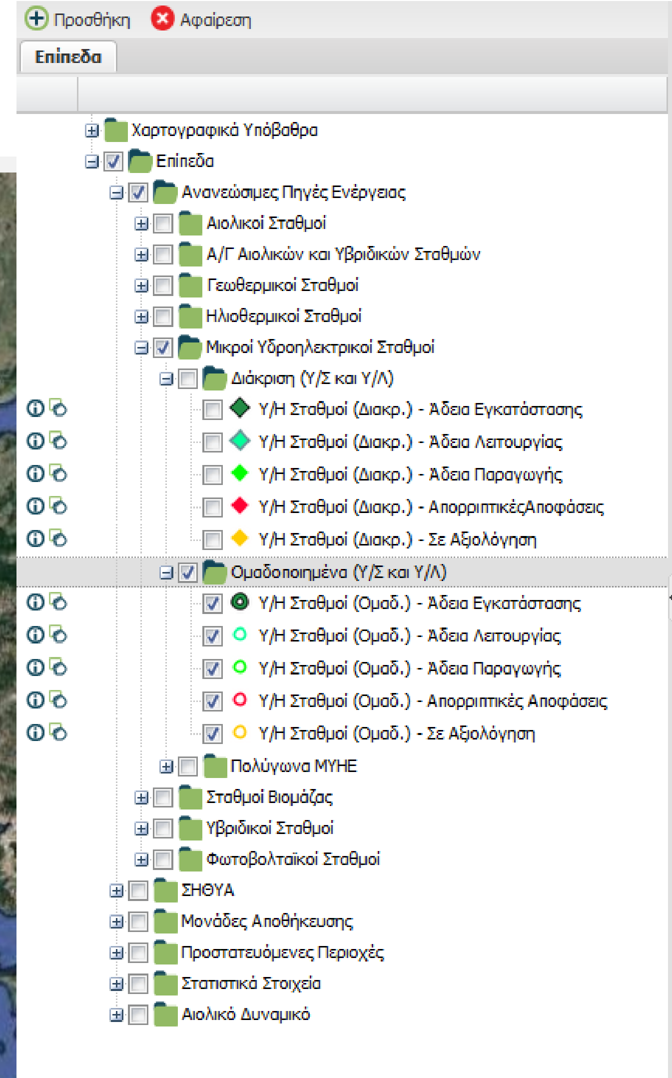
- The power station is settled downstream of large dams to take advantage of the environmental flow, which is released from an independent intake (e.g., bottom outlet)
- Run-off-river, where the streamflow is captured at a river site and permanently diverted through a conveyance system to the power station, and then released at a downstream site.
- In-stream, to take advantage of small elevation differences created by low-head dams (weirs).
- Across pressurized pipes, used instead of energy dissipation valves.
- Submerged to channels, taking advantage of the kinetic energy of water.

Typical layout of run-off-river hydropower plants



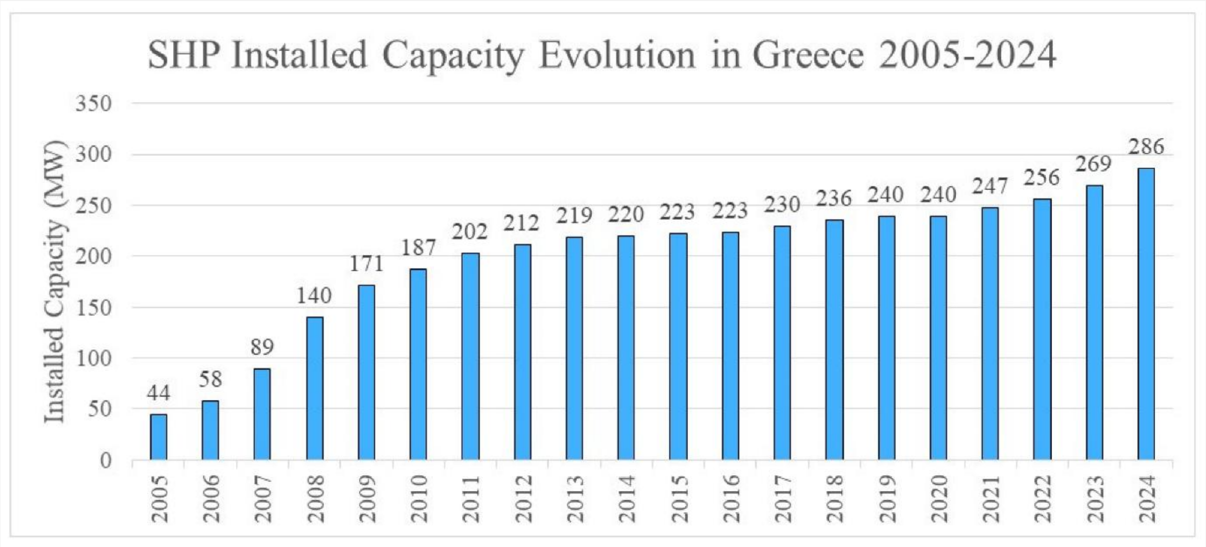
SHPPs in Greece

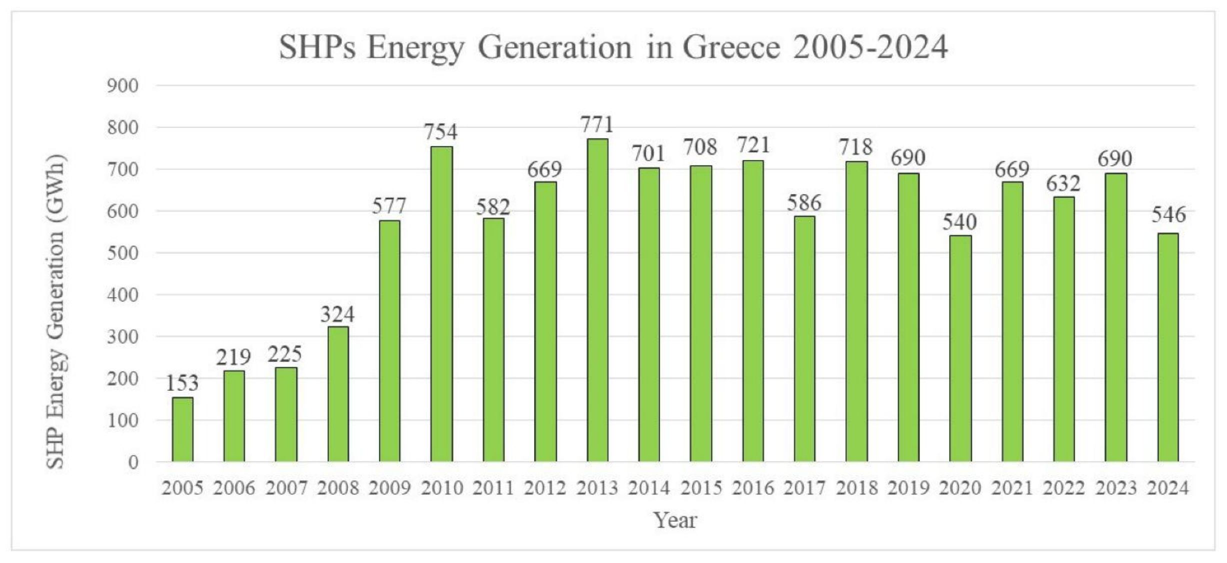




110 plants in operation, of total capacity 281 MW, ~85% unexploited

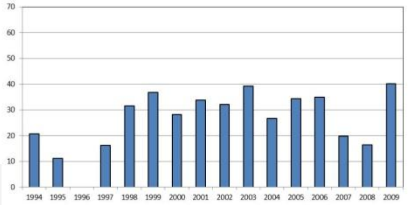
SHPPs in Greece



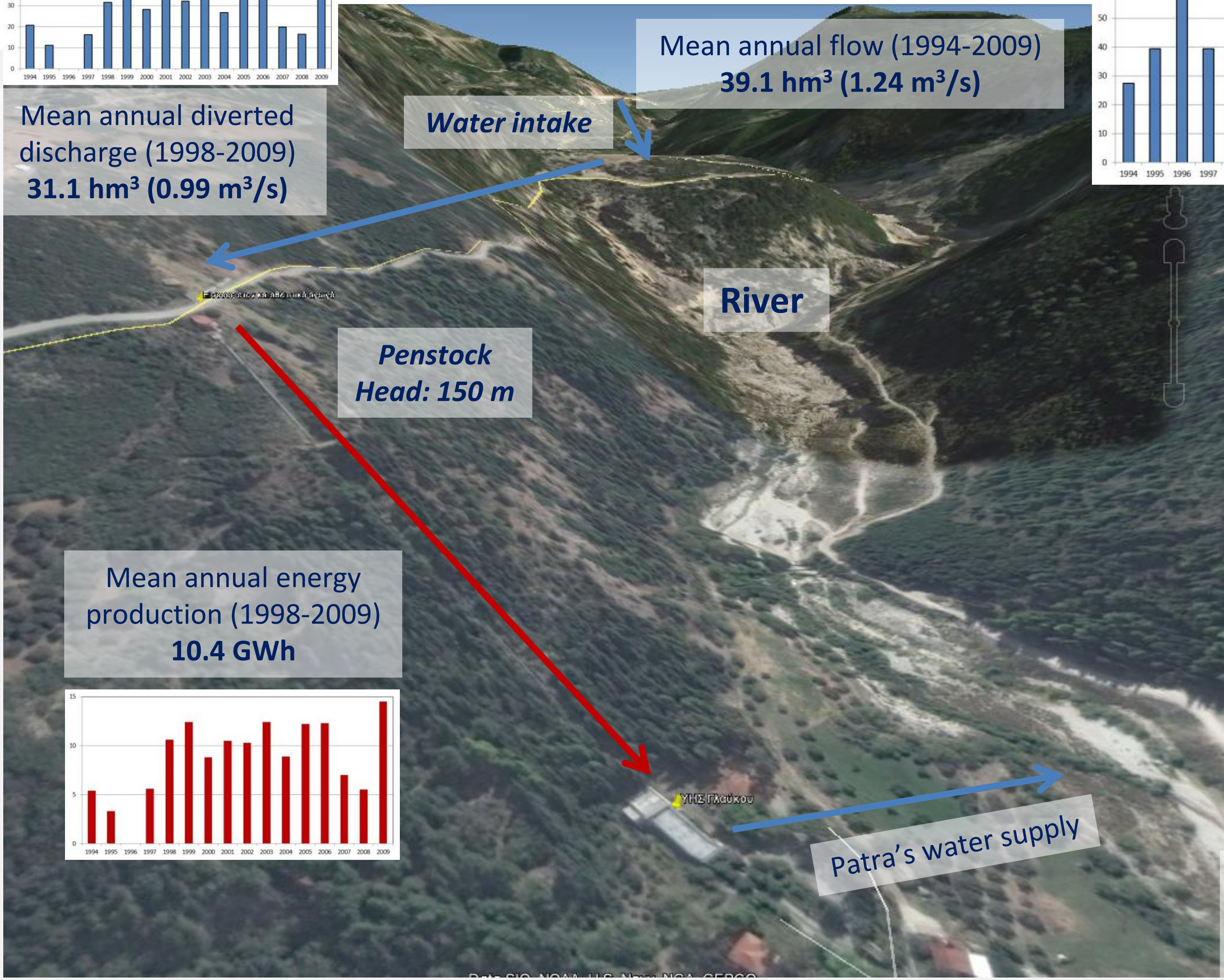


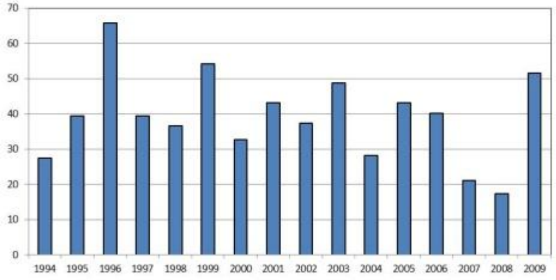
Kaldellis, J. K. The contribution of small hydropower plants in clean electrification: Current status and future prospects for Greece, *Energies*, 19(4), 880, doi:10.3390/en19040880, 2026.

Characteristic examples: Glafkos (Patra)



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





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

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

Mean annual energy production (1998-2009)
10.4 GWh

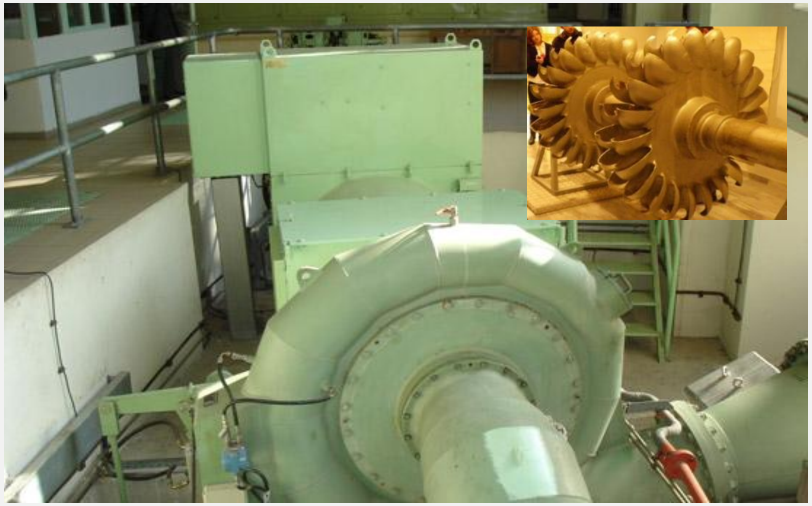
Total capacity: 3.8 MW (2.2 MW Francis, 1.6 MW Pelton)

Dam water intake

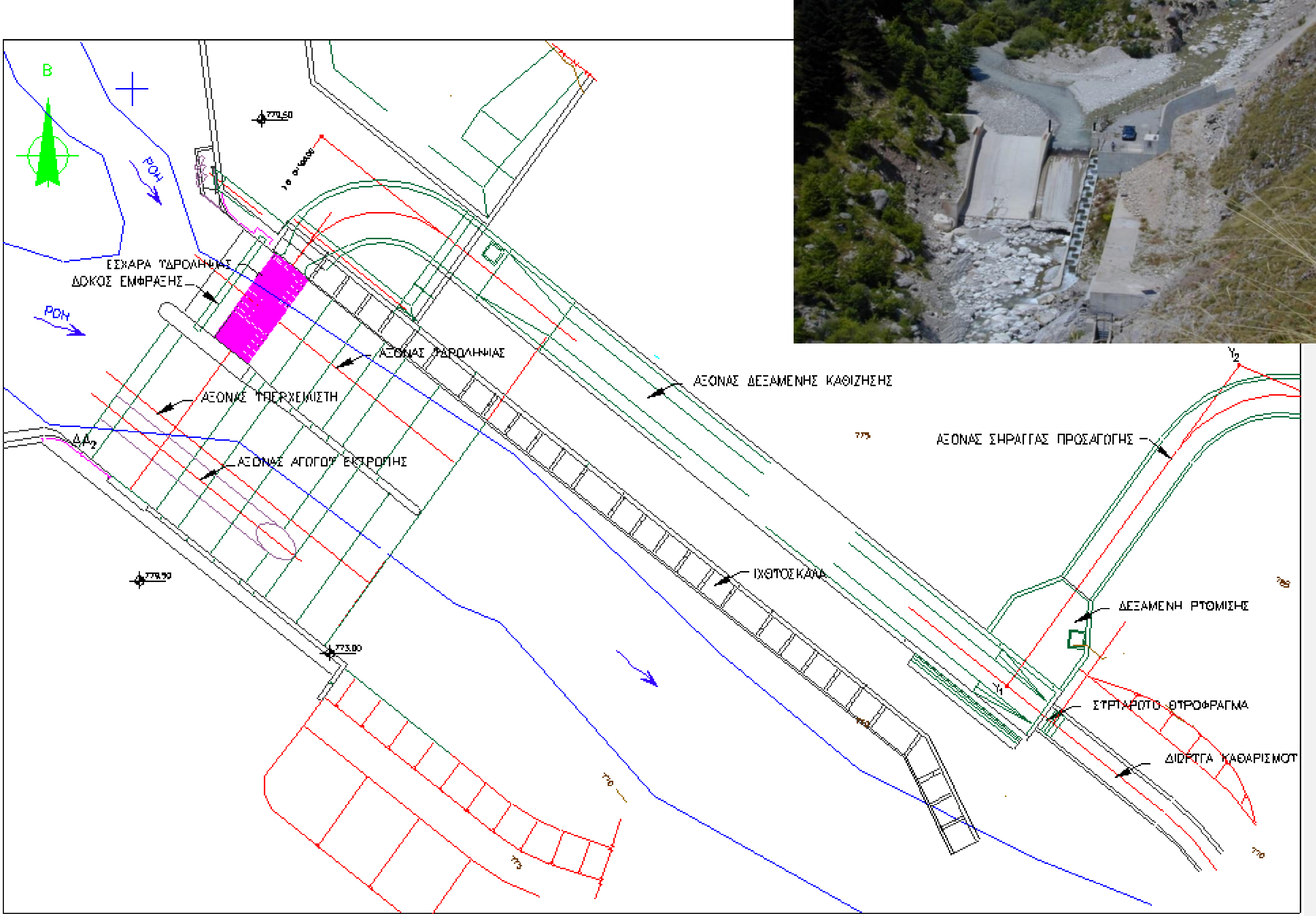
Sand trap – desilter – sedimentation tank

Penstock

Turbines



Characteristic examples: Theodoriana (Epirus)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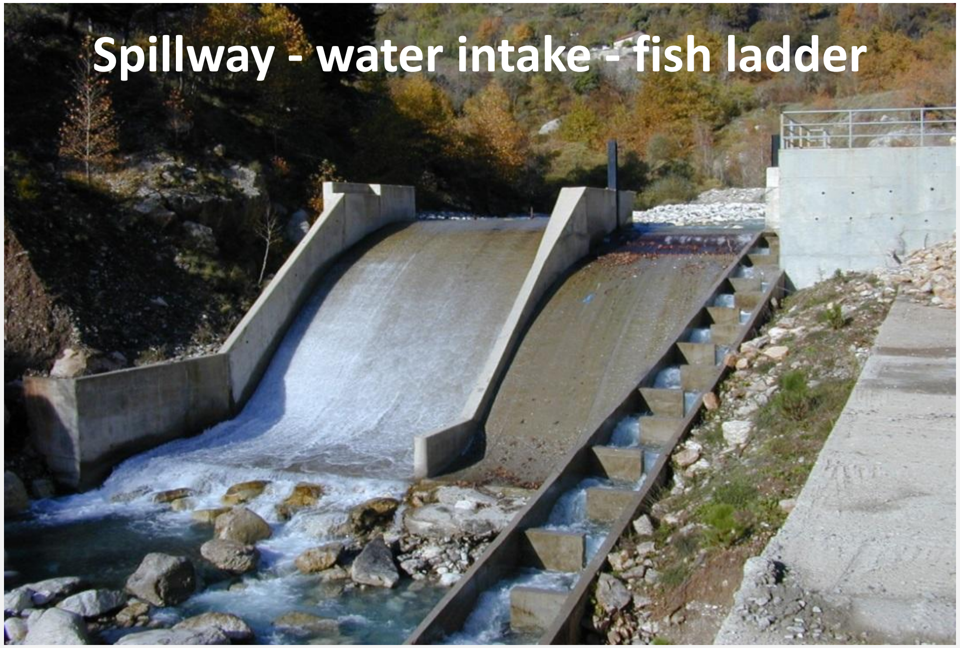
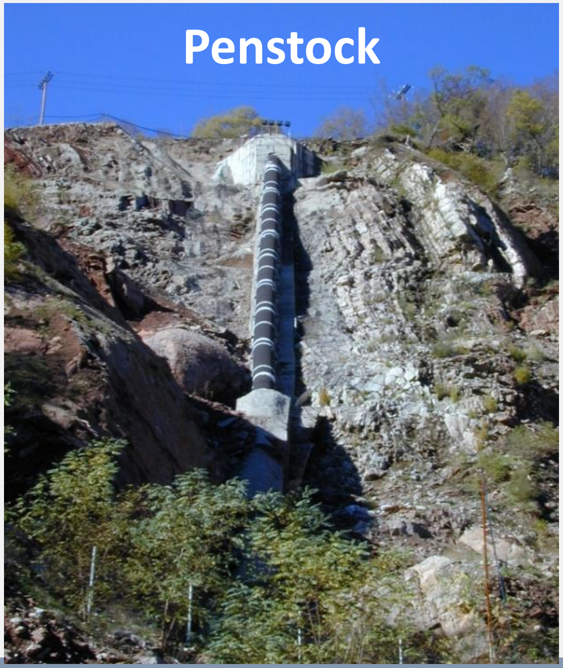

Spillway - water intake - fish ladder


Water intake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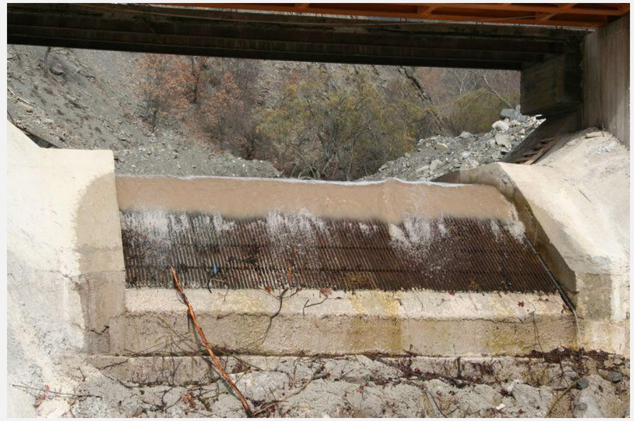
Power house

Characteristic examples: Thermorema (Spercheios)

Desilter (sand traps)

Trash rack of water intake



Headwater channel - sand traps

Forebay tank

Penstock

Photos: ΔΕΛΤΑ Project

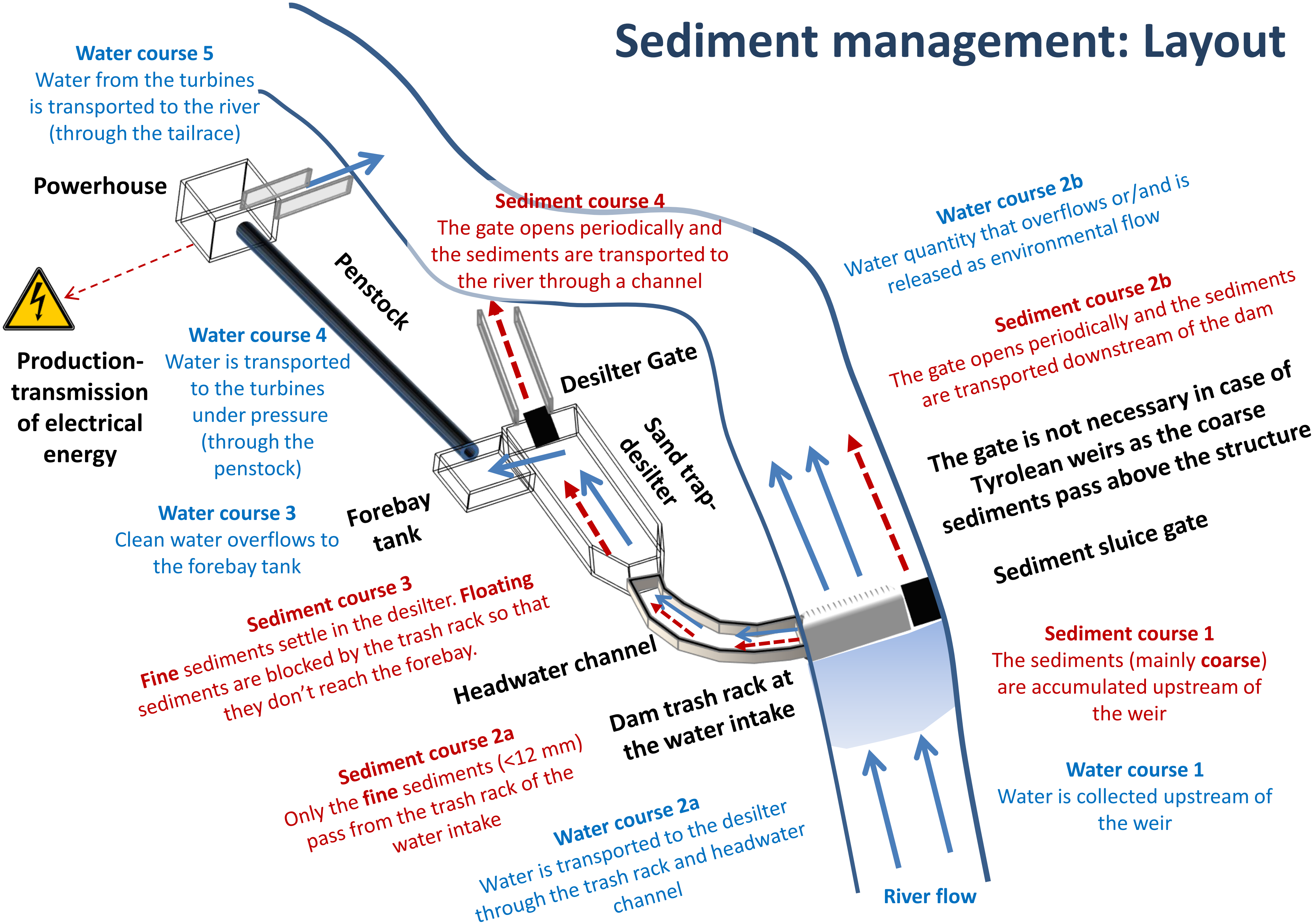
The issue of sedimentation

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.

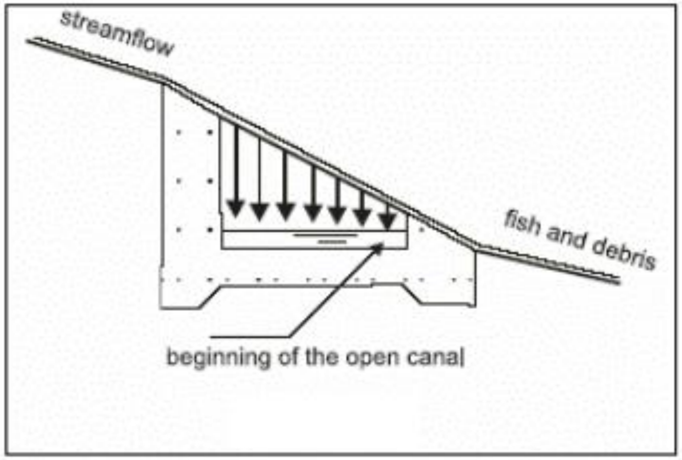
Sediment management: Layout

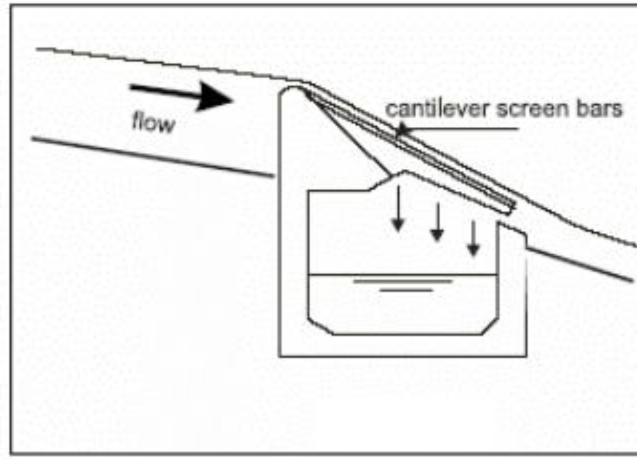


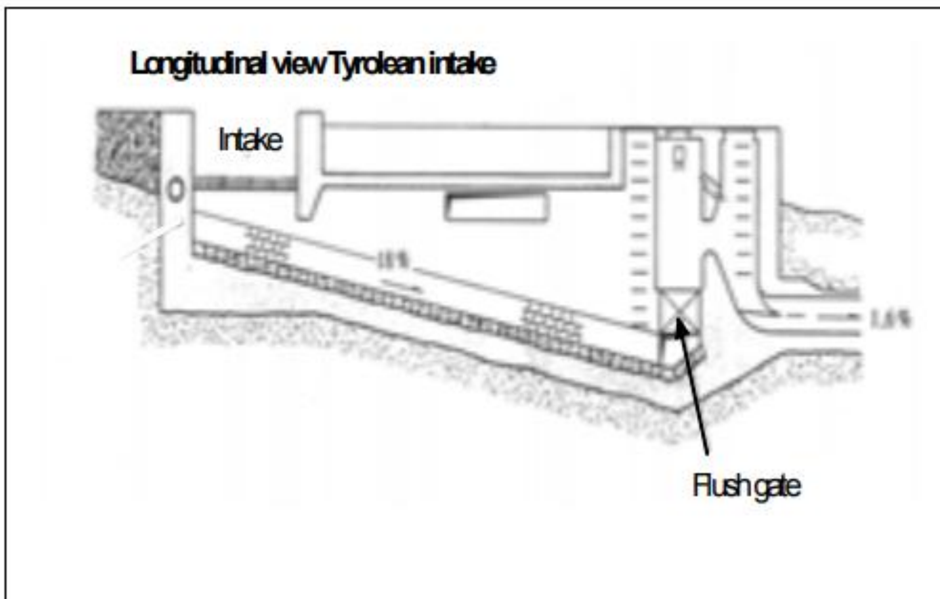
Drop intakes – Tyrolean weirs

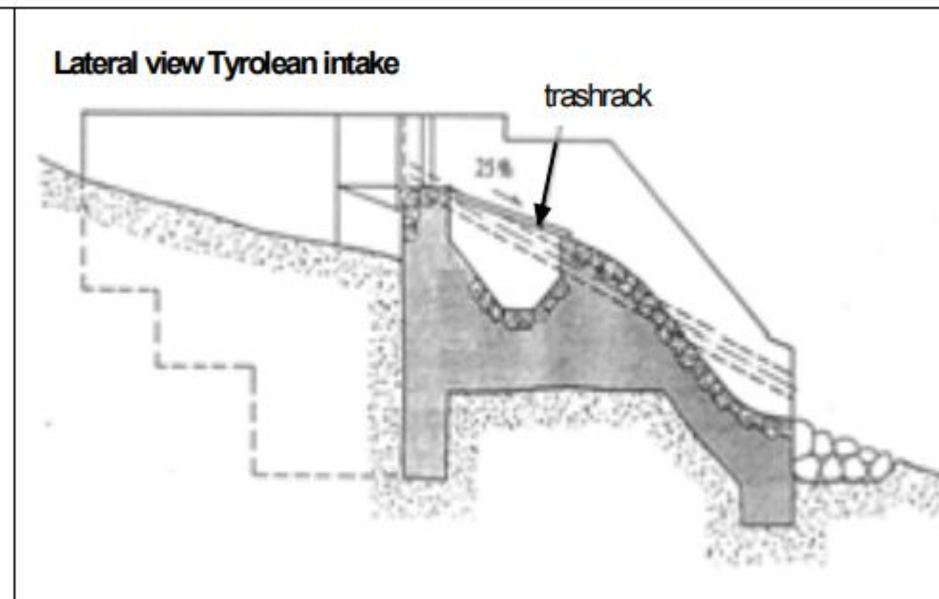
- **Tyrolean weir** is a water intake structure in which water is abstracted from the main flow through a trash rack (screen) over a gutter.
- The gutter is usually made of concrete and built into the river bed.
- The trash rack on the crest should slope downstream (15-30 degrees), to ensure adequate 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



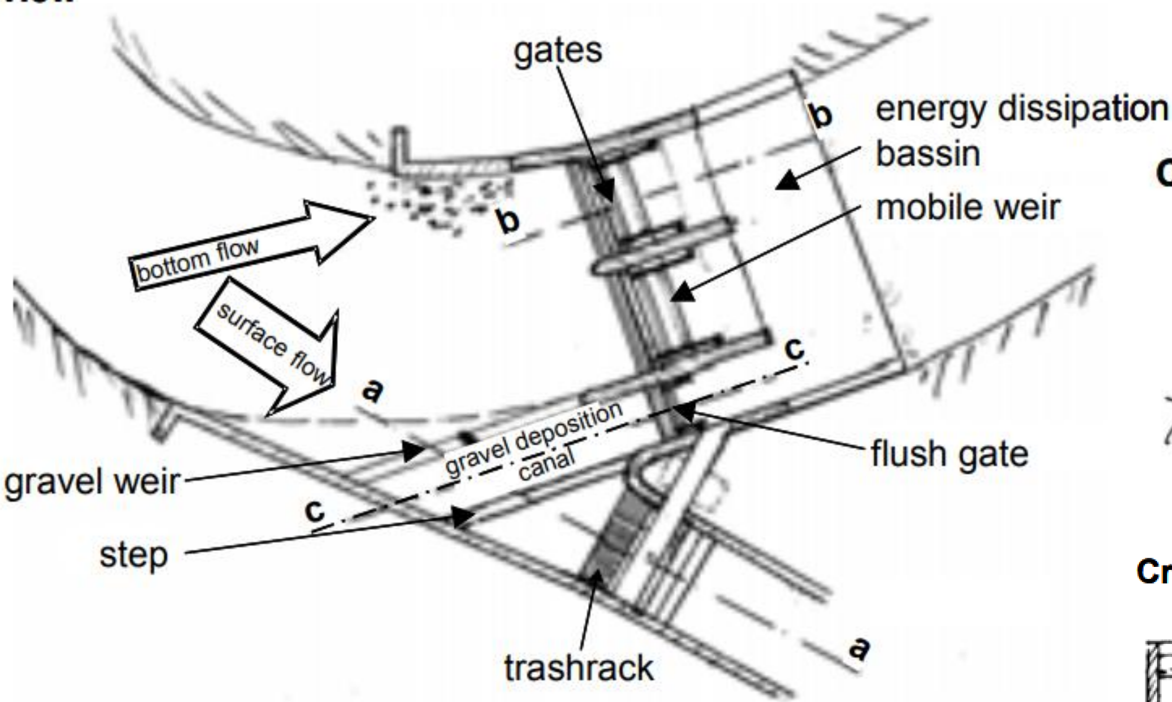




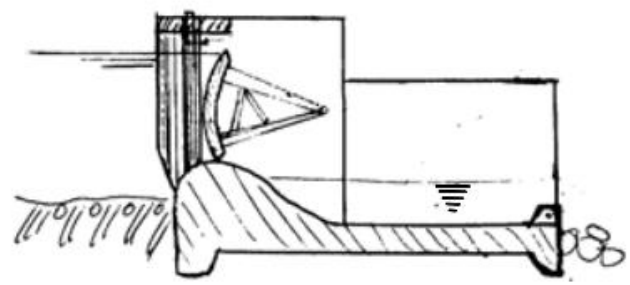


Lateral intakes

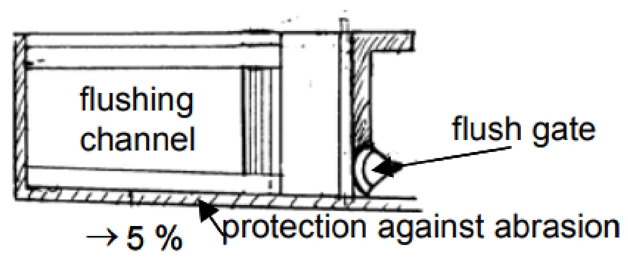
Plan view



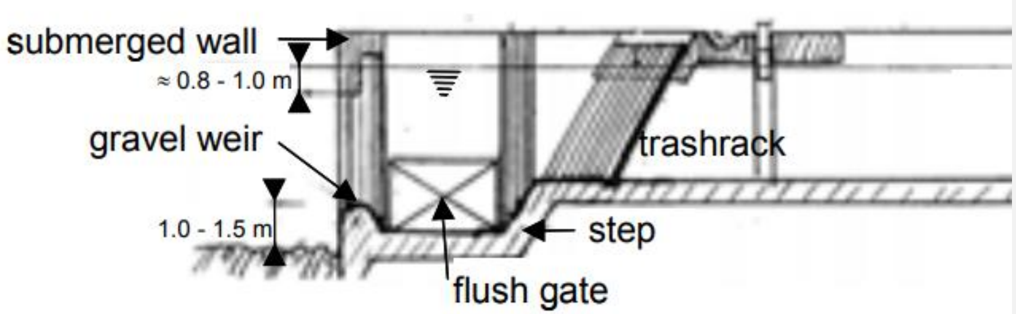
Cross section b - b : Weir /dam



Cross section c - c : Gravel weir



Cross section a - a : Intake

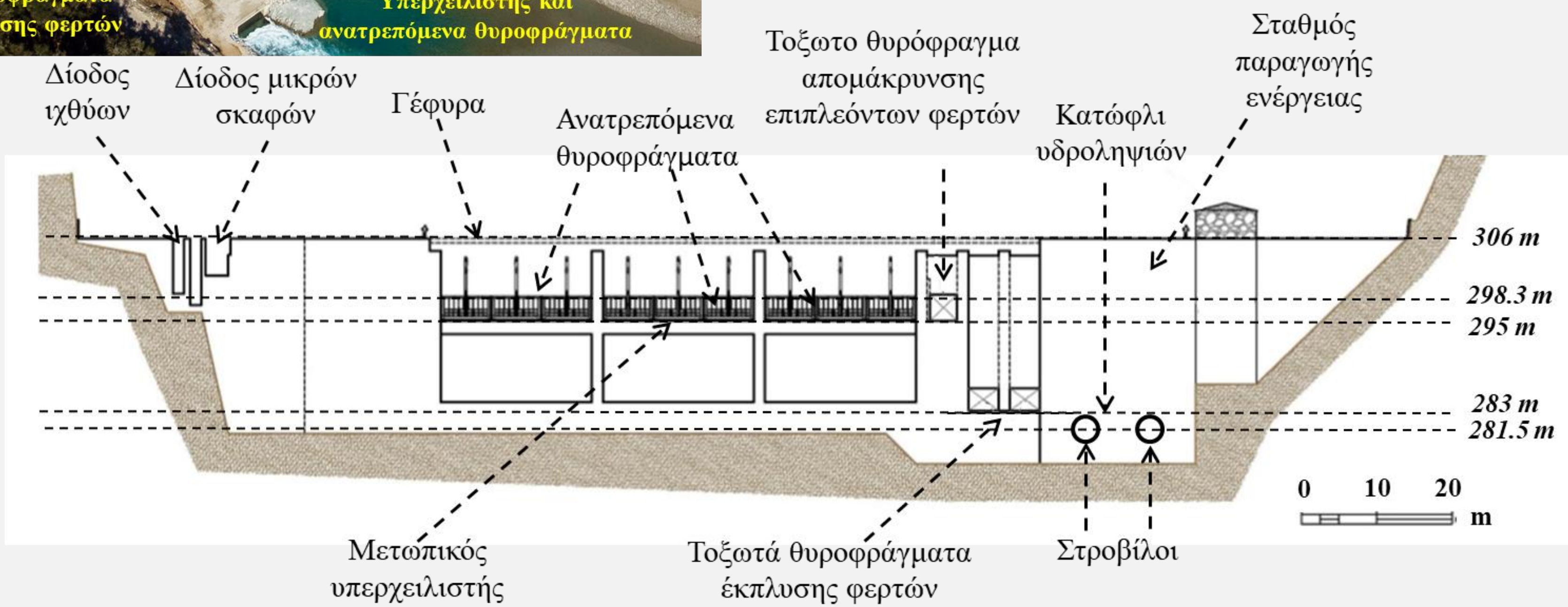


Source: Guide on How to Develop a Small Hydropower Plant, European Small Hydropower Association (ESHA), 2004

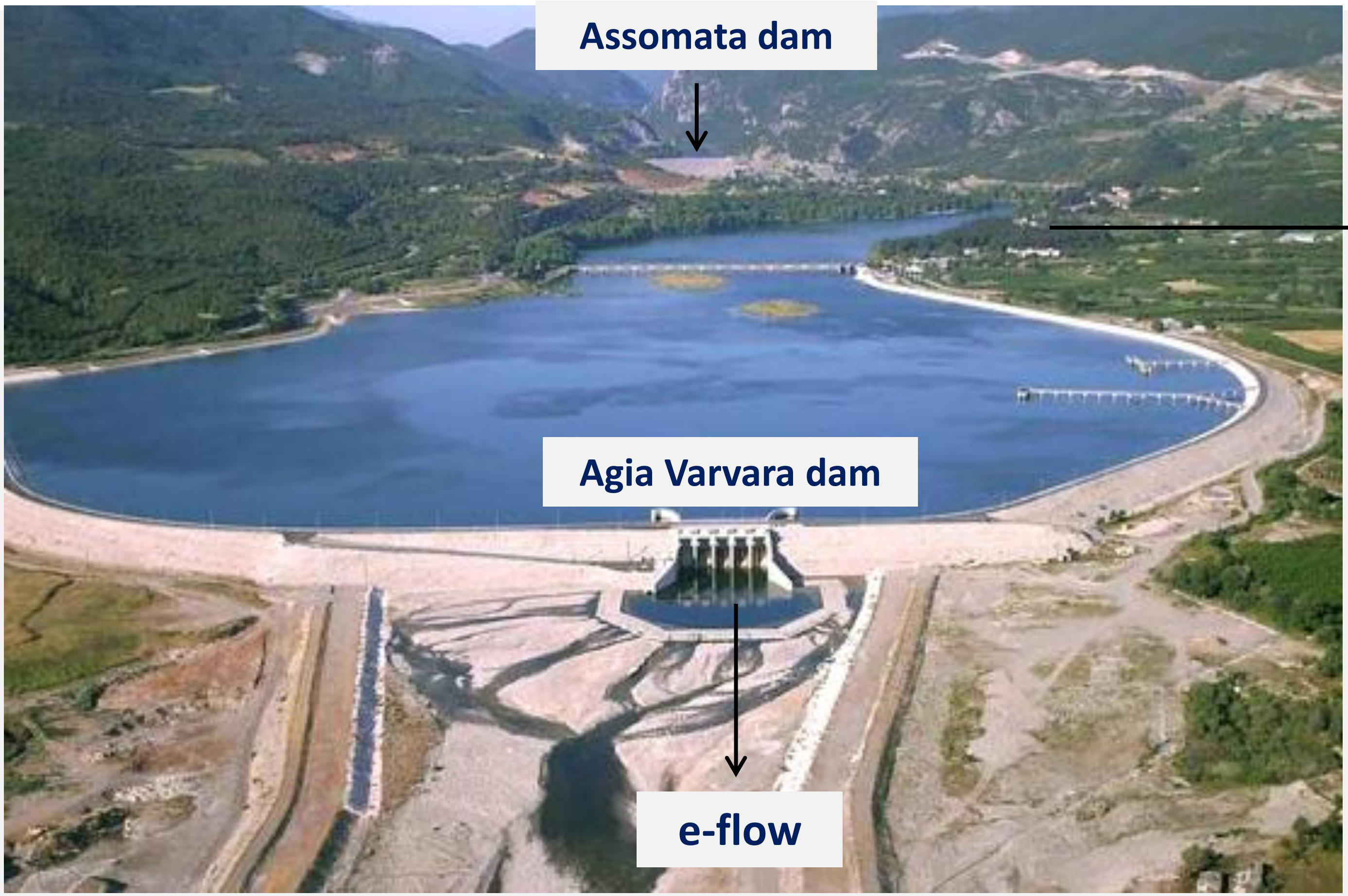
Characteristic examples: Dafnozonara (Achelous)

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)



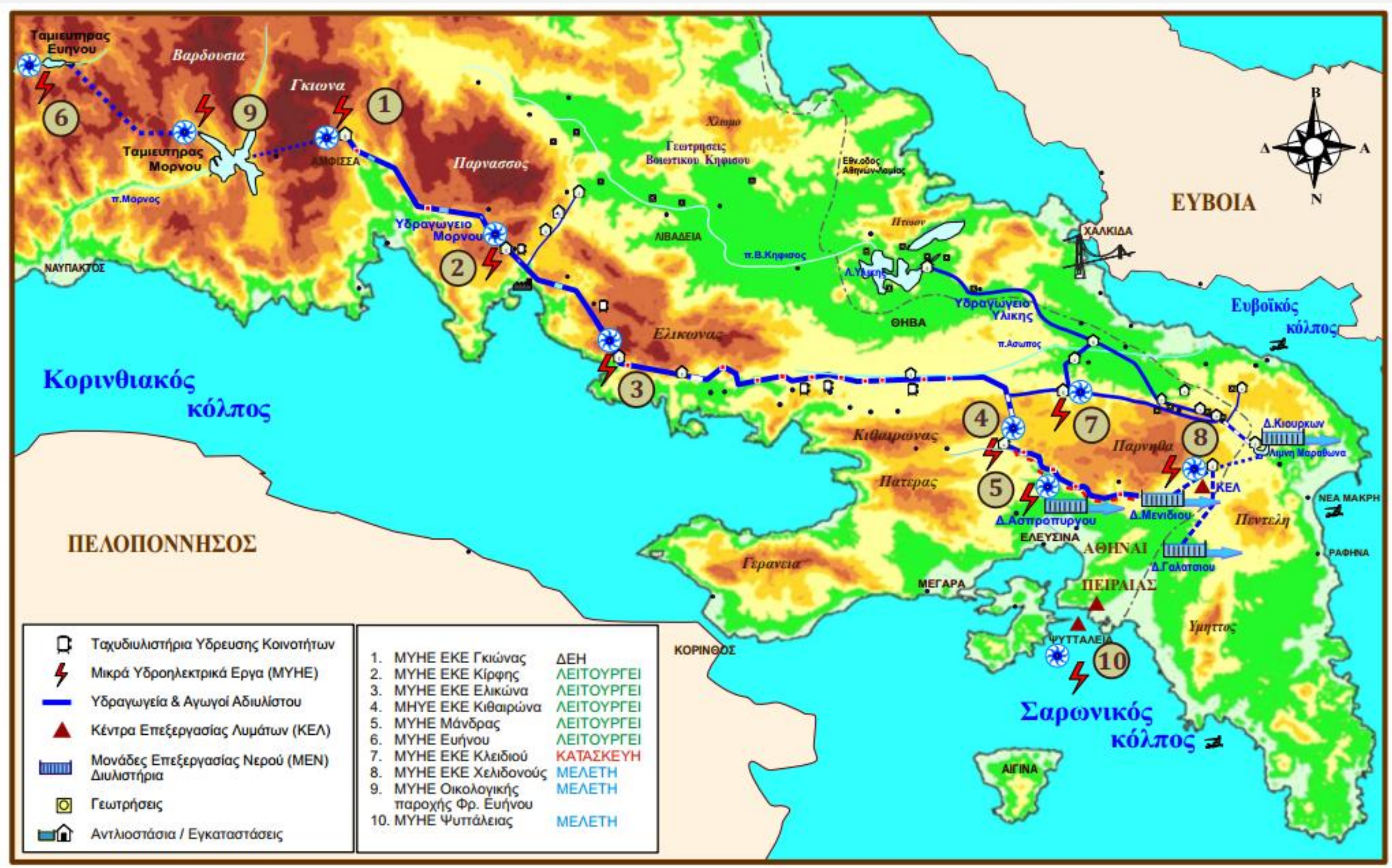
Thessaloniki water supply 7.0 m^3/s

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 m^3/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**.

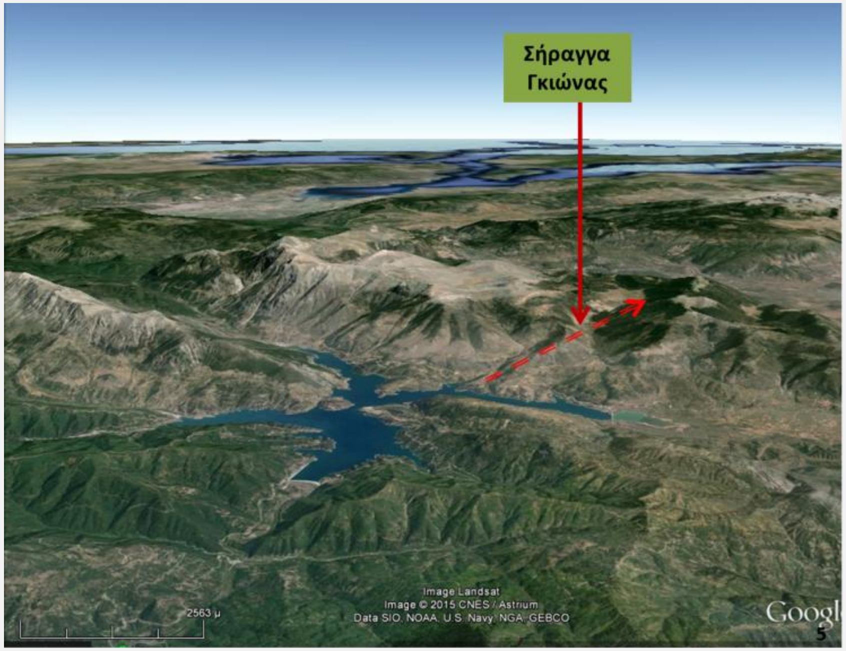
SHPPs as additions: Athens water supply system

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)

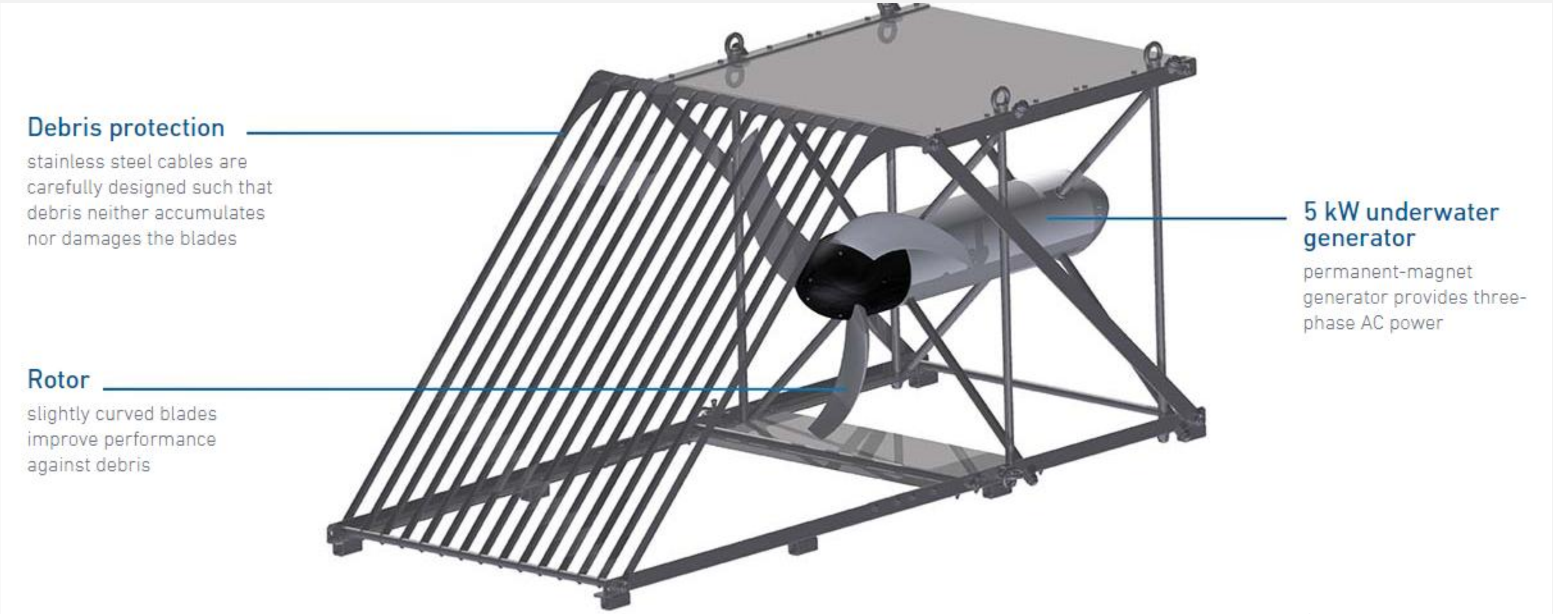


The largest SHPP across Mornos aqueduct is Giona, which operates since 1987. It is located near the city of Amfissa, belongs to the PPC and exploits part of the flow conveyed to Athens. The operational discharge fluctuates from 7.8 to 14.5 m^3/s, and the head from 30.0 to 66.1 m. The installed capacity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

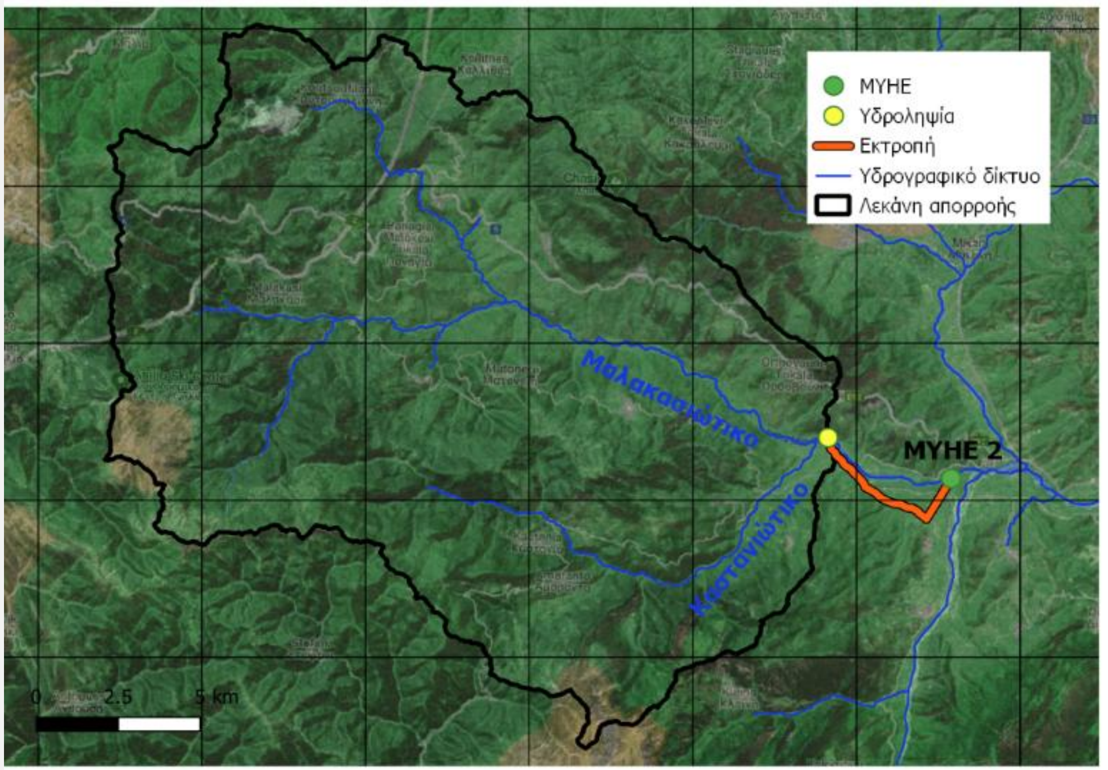
River current turbines



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

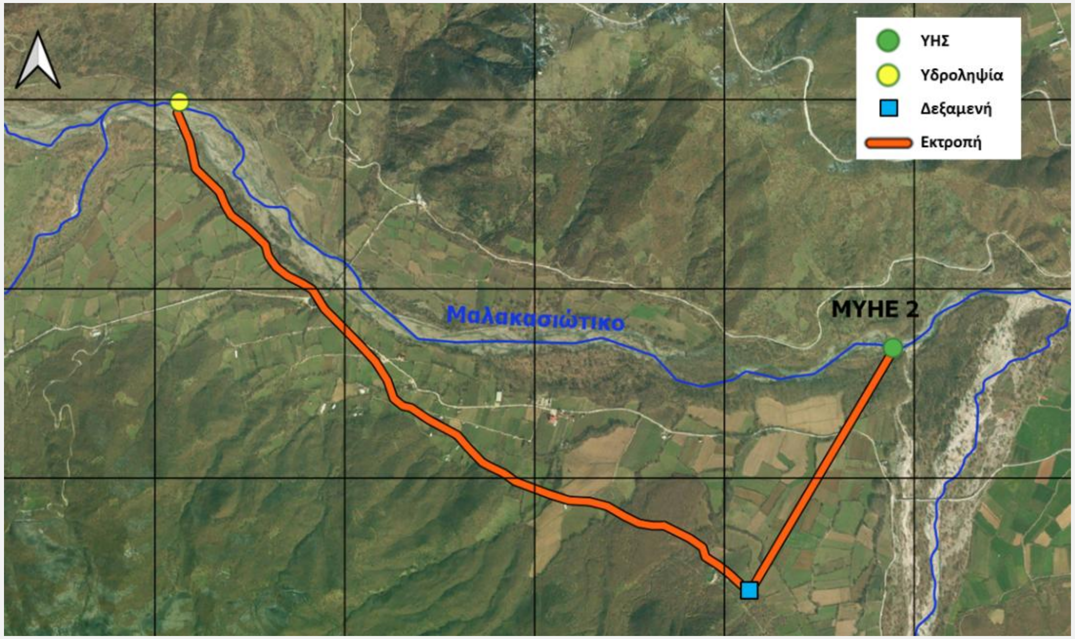
Design issues: Legal framework & constraints

- 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.

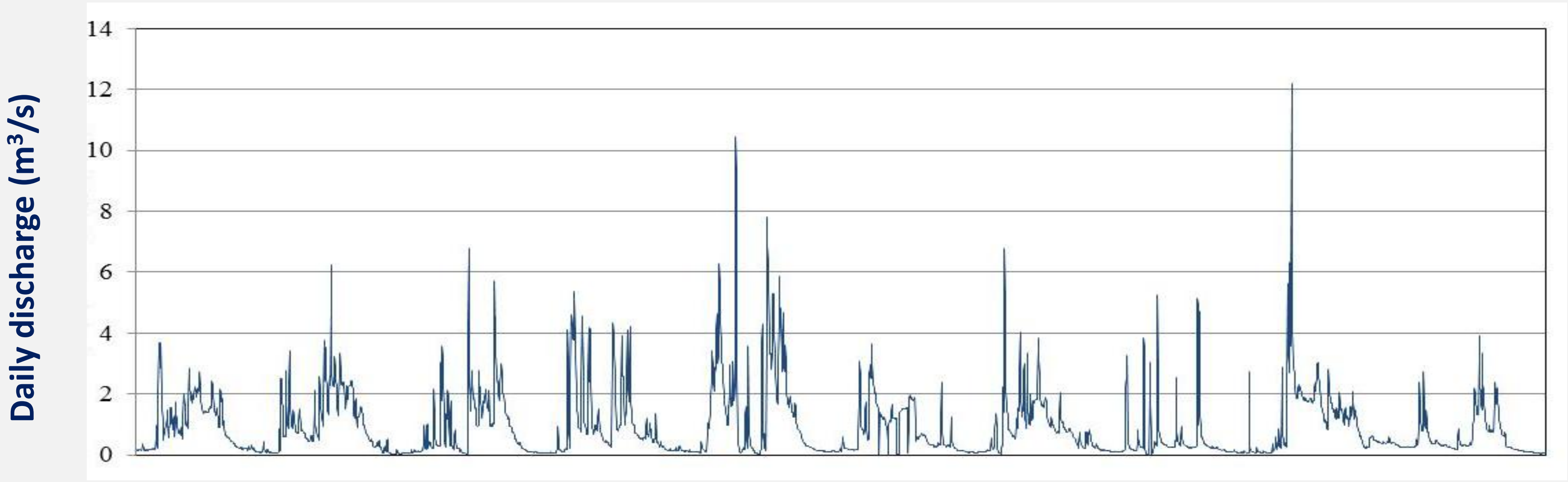
- For $P < 0.30$ MW, the length is up to 0.25 km
- **Recent legal status**: 8 km in Natura areas, 15 km in general (ΔΙΠΑ/ΟΙΚ. 37674/ 2016 Β'2471)



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)
- Hydrological analysis, for given streamflow data, $q(t)$
  - Estimation of environmental flow, q_e (typically constant)
  - Estimation of exploitable discharge:

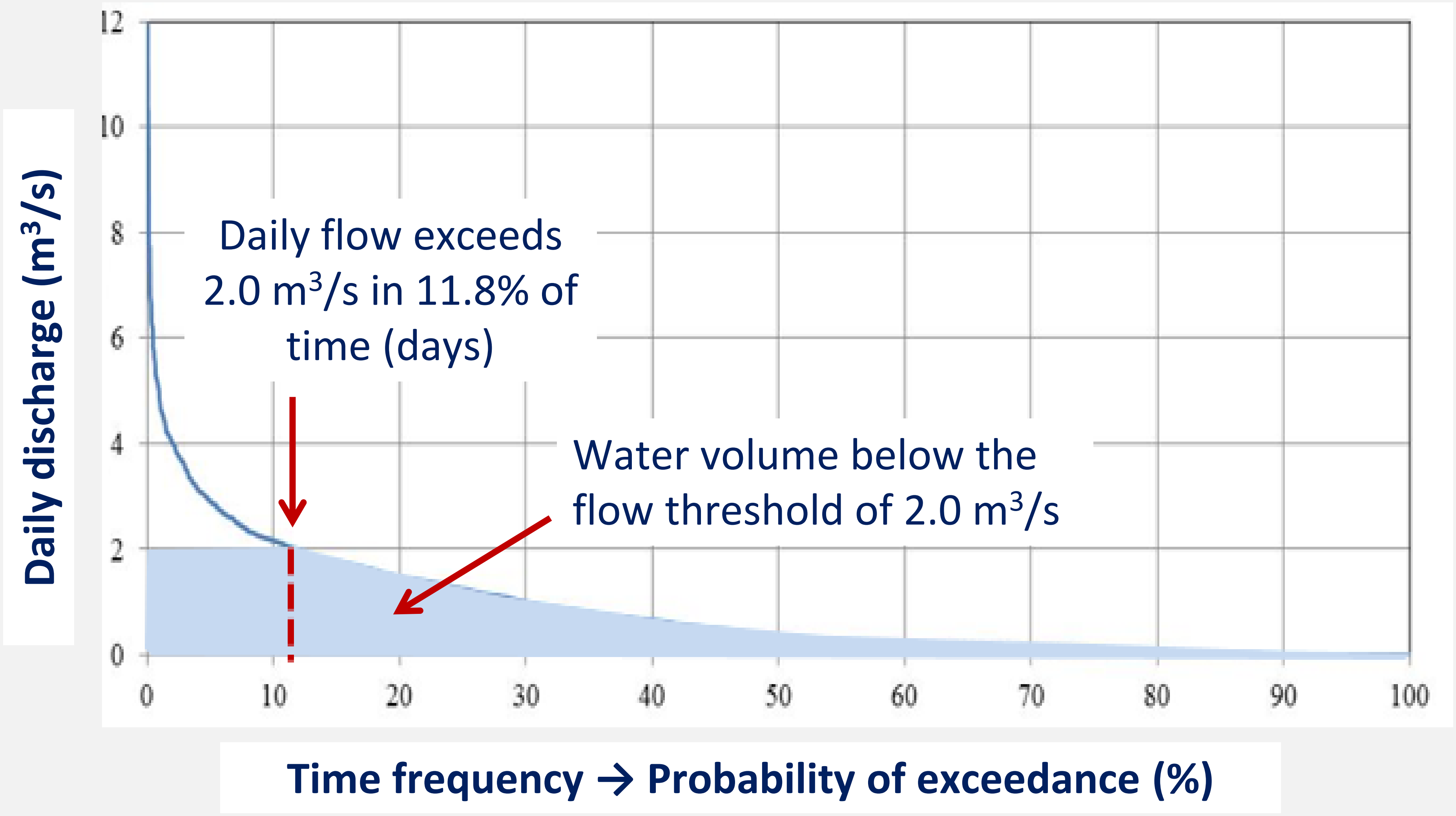
$$q'(t) = \max[0, q(t) - q_e]$$



Flow-duration curves

- 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**.
- 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).

Example of using FDCs



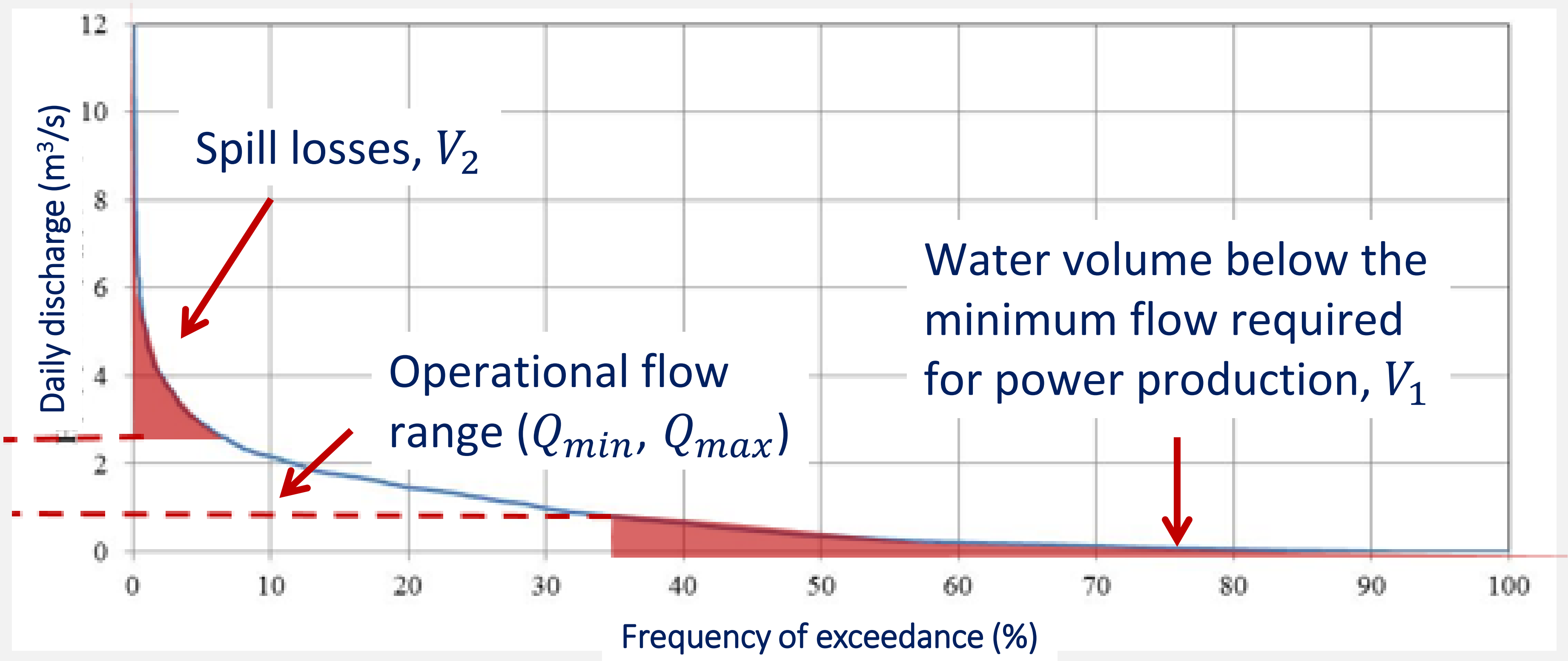
Design issues: Environmental flows

- **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**. 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 flow downstream of SHPPs, defined as the maximum of:
  - 30% of average streamflow during summer months (June to August);
  - 50% of average streamflow of September;
  - 30 L/s, otherwise.
- The above value is typically released through the fish ladder, and must be increased, in case of an important ecosystem downstream.

Design issues: Operational flow range

- A small hydropower plant exploits a feasible **flow range** between a minimum and a maximum discharge value:
  - Q_{min} depends on the on the installed capacity of the smallest turbine and its type.
  - Q_{max} depends on the total installed capacity of all turbines;
- The associated volumes V_1 and V_2 are not exploited for energy production. V_1 is the volume passed through the turbines without generating power, while V_2 cannot be enter the conveyance systems and refers to spill losses.
- Key design objective is the minimization of V_1 and V_2, which is achieved through the combination of several turbines with different power capacity (**turbine mixing**).
- According to the Greek legislation, the design of SHPPs must ensure:
  - **exploitation of at least 75% of the available volume;**
  - **time percentage of operation >30%**.

Graphical solution using the daily FDC



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

Turbine selection: Numerical example 1

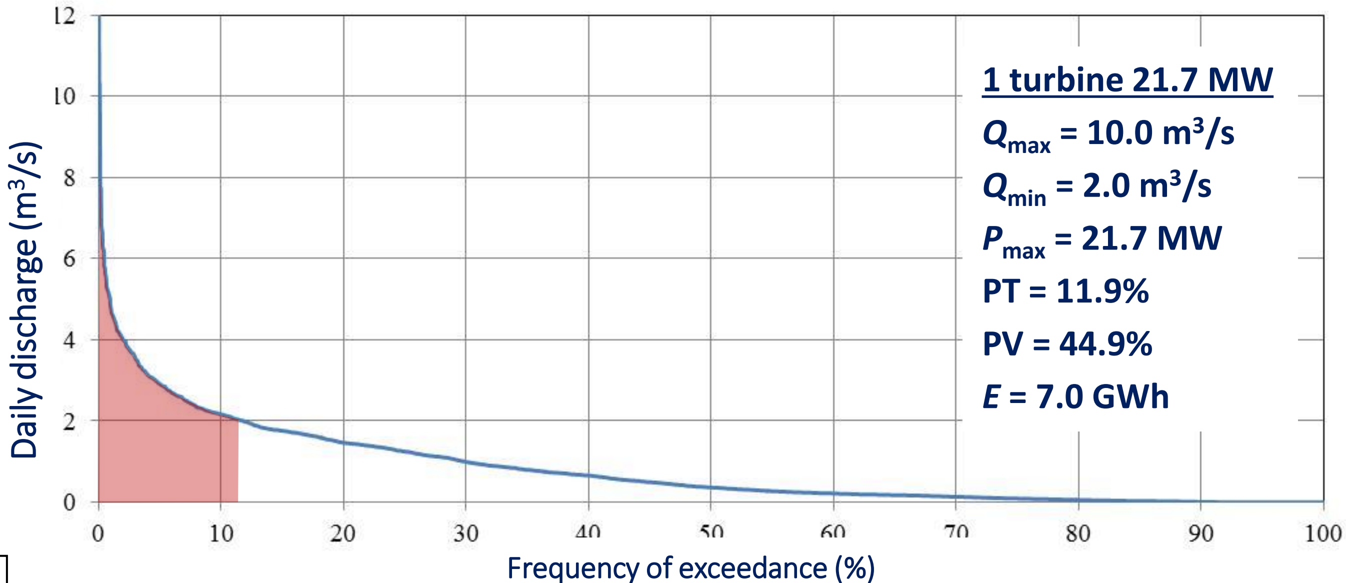
Data

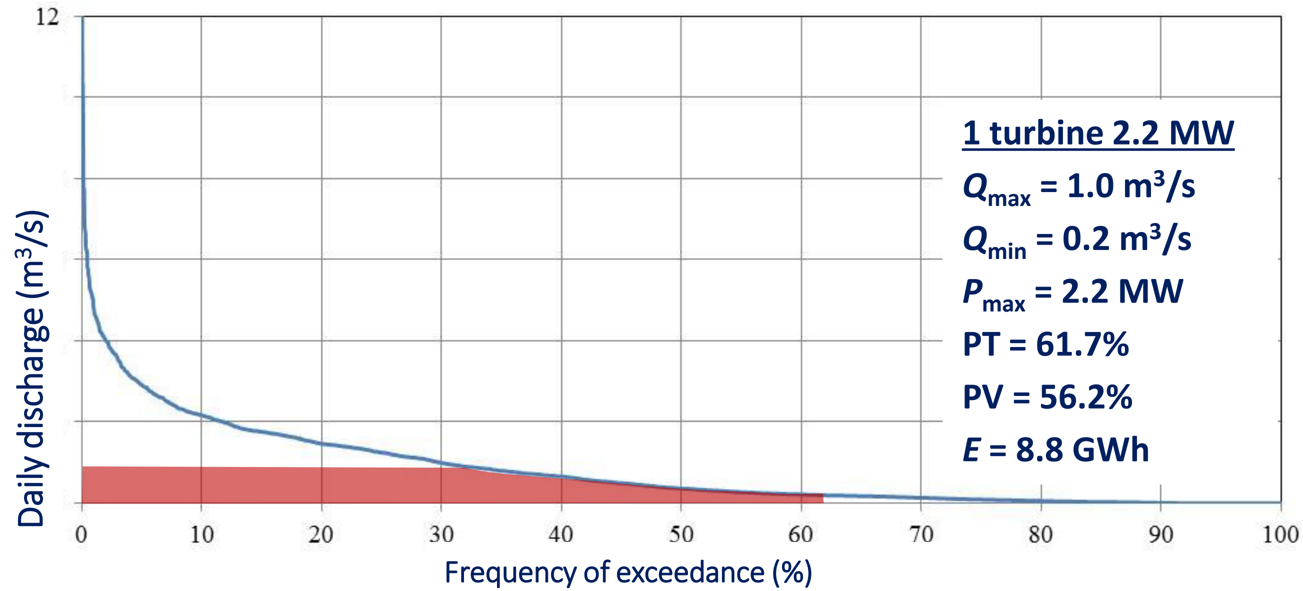
H = 260 m

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





***Q_{min}*, *Q_{max}*:** Min and max exploited 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)

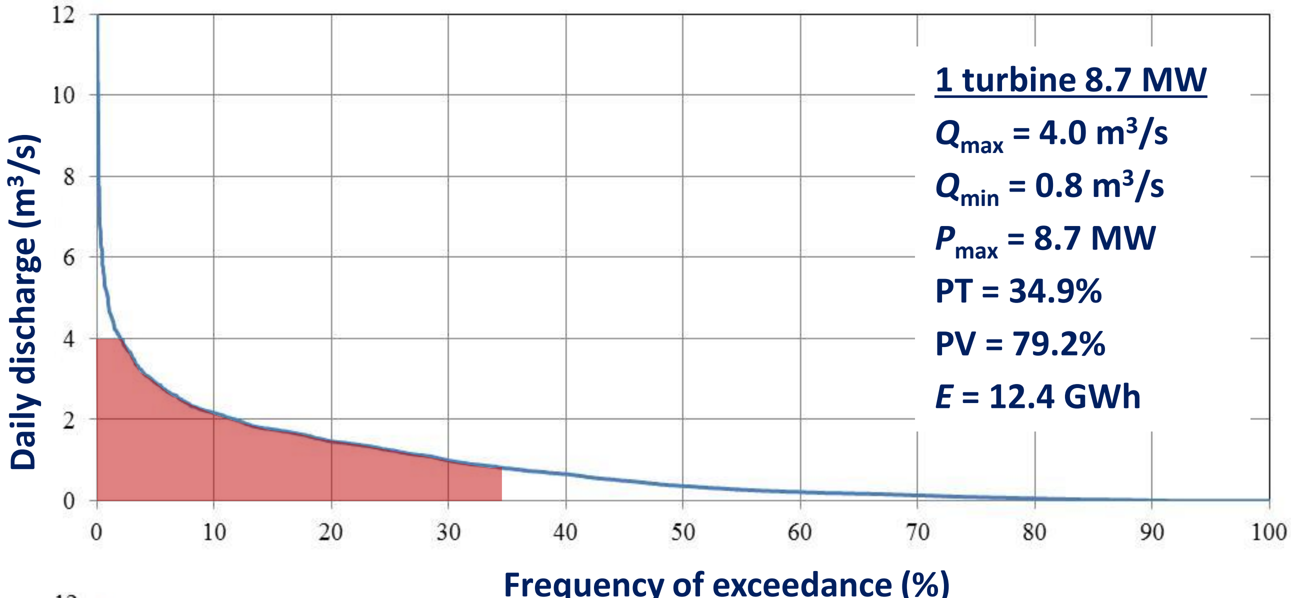
Turbine selection: Numerical example 2

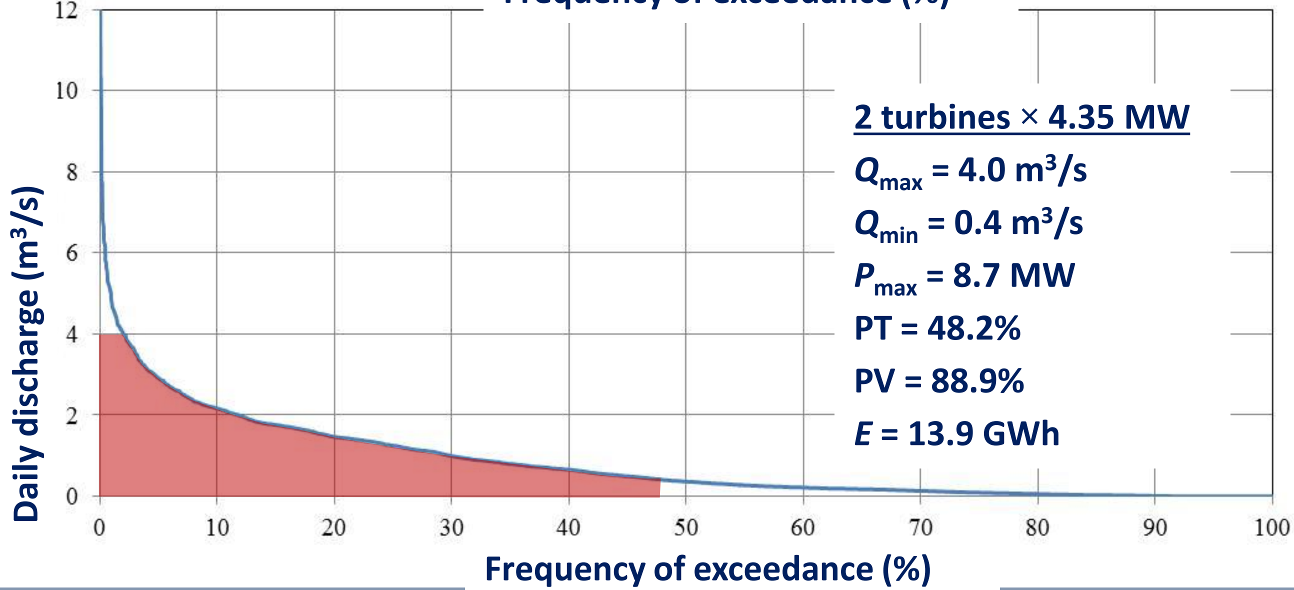
Data

H = 260 m
η = 0.85

Theoretical power for various discharges

Q (m^3/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





Q_{min}, Q_{max}: Min and max exploited discharge (m^3/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
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Q_{min}, Q_{max}: Min and max exploited discharge (m³/s)

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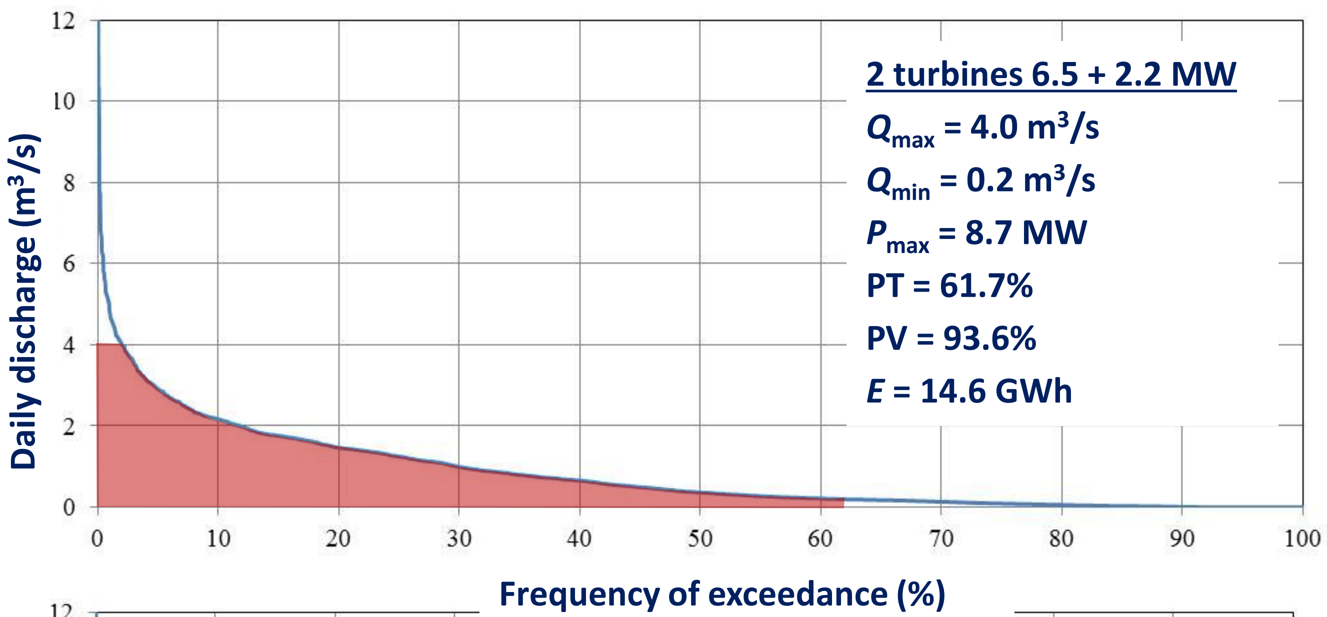
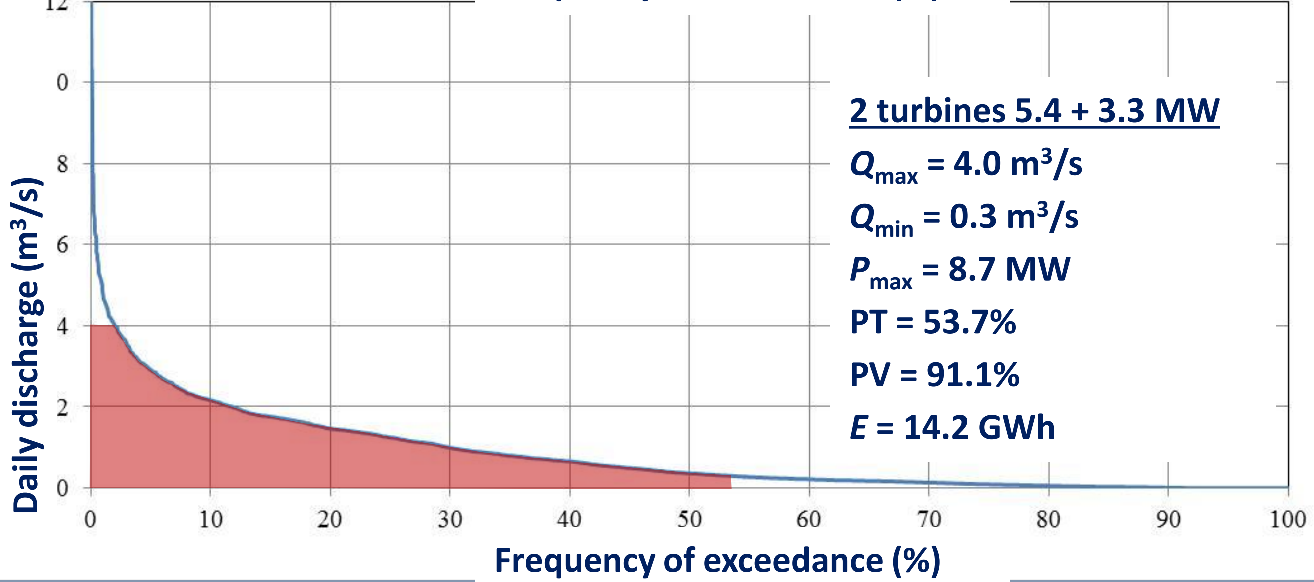
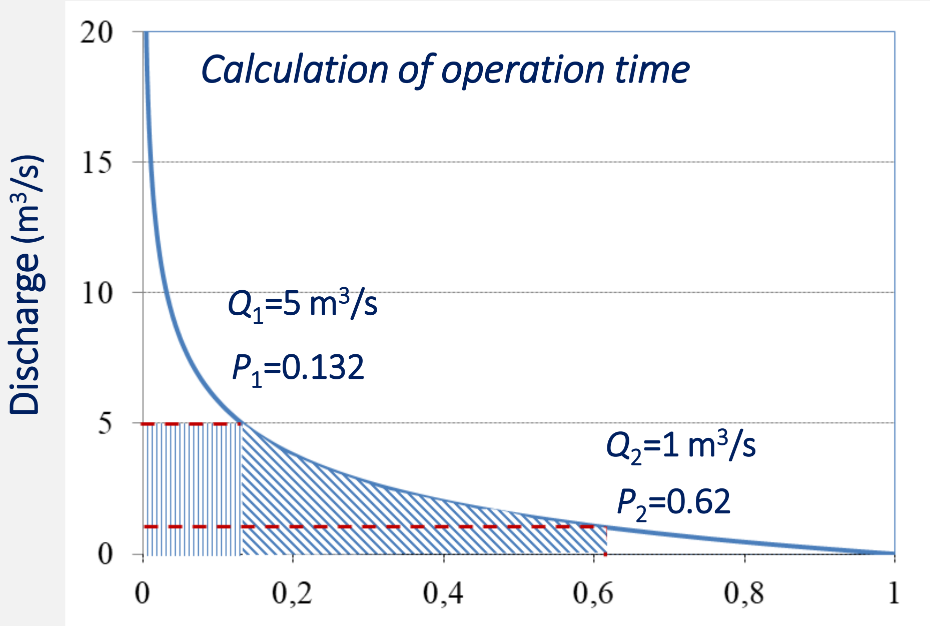
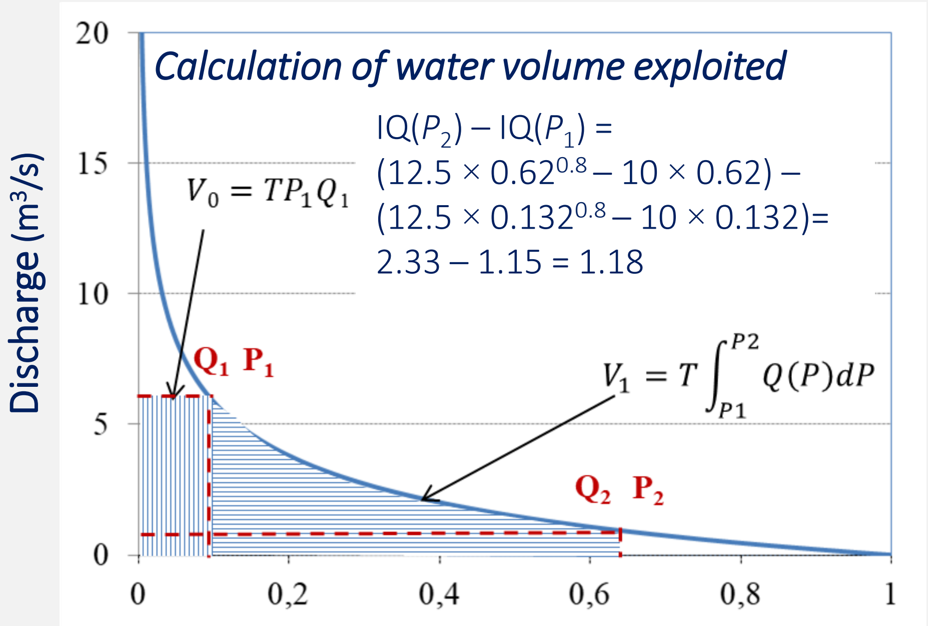




Estimations based on analytical expressions of FDCs

- Single turbine, operating within 1.0 to 5.0 m^3/s
- Analytical FDC formula (q discharge, P probability): $P(QQ) = 1 – F(Q) = (1 + Q/10)^{–5}$
- 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

- Two turbines of power capacity, P_1 and P_2, of specific type.
- Streamflow data 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;
- The **discharge capacity** of the overall turbine system is given by:

$$Q_{max} = \frac{P_1 + P_2}{\gamma\, \eta_{max}\, H_n}$$

where η_{max} is the total efficiency at the maximum discharge, which depends on the turbine type, γ = 9.81 KN/m^3, and H_n is the net head, i.e. the gross head, *H*, after subtracting hydraulic losses, $\Delta H = f(Q_{max})$.

- The **maximum discharge** that can pass from each turbine is estimated as:

$$Q_{i,max} = P_i/(P_1 + P_2)Q_{max}$$

- The **minimum discharge** of each turbine is expressed as percentage of the maximum one, i.e. $Q_{i,min} = \theta_i\, Q_{i,max}$ (θ ranges from 10 to 40%).

Design through simulation: Calculations

- Let Q be the streamflow arriving at the intake (total streamflow, 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 electicity 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.

Design through simulation: Performance metrics

- At the end of each time step the following quantities are calculated:
  - The volume exploited by each turbine:

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

  - The total energy produced by the system, $E = E_1 + E_2$.
- Performance metrics, calculated at the end of simulation:
  - 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 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.

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