Postgraduate program:
Environment and Development

National Technical
University of Athens

Course: Energy and Environment

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 under 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

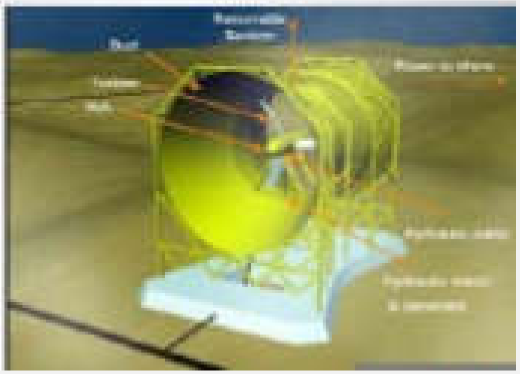
Settled downstream of large dams to take advantage of the environmental flow, which is released from an independent intake (e.g. bottom outlet)

Run-off-river

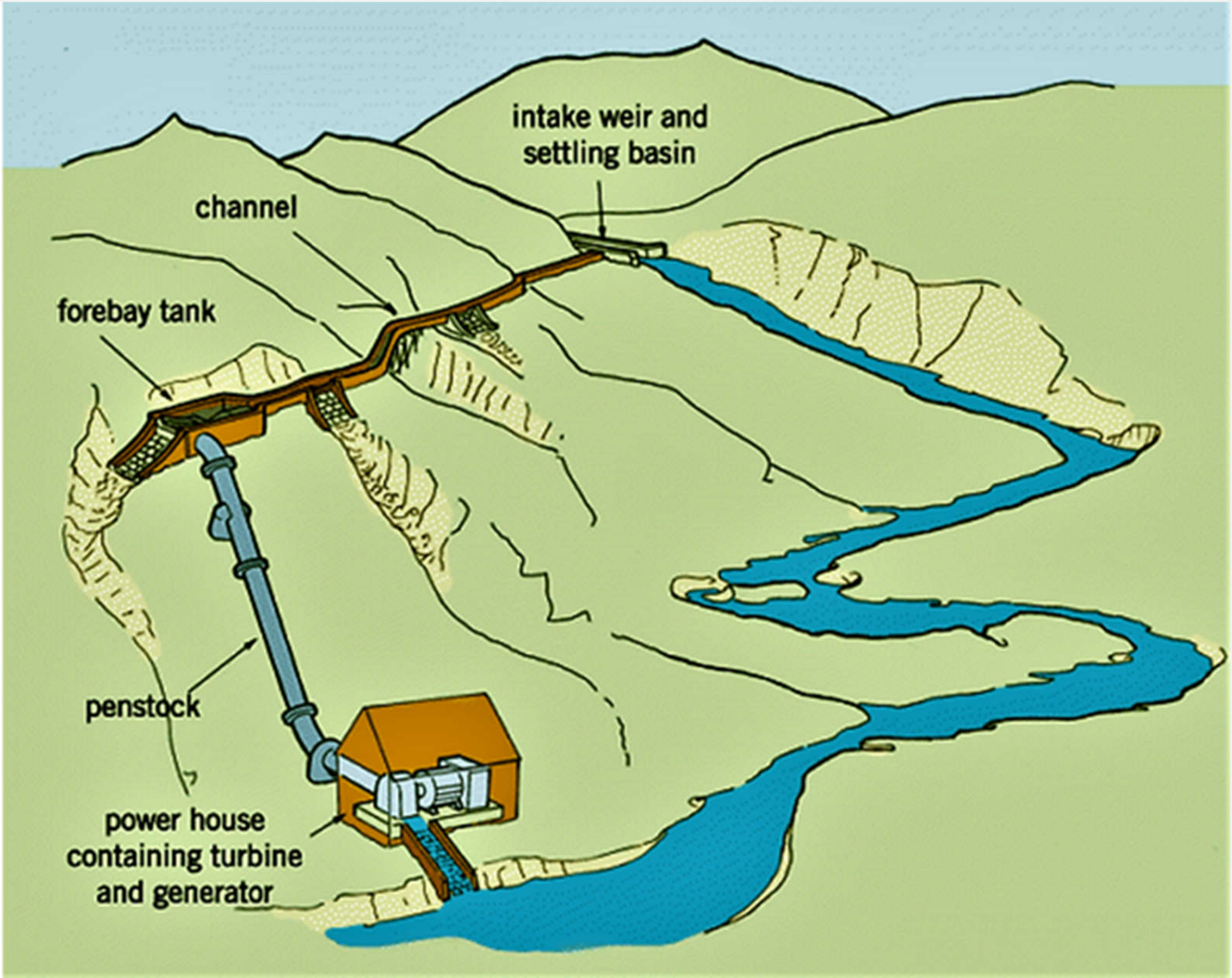
Utilizes the streamflow as it arrives, without the ability to store water. This is the most common type of SHPPs.

In-stream

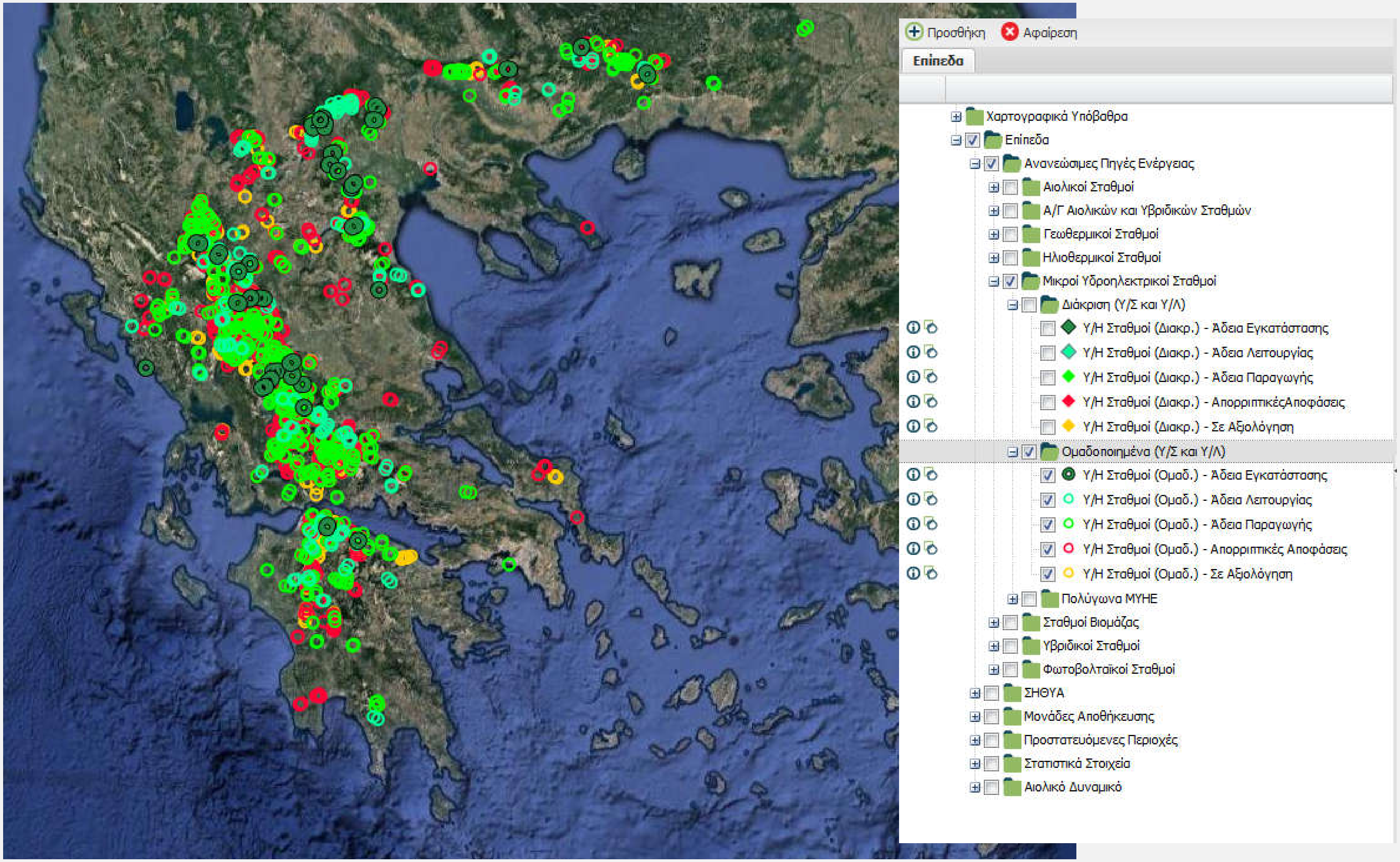
Utilizes the streamflow velocity to produce electric energy. Very few projects of this type exist in rivers.



Typical layout of run-off-river plants



SHPPs in Greece (110 in operation, ~85% still unexploited)



- ⊞ Χαρτογραφικά Υπόβαθρα
- ⊟ ☑ Επίπεδα
  - ⊟ ☑ Ανανεώσιμες Πηγές Ενέργειας
    - ⊞ ☐ Αιολικοί Σταθμοί
    - ⊞ ☐ Α/Γ Αιολικών και Υβριδικών Σταθμών
    - ⊞ ☐ Γεωθερμικοί Σταθμοί
    - ⊞ ☐ Ηλιοθερμικοί Σταθμοί
    - ⊟ ☑ Μικροί Υδροηλεκτρικοί Σταθμοί
      - ⊟ ☐ Διάκριση (Υ/Σ και Υ/Λ)
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        - ☐ ◆ Υ/Η Σταθμοί (Διακρ.) - Άδεια Λειτουργίας
        - ☐ ◆ Υ/Η Σταθμοί (Διακρ.) - Άδεια Παραγωγής
        - ☐ ◆ Υ/Η Σταθμοί (Διακρ.) - ΑπορριπτικέςΑποφάσεις
        - ☐ ◆ Υ/Η Σταθμοί (Διακρ.) - Σε Αξιολόγηση
      - ⊟ ☑ Ομαδοποιημένα (Υ/Σ και Υ/Λ)
        - ☑ ◎ Υ/Η Σταθμοί (Ομαδ.) - Άδεια Εγκατάστασης
        - ☑ ○ Υ/Η Σταθμοί (Ομαδ.) - Άδεια Λειτουργίας
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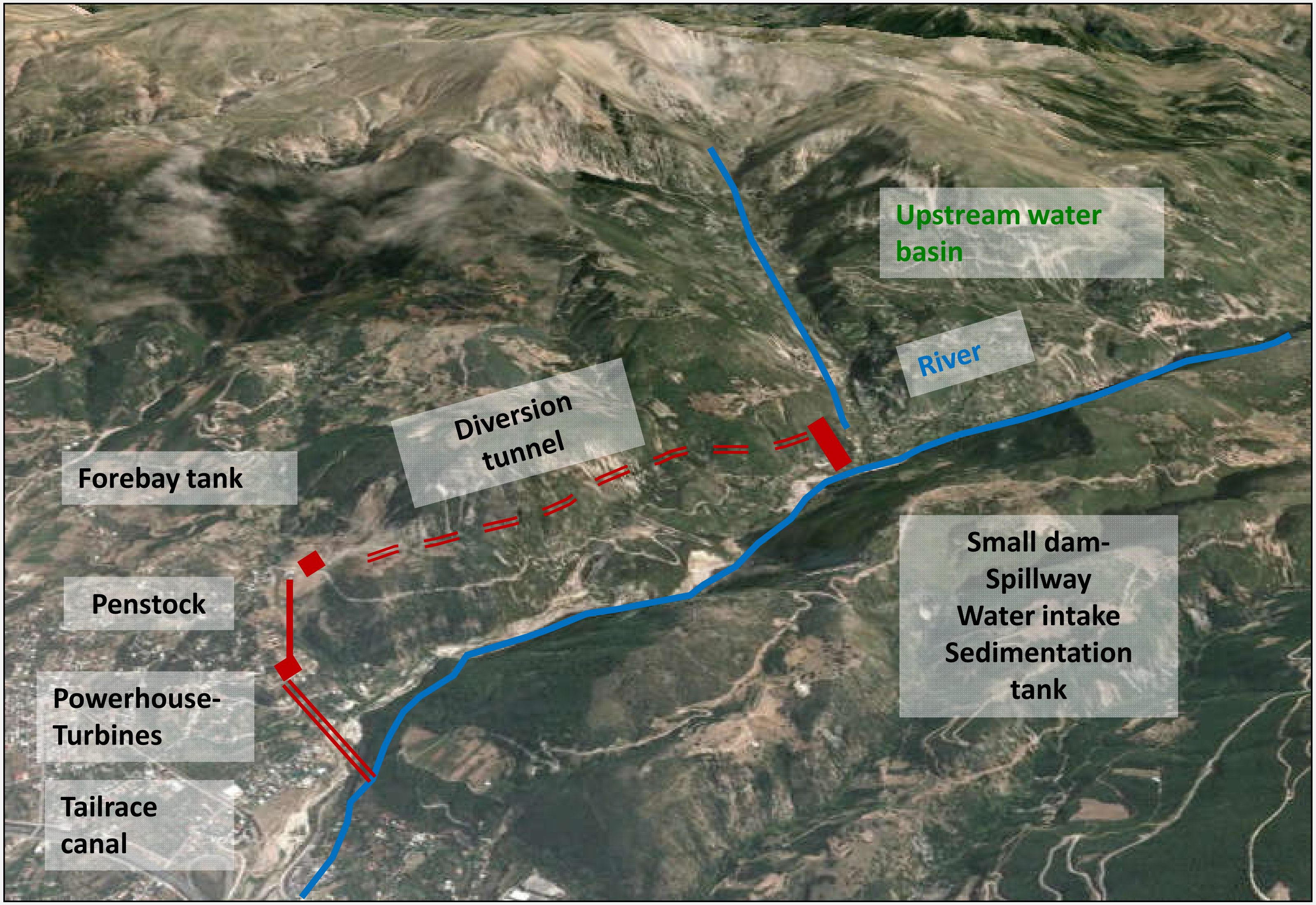
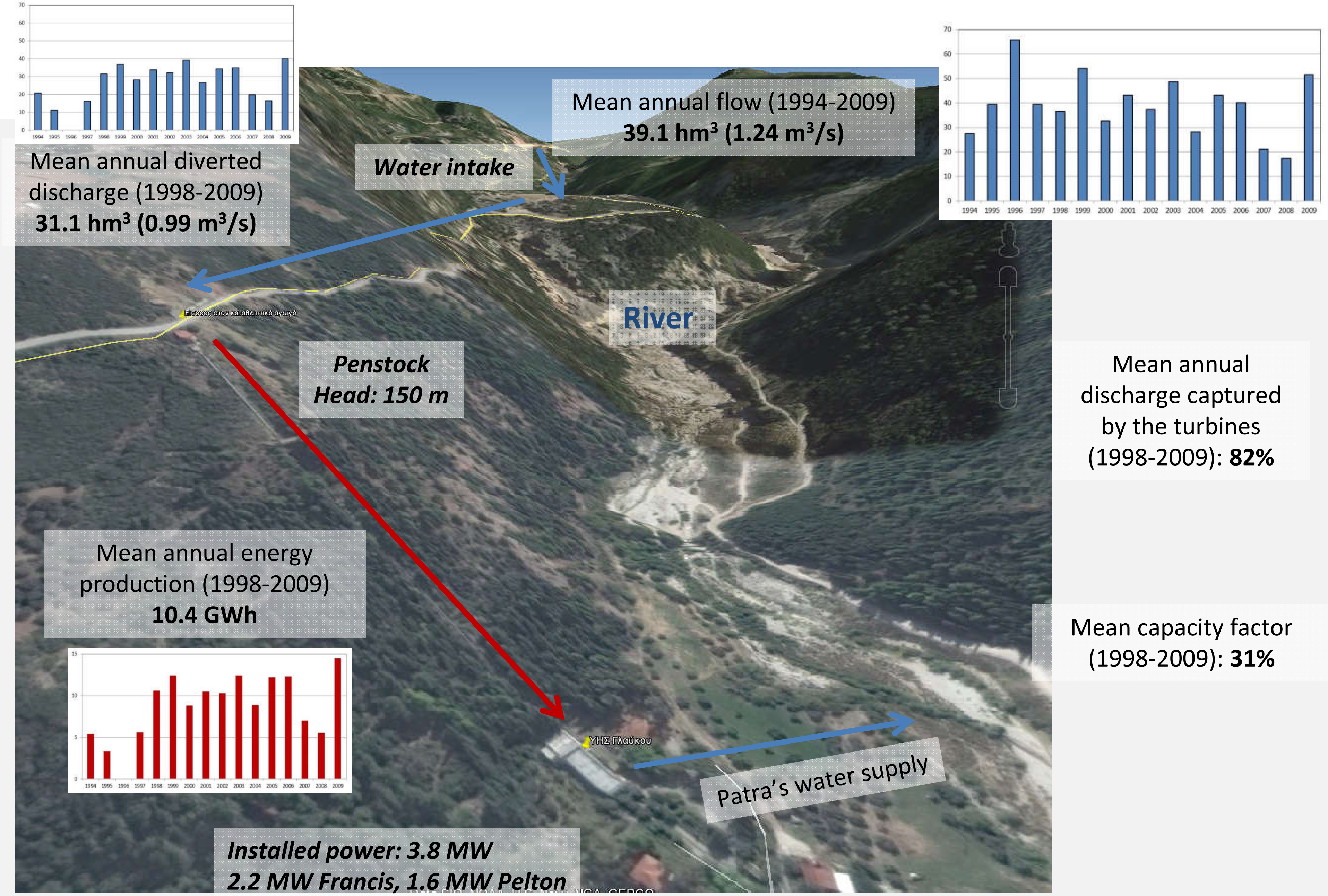
    - ⊞ ☐ Σταθμοί Βιομάζας
    - ⊞ ☐ Υβριδικοί Σταθμοί
    - ⊞ ☐ Φωτοβολταϊκοί Σταθμοί
  - ⊞ ☐ ΣΗΘΥΑ
  - ⊞ ☐ Μονάδες Αποθήκευσης
  - ⊞ ☐ Προστατευόμενες Περιοχές
  - ⊞ ☐ Στατιστικά Στοιχεία
  - ⊞ ☐ Αιολικό Δυναμικό

Characteristic examples: Glafkos (Patra)

The project was constructed in 1927 and it is one of the first hydroelectric works in Greece





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

Water intake

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

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

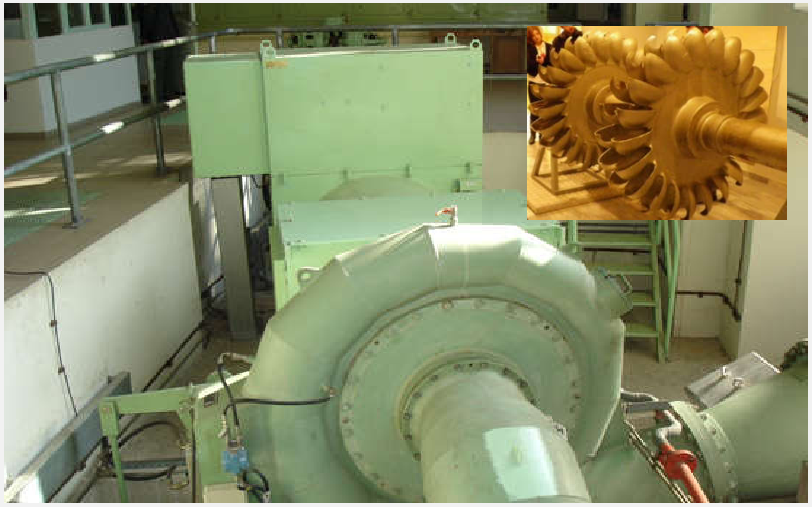
Installed power: 3.8 MW
2.2 MW Francis, 1.6 MW Pelton

Dam water intake

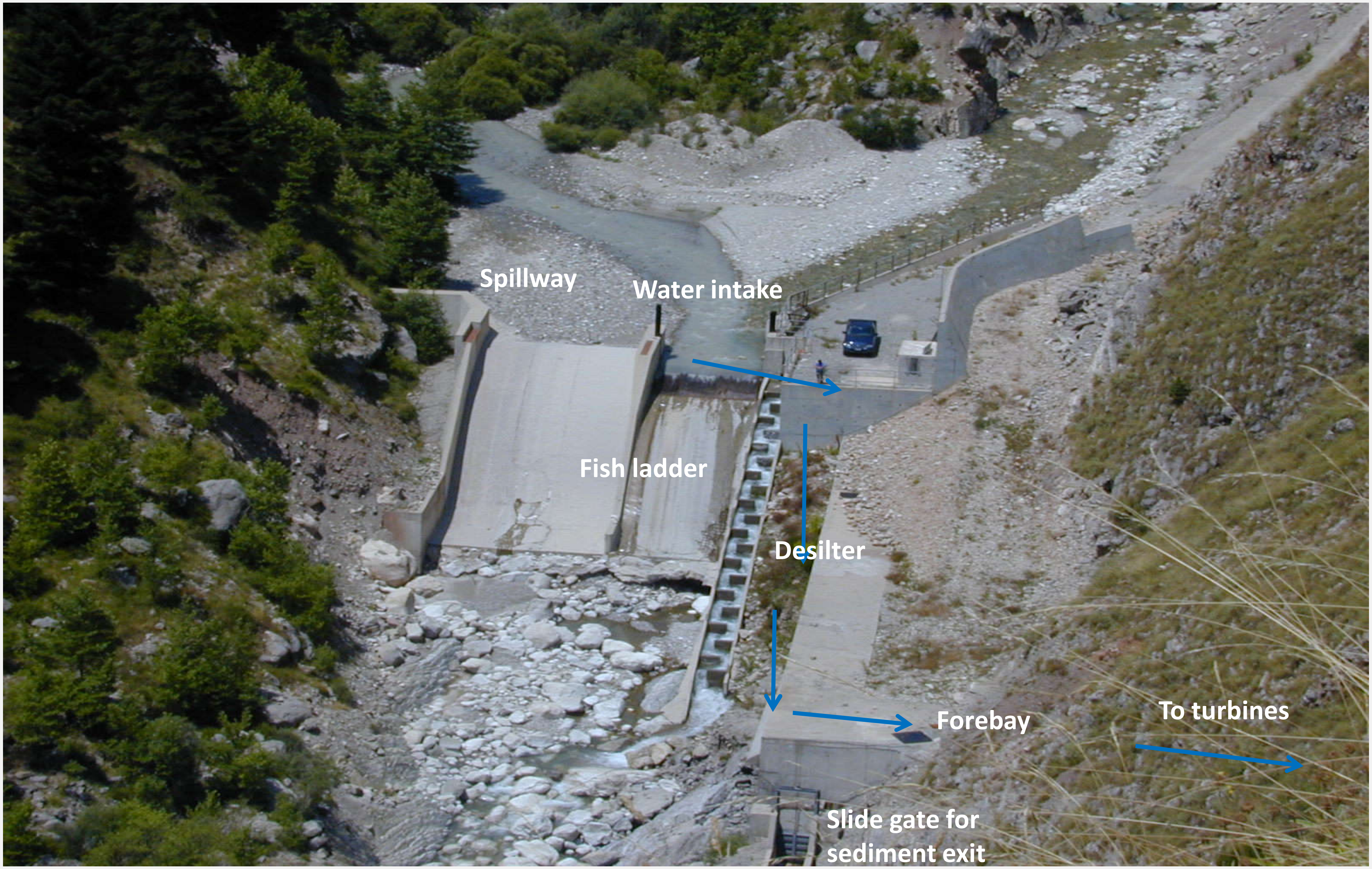
Sand trap – desilter – sedimentation tank

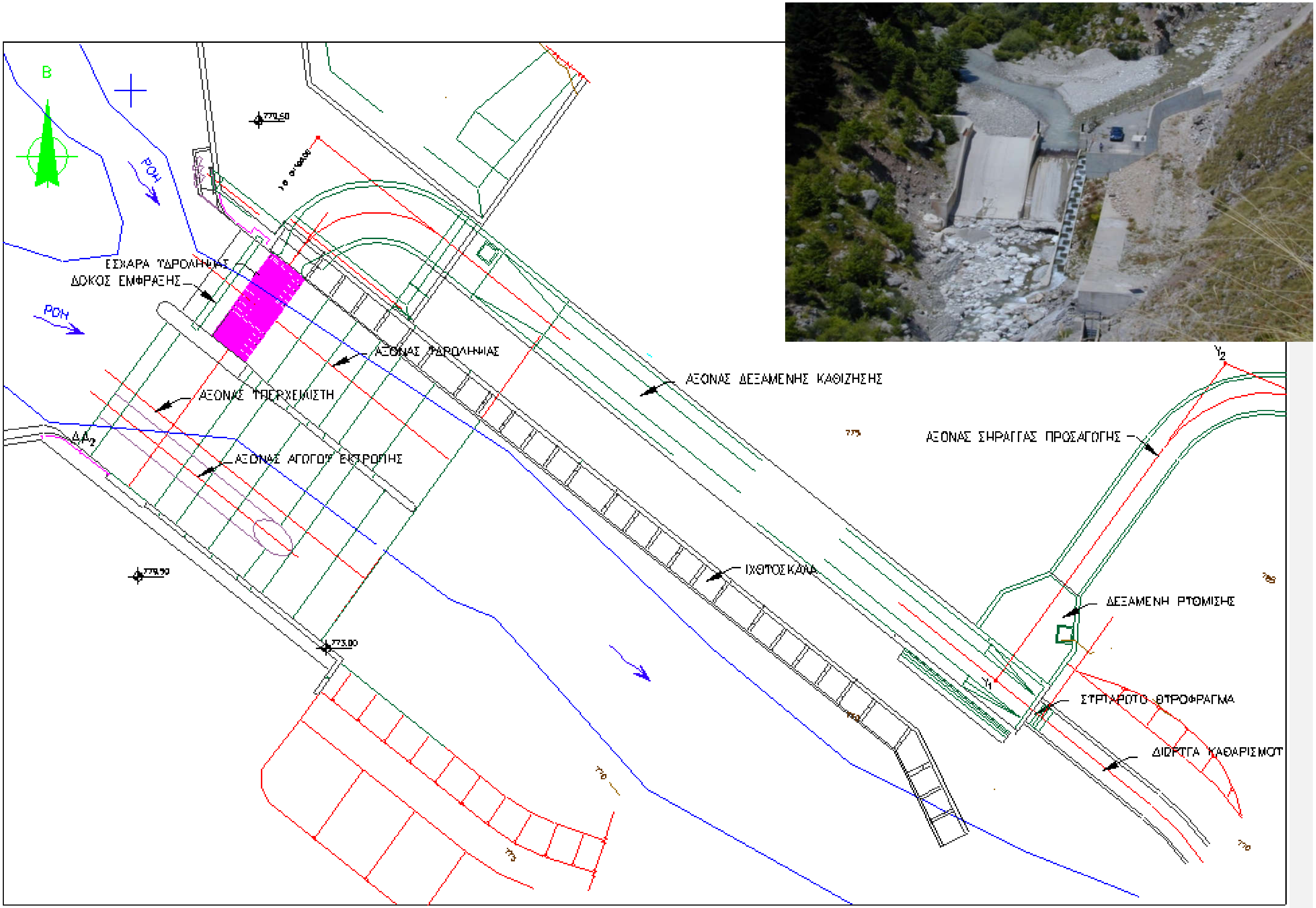
Penstock

Turbines



Characteristic examples: Theodoriana (Epirus)

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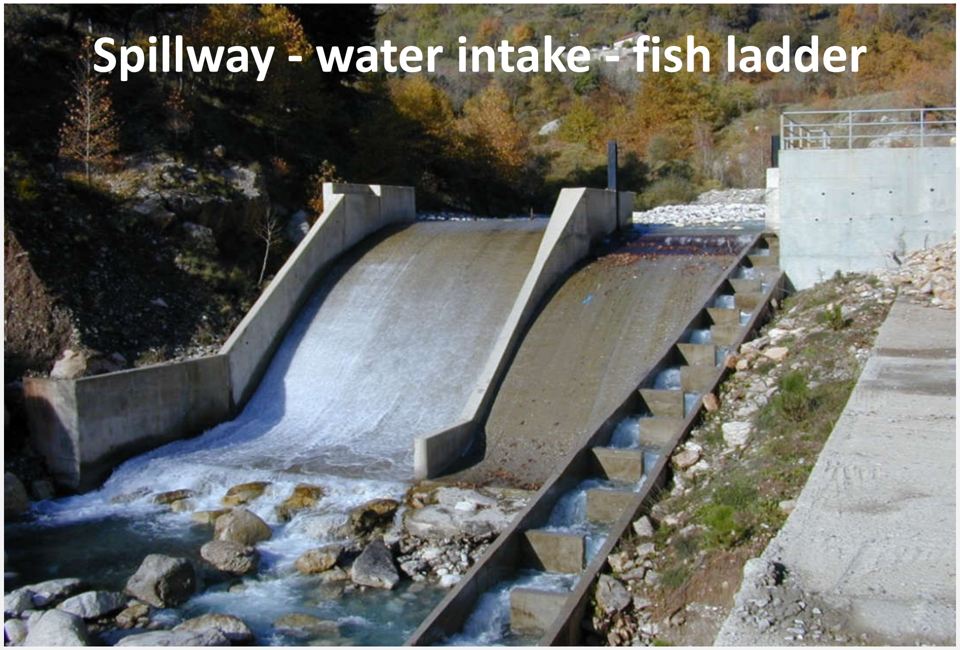
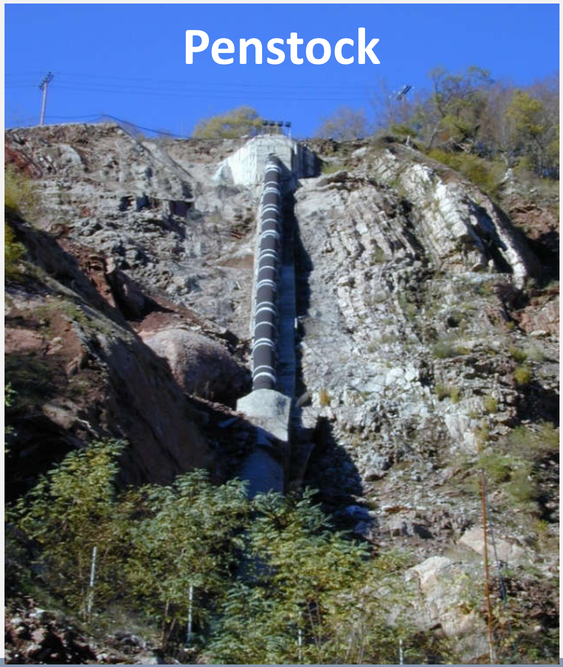

Spillway - water intake - fish ladder


Water intake


Penstock


Power house

Characteristic examples: Thermorema (Sterea Hellas)

Desilter (sand traps)

Trash rack of water intake

Headwater channel - sand traps

Forebay tank

Penstock

Photos: ΔΕΛΤΑ Project

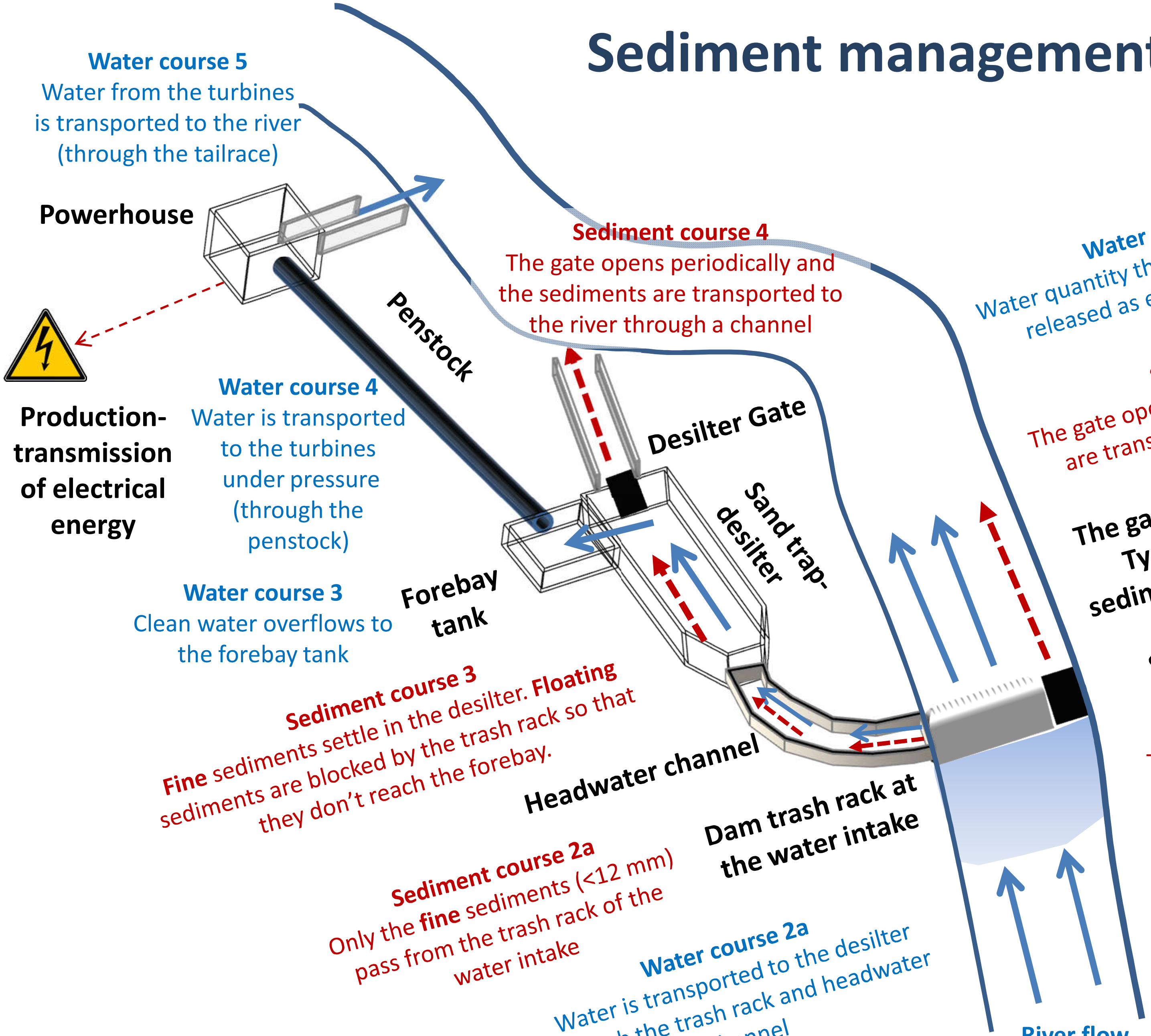
Characteristic examples: Thermorema (Sterea Hellas)

Bed load: Mainly includes stony material, such as gravel and cobbles. These are transported on or near the river bed (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 in the water.

Sediment management: Layout



Water course 5
Water from the turbines is transported to the river (through the tailrace)

Sediment course 4
The gate opens periodically and the sediments are transported to the river through a channel

Water course 2b
Water quantity that overflows or/and is released as environmental flow

Sediment course 2b
The gate opens periodically and the sediments are transported downstream of the dam

The gate is not necessary in case of Tyrolean weirs as the coarse sediments pass above the structure

Water course 4
Water is transported to the turbines under pressure (through the penstock)

Water course 3
Clean water overflows to the forebay tank

Sediment course 3
Fine sediments settle in the desilter. **Floating** sediments are blocked by the trash rack so that they don't reach the forebay.

Sediment course 1
The sediments (mainly **coarse**) are accumulated upstream of the weir

Water course 1
Water is collected upstream of the weir

Sediment course 2a
Only the **fine** sediments (<12 mm) pass from the trash rack of the water intake

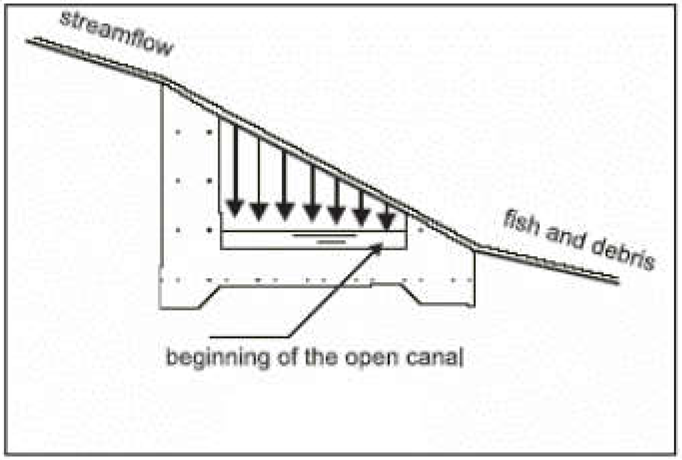
Water course 2a
Water is transported to the desilter through the trash rack and headwater channel

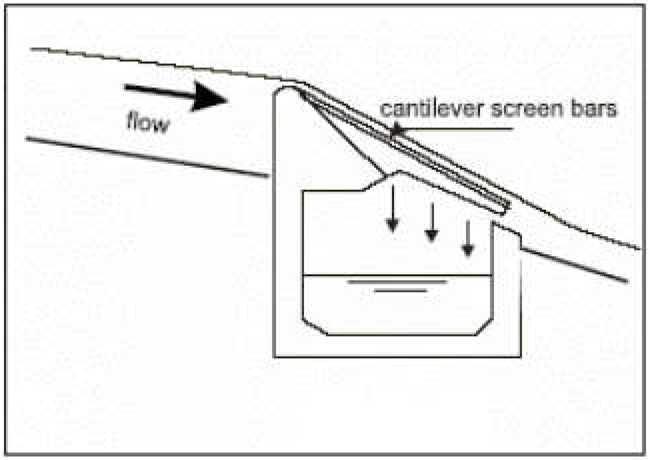
Drop intakes – Tyrolean weirs – water intakes for mountainous regions

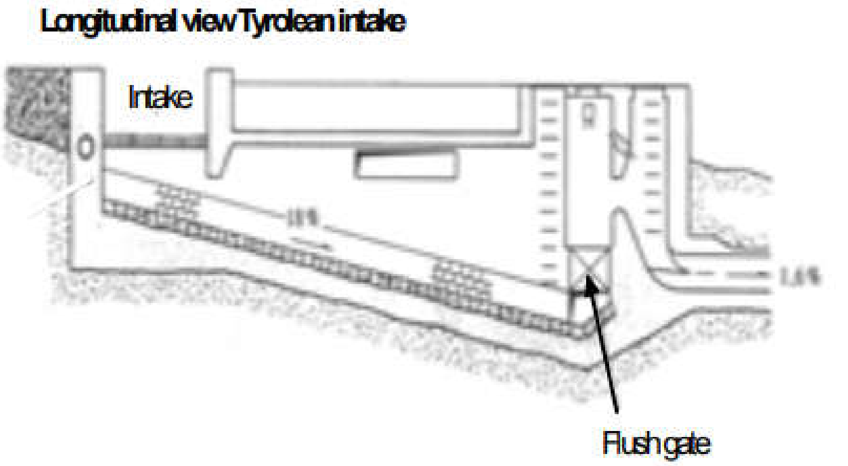
- **Tyrolean weir** is a water intake structure in which water is abstracted from the main flow through a trash rack (screen) over a gutter.
- The gutter is usually made of concrete and built into the river bed.
- The trash rack on the crest should slope downstream (15-30 degrees), to ensure adequate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

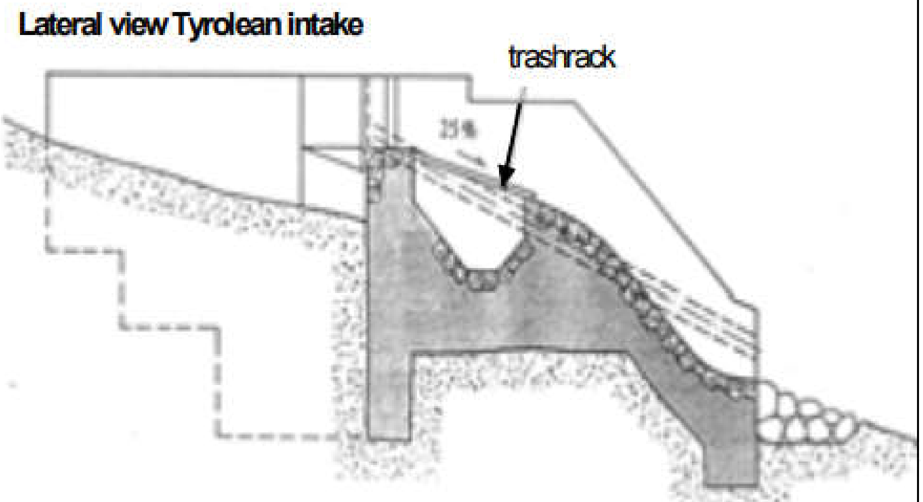
Kerasovo (Epirus)

Drop intakes – Tyrolean weirs – water intakes for mountainous regions





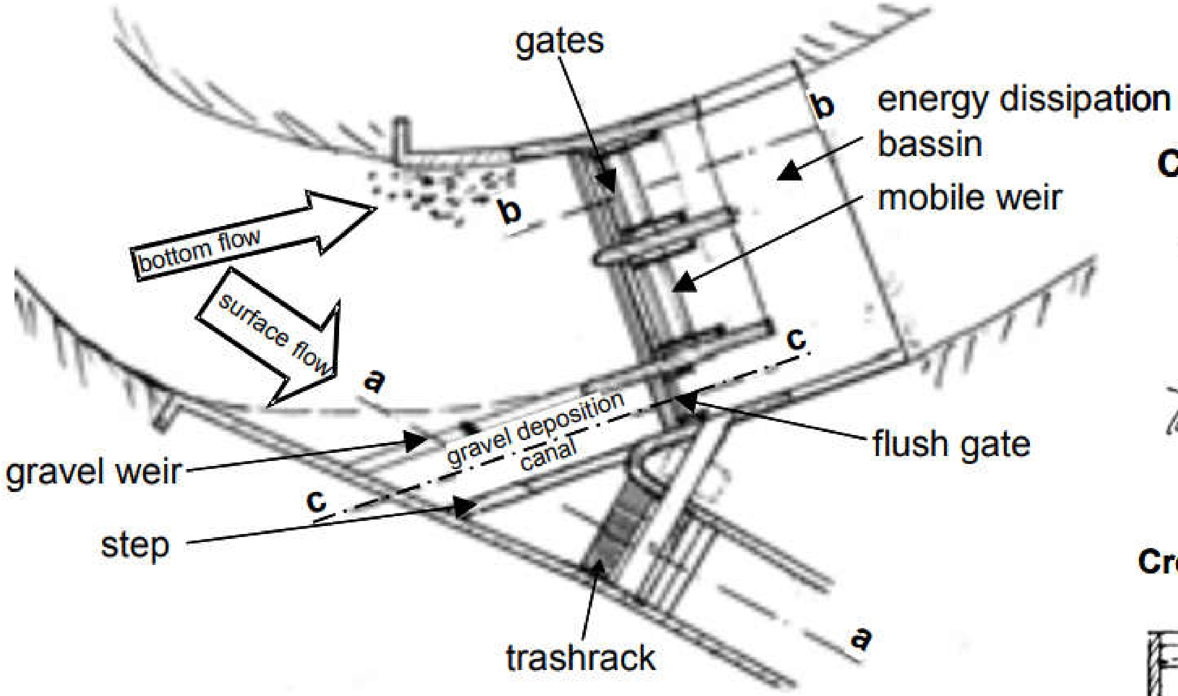




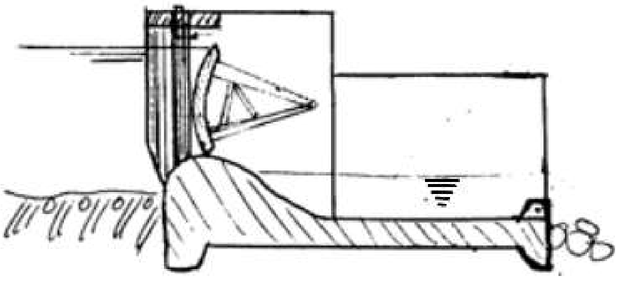
Source: Guide on How to Develop a Small Hydropower Plant, European Small Hydropower Association (ESHA), 2004

Lateral intakes

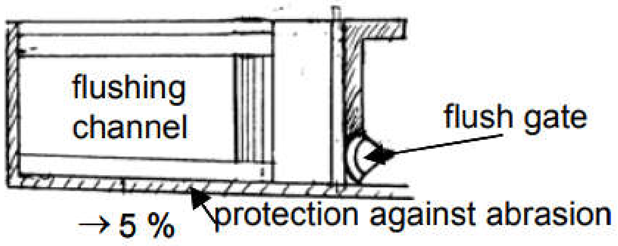
Plan view



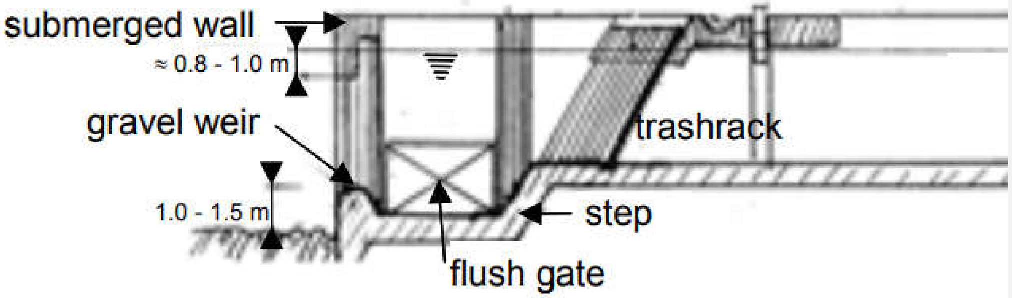
Cross section b - b : Weir /dam



Cross section c - c : Gravel weir

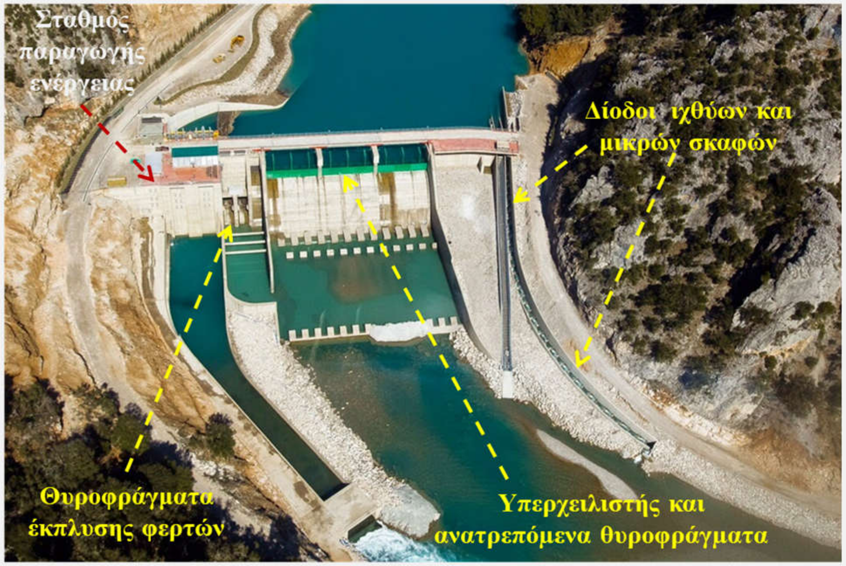


Cross section a - a : Intake

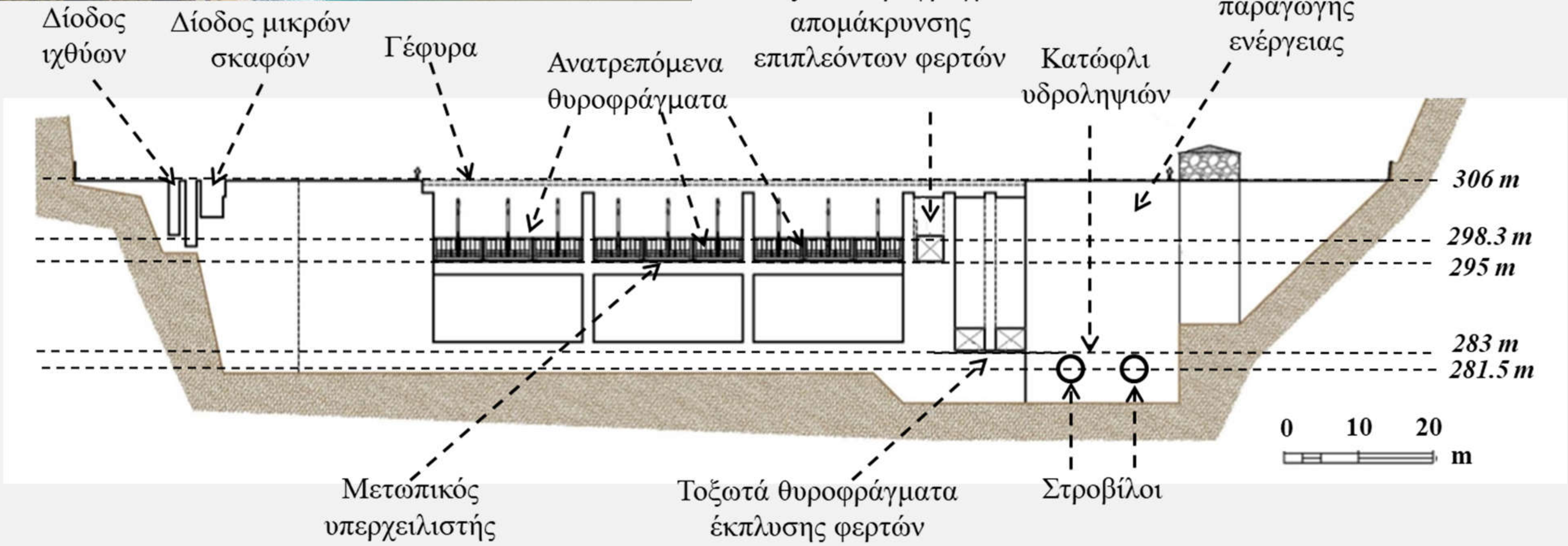


Source: Guide on How to Develop a Small Hydropower Plant, European Small Hydropower Association (ESHA), 2004

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)

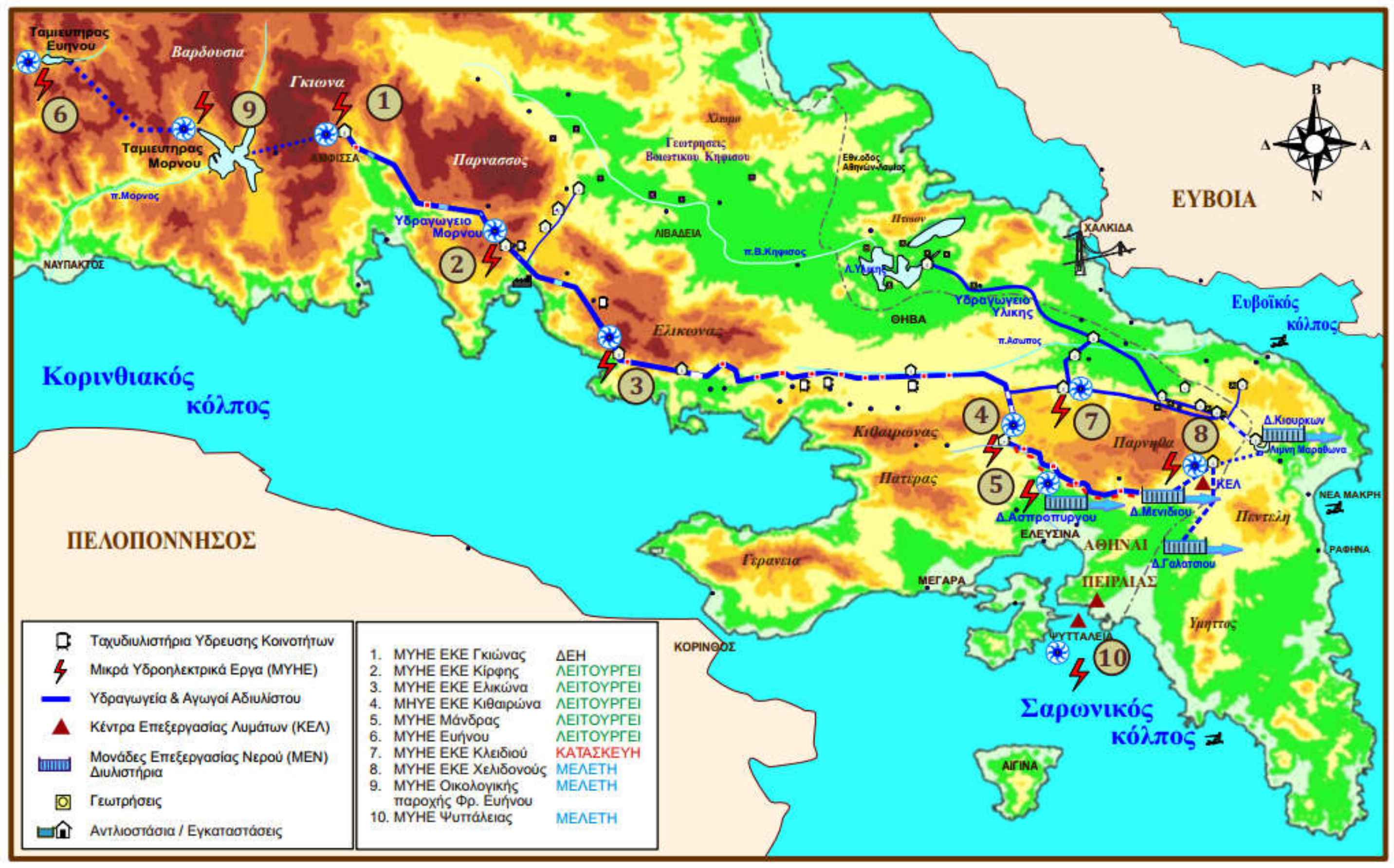
Thessaloniki water supply 7 m^3/s

Source:
PPC Renewables

It is constructed at the foot of the Agia Varvara regulatory dam. The SHPP belongs to the Public Power Corporation (PPC) and exploits the environmental flow of Aliakmon river. It includes a Kaplan S-type horizontal-axis turbine of 23 m head and 0.92 MW capacity. It operates from 2008 and has mean annual electrical energy production of **4.5 GWh.**

SHPPs as additions: Athens water supply system

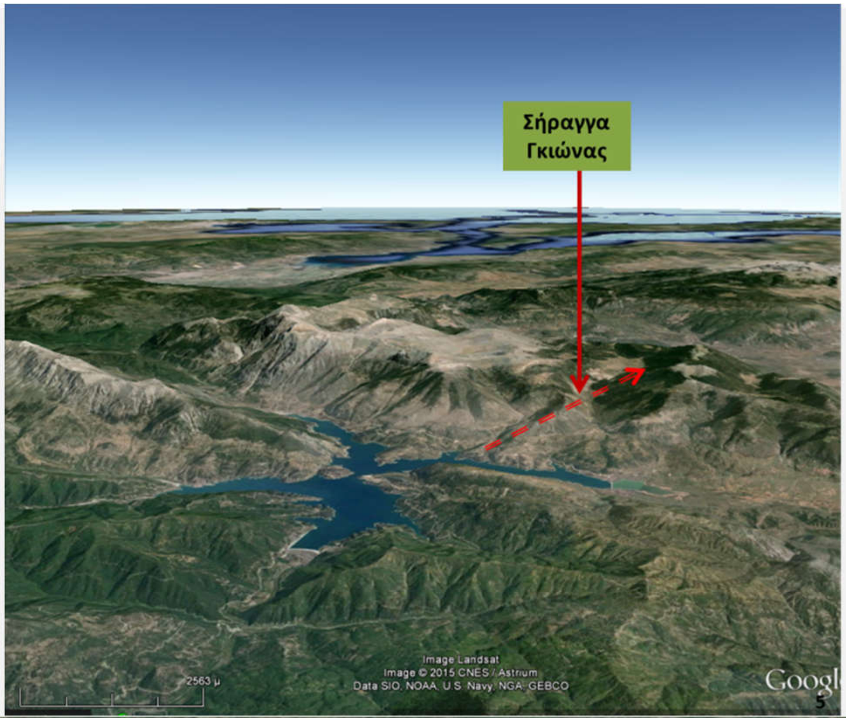
The Water Supply and Sewage Company of Athens (EYDAP) has constructed several SHPPs along the aqueducts that convey the water to Athens. In each SHPP location, the water is diverted to a lateral canal where electrical energy is produced, and the water is then returned to the main canal.



Athens Water Supply System SHPPs:	*Evinos Dam (820 kW), Kirfi (760 kW), Elikona (650 kW), Kitheronas (1.200 kW), Mandra (630 kW), Klidi (590 kW)*

Source: EYDAP

SHPPs as additions: Giona (Mornos aqueduct)

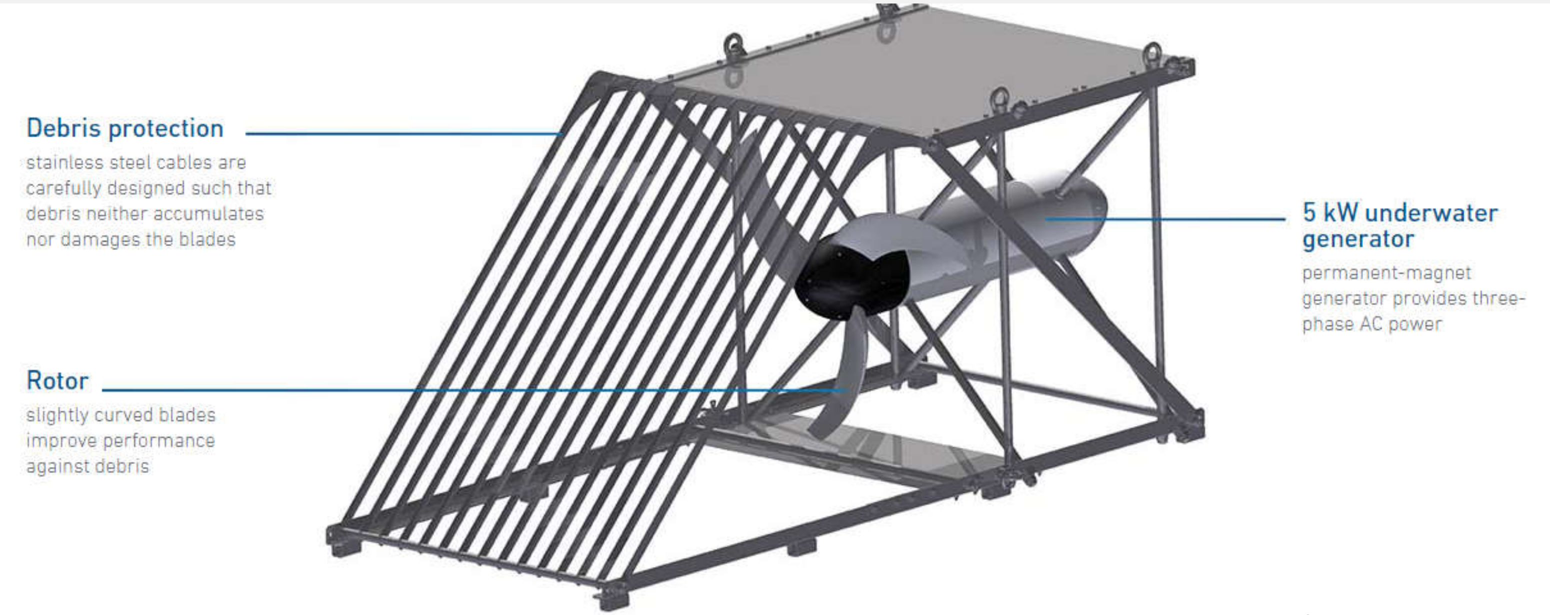


The largest SHPP across Mornos aqueduct is Giona, which operates since 1987. It is located near the city of Amfissa, belongs to the PPC and exploits a part of the water volume transported to the city of Athens. The operational discharge fluctuates from 7.8 to 14.5 m^3/s, and the head from 30.0 to 66.1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



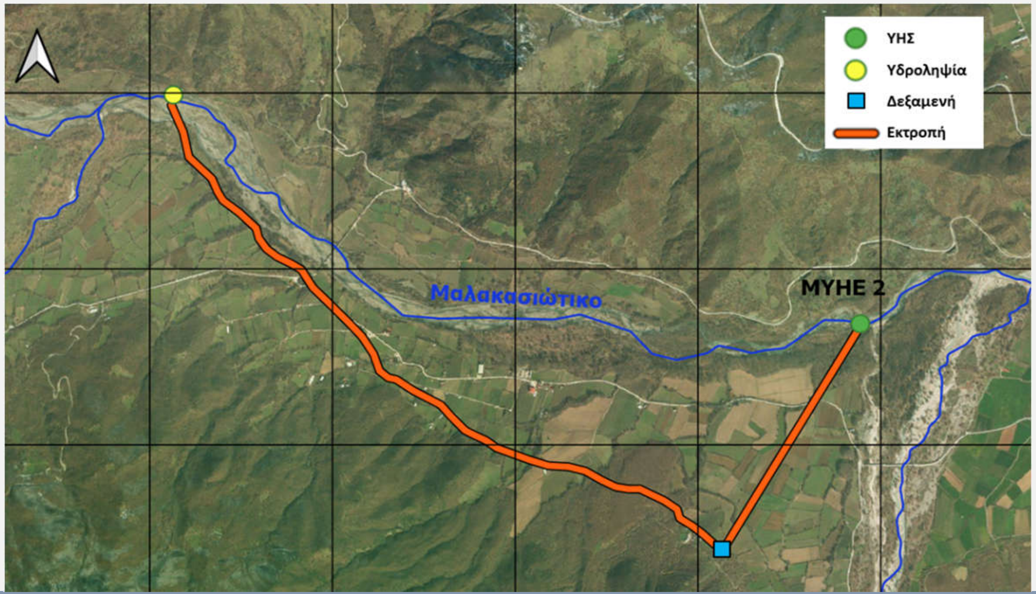
HydroQuest River: **80 kW**, Minimum water head: **4.2 m**, Nominal current flow velocity: **3.1 m/s**

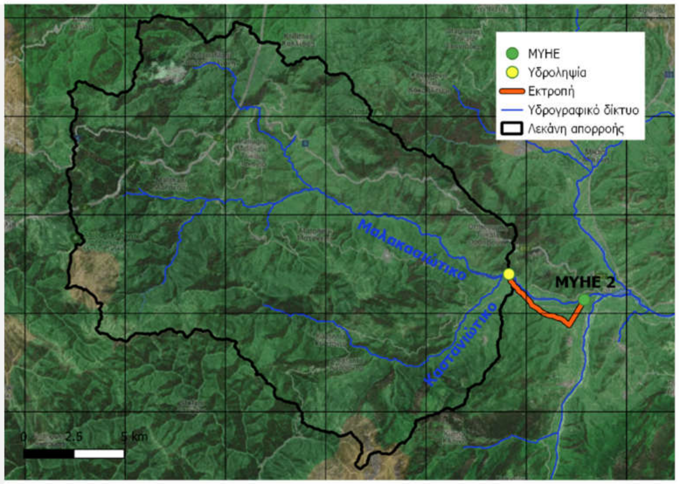
Run-of-river plants: Key design challenges

- **Siting and layout:**
  - Maximization of discharge (depends on the river basin area upstream of the intake)
  - Maximization of head (elevation difference between the intake and the outflow site)
  - Minimization of diversion length (cost of diversion works, impacts to river system)
  - Under several legal and environmental constraints
- **Intake system:**
  - 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

- ΚΥΑ 49828/2008 (ΦΕΚ 2464/Β'/3-12-2008): *Έγκριση ειδικού πλαισίου χωροταξικού σχεδιασμού και αειφόρου ανάπτυξης για τις ΑΠΕ και της στρατηγικής μελέτης περιβαλλοντικών επιπτώσεων αυτού*
- Υ.Α. 196978/2001 (ΦΕΚ 518Β/5-4-2011): *Συμπλήρωση και εξειδίκευση τεχνικών και λοιπών λεπτομέρειών των κριτηρίων χωροθέτησης ΜΥΗΕ με την παρ. 5 του άρθρου 9 του Ν.3851/2010*
- *ΔΙΠΑ/ΟΙΚ. 37674/ 2016 (Β'2471): Το επιτρεπόμενο μήκος εκτροπής για Υ/Η έργα σε περιοχή Natura 2000 αυξήθηκε από τα 4 στα 8 km, ενώ στα εκτός περιοχής Natura 2000, το μήκος αυξήθηκε από τα 8 στα 15 km.*





Key constraints for SHPP siting (P < 15 MW)

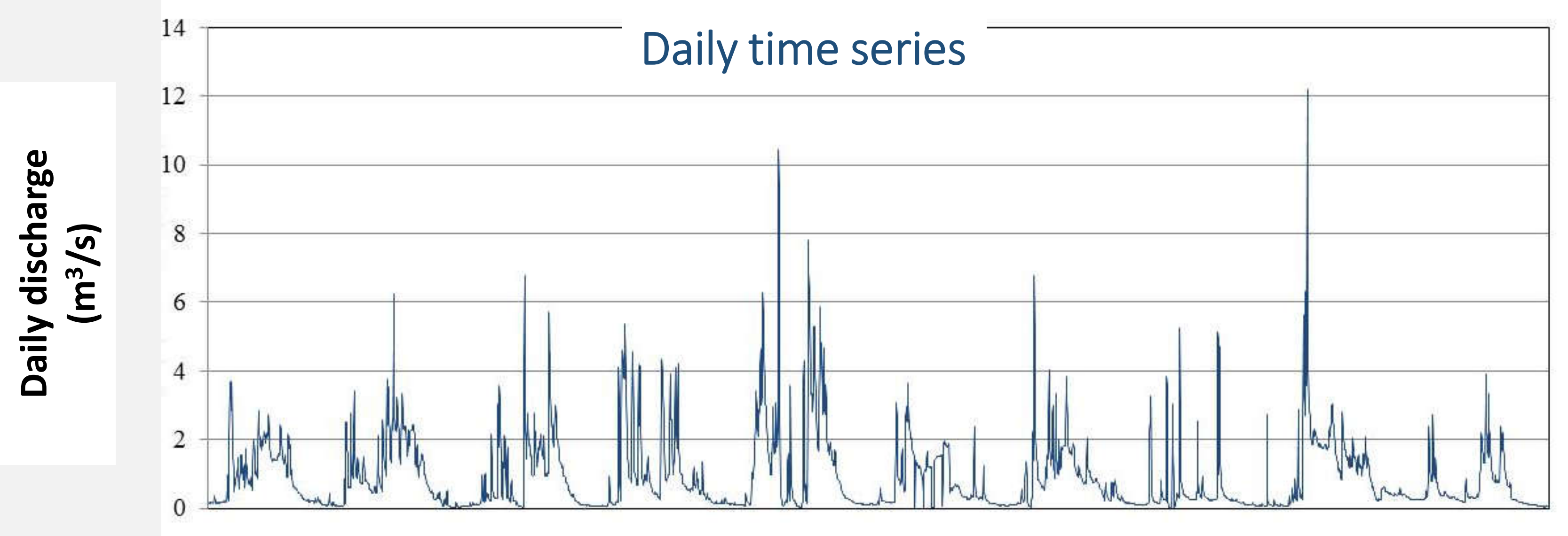
- Minimum allowable distance from upstream SHPPs: 1.0 km
- Maximum allowable length of diversion (for installed power capacity, $P > 0.3$ MW):

$$0.25 + \left[1.4 - 0.4\left(\frac{q_e}{q'_e}\right)^{0.5}\right]\left[11.2\ \frac{P - 0.3}{5 + (P - 0.3)}\right]$$

  where q_e is the environmental flow and q'_e is the flow which is allowed to pass from the operator of the project.
- For P < 0.3 MW, the length is up to 0.25 km

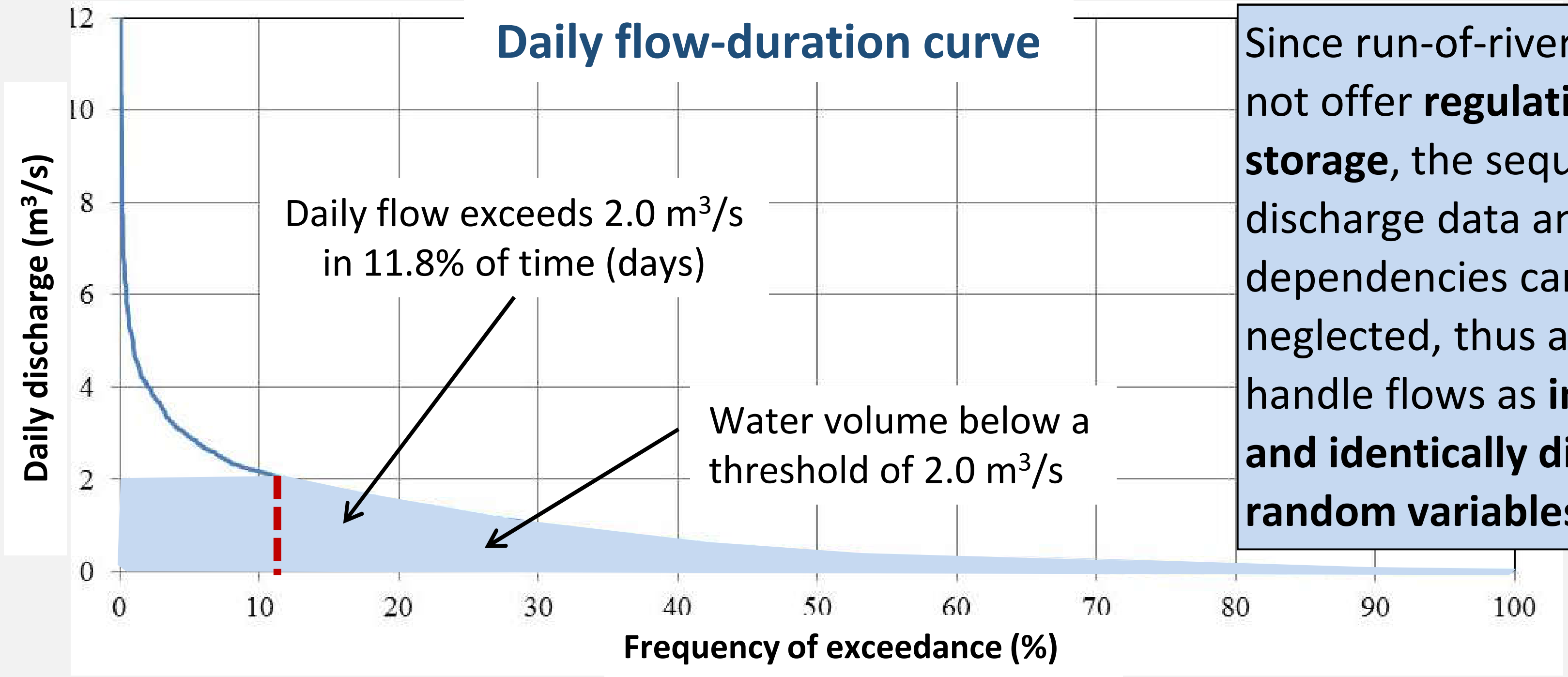
Design issues: Hydrological analysis

- 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).



Daily flow-duration curve

Daily flow exceeds 2.0 m^3/s in 11.8% of time (days)

Water volume below a threshold of 2.0 m^3/s

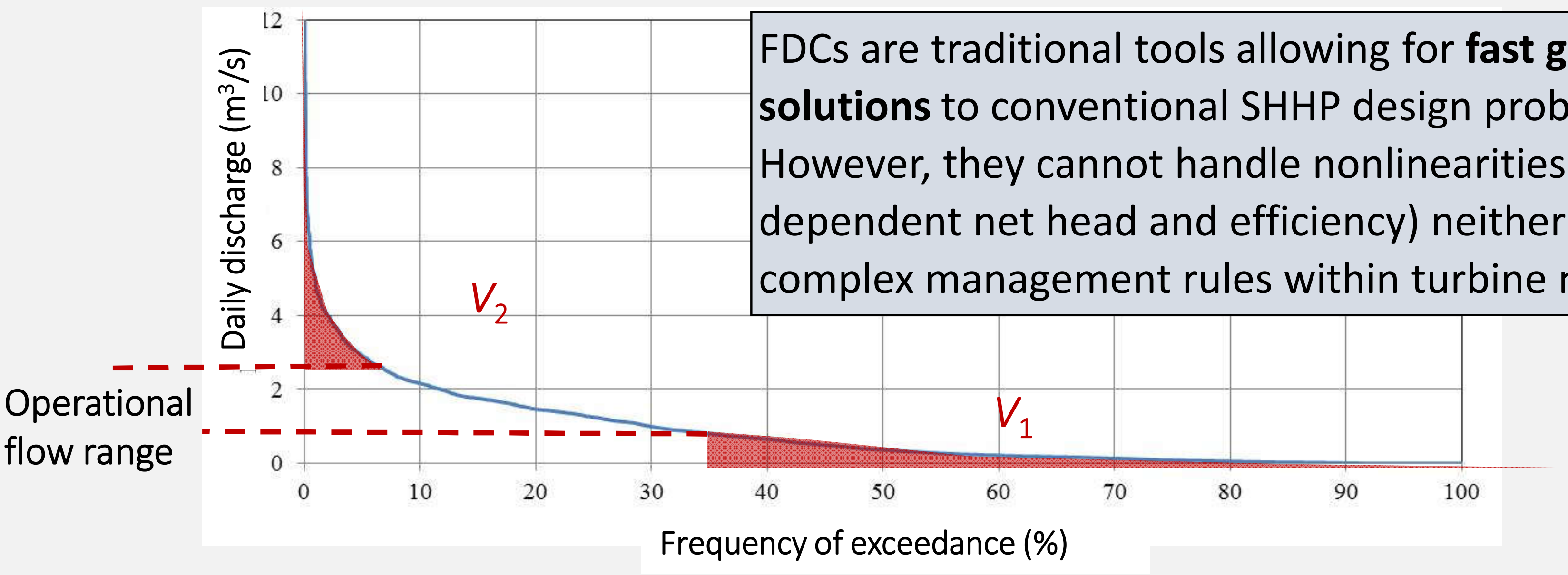
Since run-of-river plants do not offer **regulation through storage**, the sequence of discharge data and their time dependencies can be neglected, thus allowing to handle flows as **independent and identically distributed random variables**

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%**.



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 (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

Legend

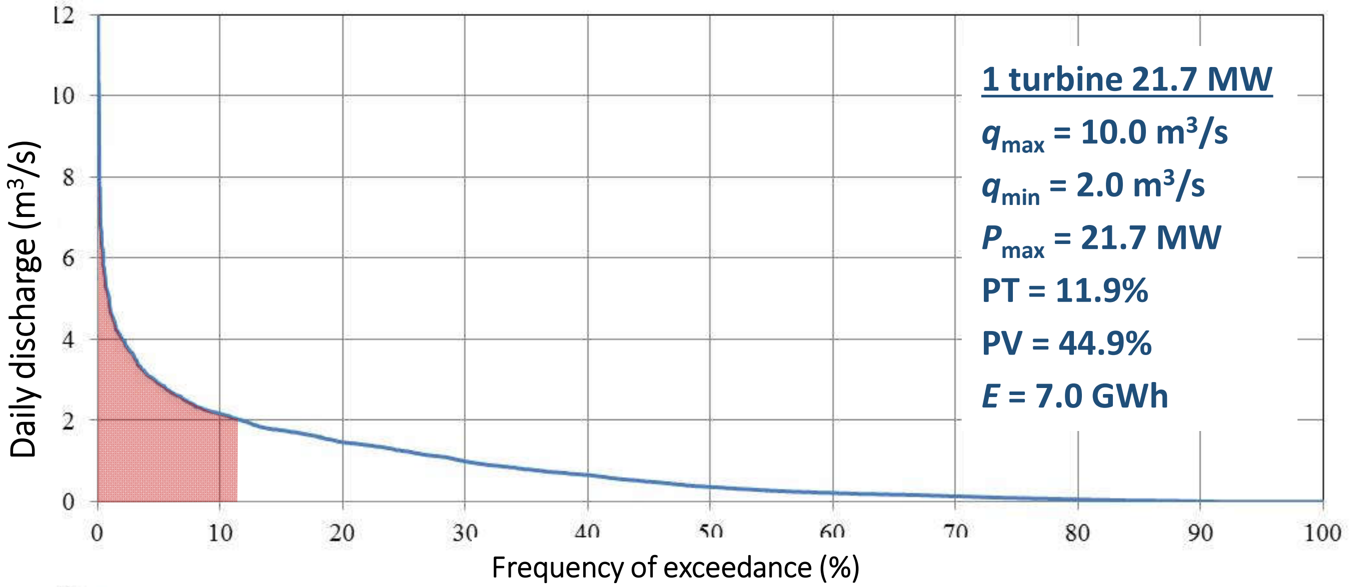
q_{min}, q_{max}: Minimum, maximum exploitation discharge (m^3/s)

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)



1 turbine 21.7 MW

q_{max} = 10.0 m^3/s

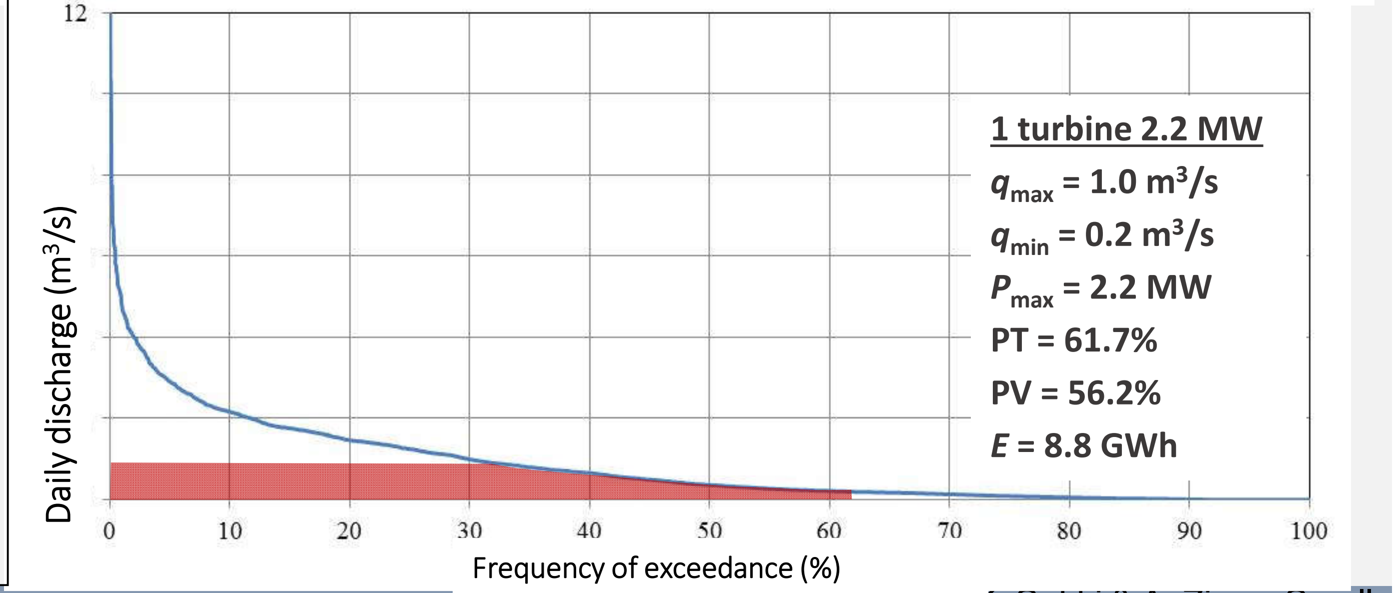
q_{min} = 2.0 m^3/s

P_{max} = 21.7 MW

PT = 11.9%

PV = 44.9%

E = 7.0 GWh



1 turbine 2.2 MW

q_{max} = 1.0 m^3/s

q_{min} = 0.2 m^3/s

P_{max} = 2.2 MW

PT = 61.7%

PV = 56.2%

E = 8.8 GWh

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

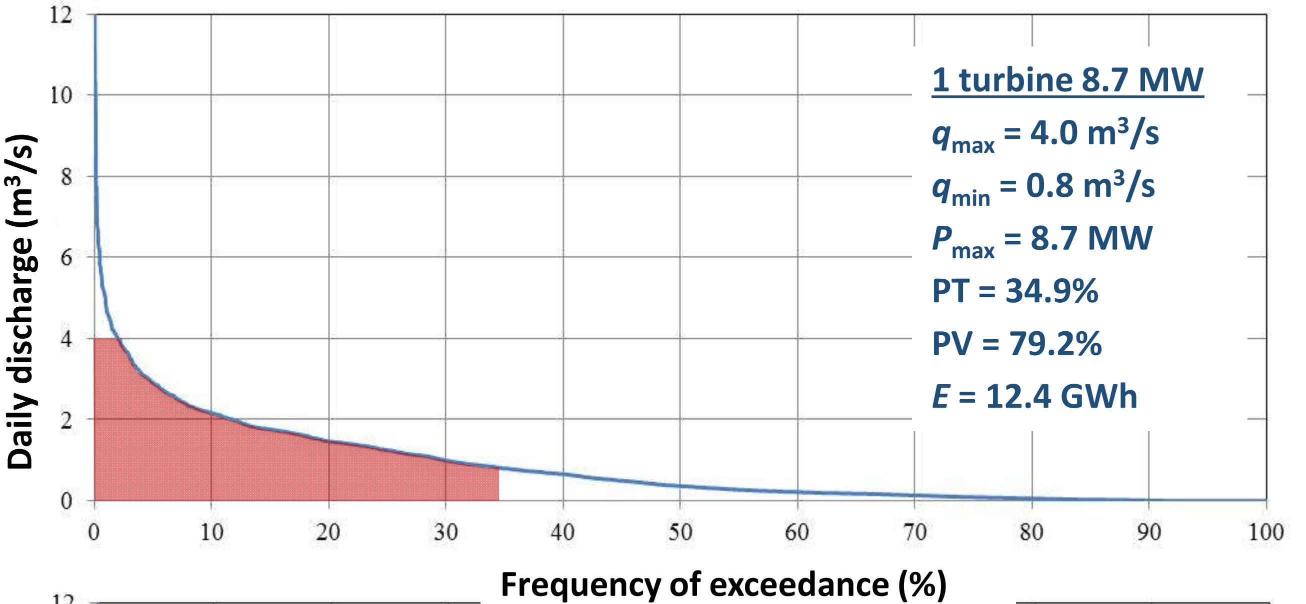
q_{min}, q_{max}: Minimum, maximum exploitation discharge (m³/s)

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

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

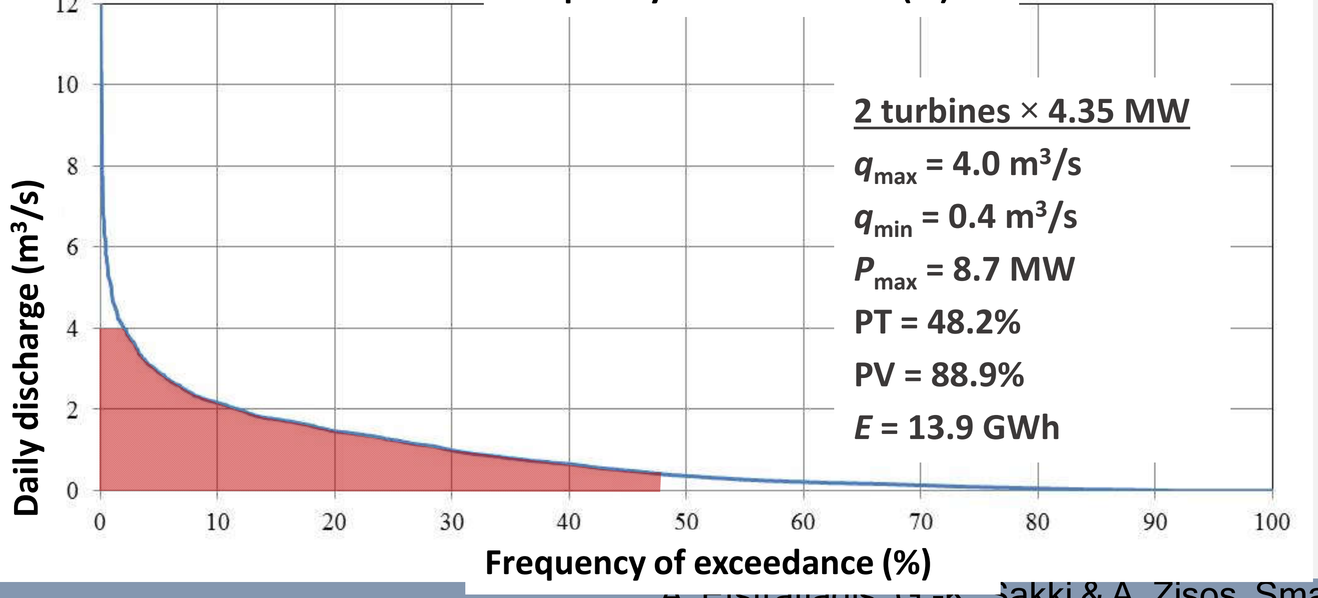
PV: Percentage of water volume used (%)

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



1 turbine 8.7 MW

q_{max} = 4.0 m³/s
q_{min} = 0.8 m³/s
P_{max} = 8.7 MW
PT = 34.9%
PV = 79.2%
E = 12.4 GWh



2 turbines × 4.35 MW

q_{max} = 4.0 m³/s
q_{min} = 0.4 m³/s
P_{max} = 8.7 MW
PT = 48.2%
PV = 88.9%
E = 13.9 GWh

Turbine selection: Numerical example 3

Data

$H = 260$ m

$\eta = 0.85$

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

Legend

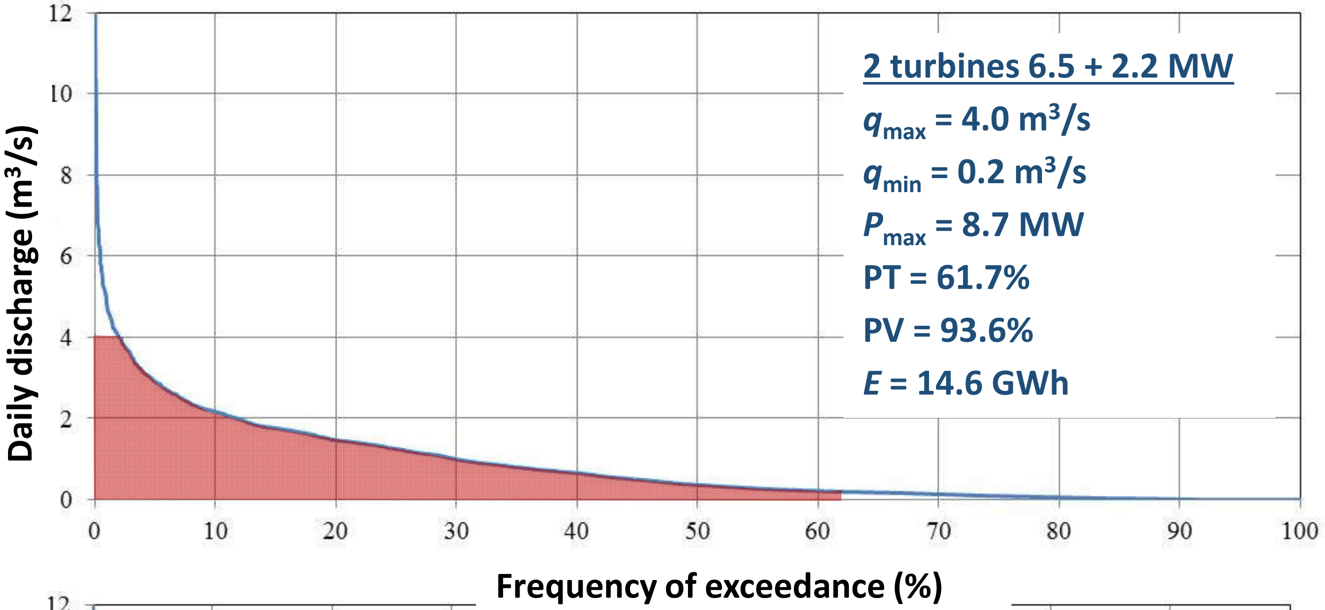
q_{min}, q_{max}: Minimum, maximum exploitation discharge (m^3/s)

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)



2 turbines 6.5 + 2.2 MW

$q_{max} = 4.0$ m^3/s

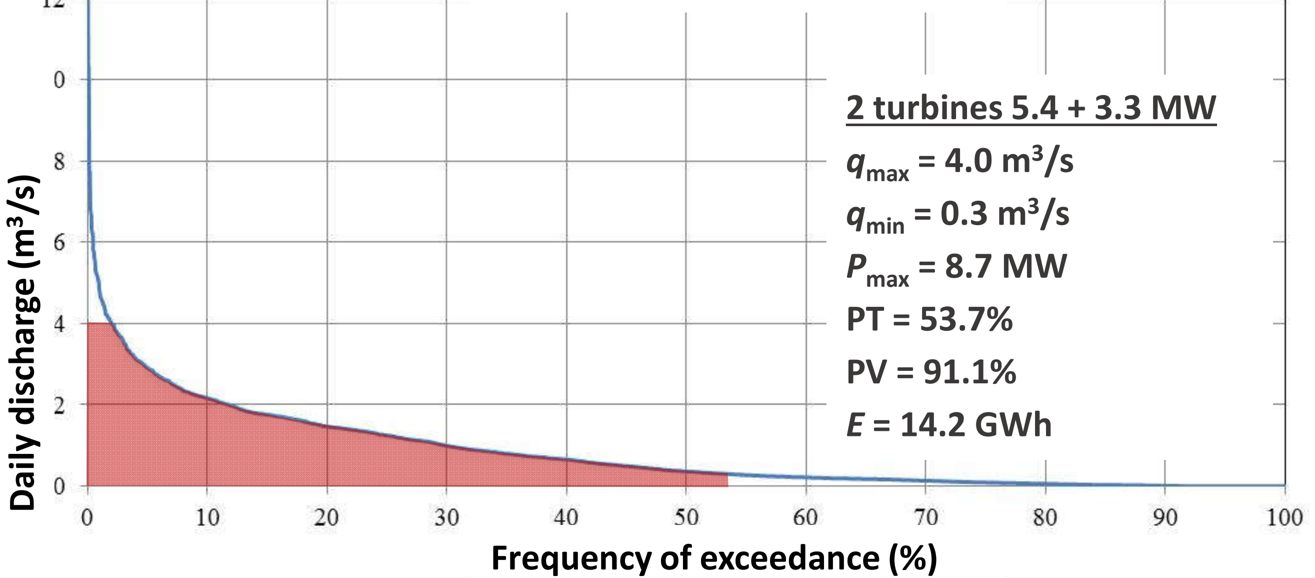
$q_{min} = 0.2$ m^3/s

$P_{max} = 8.7$ MW

PT = 61.7%

PV = 93.6%

$E = 14.6$ GWh



2 turbines 5.4 + 3.3 MW

$q_{max} = 4.0$ m^3/s

$q_{min} = 0.3$ m^3/s

$P_{max} = 8.7$ MW

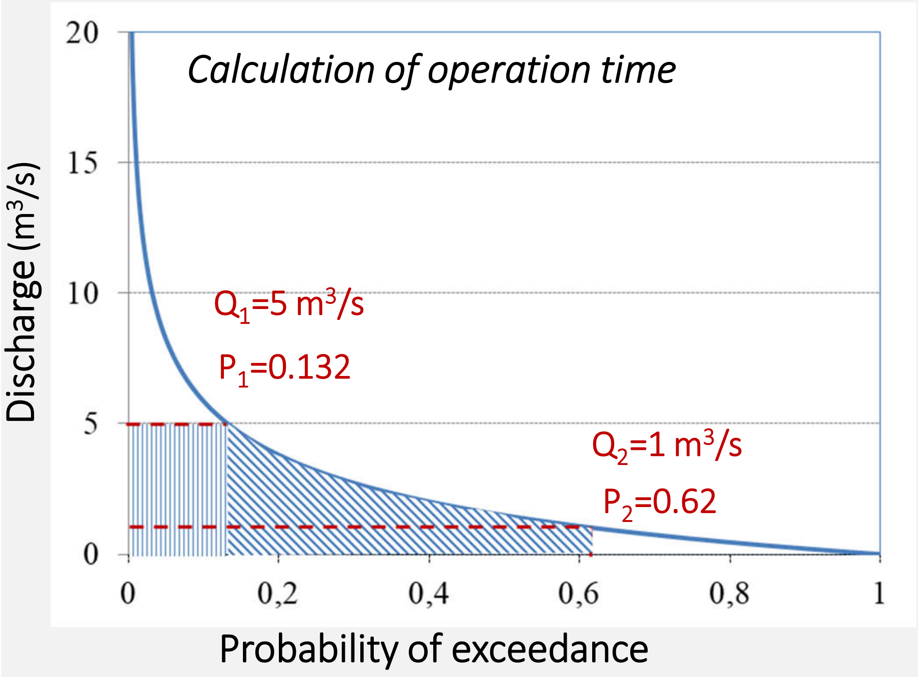
PT = 53.7%

PV = 91.1%

$E = 14.2$ GWh

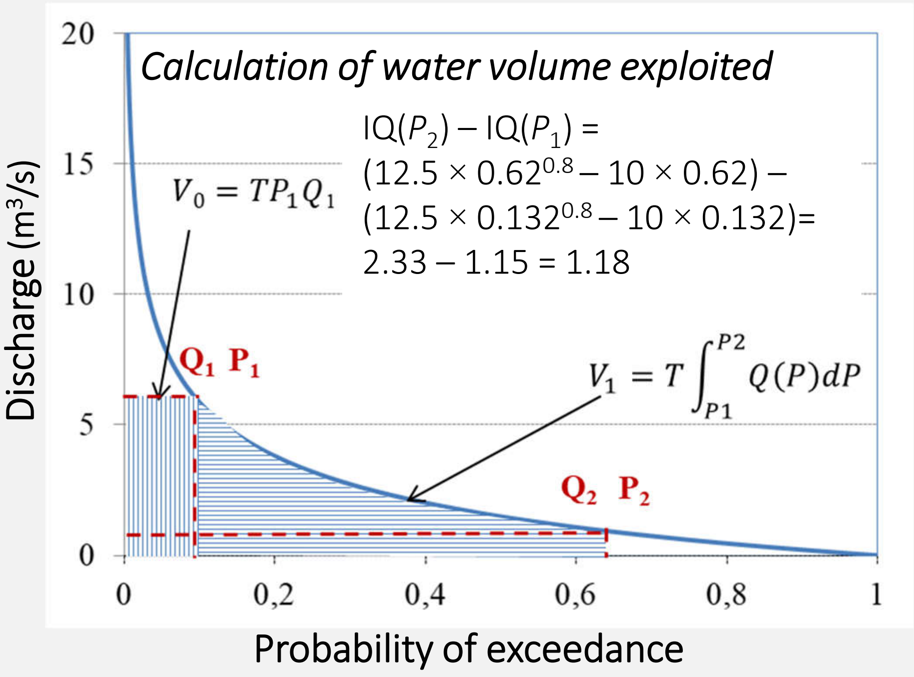
Estimations based on analytical expressions of FDCs

- Problem assumptions and key calculations:
  - Single turbine, operating within the range 1.0 to 5.0 m³/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%**



$\mathrm{IQ}(P_2) – \mathrm{IQ}(P_1) =$
$(12.5 \times 0.62^{0.8} – 10 \times 0.62) –$
$(12.5 \times 0.132^{0.8} – 10 \times 0.132) =$
$2.33 – 1.15 = 1.18$

For one-year operation, T =31.56 × 10⁶ s

V_0 = 31.56 × 0.132 × 5 = **20.8 hm³**

V_1 = 31.56 × 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)