Renewable Energy & Hydroelectric Works

Small Hydroelectric Power Plants (SHPPs)

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Definition and Classification of SHPPs

- To define a HPP as **"small"**, the installed power must be under a certain limit, that is defined by national legislation.
- This limit varies considerably among different counties, but the most common values are between 10 and 30 MW. For example, in Canada, China and New Zealand the limit is ***50 MW***, in the United States and several South America countries it is ***30 MW*** and in Thailand 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)

Types of SHPPs

Storage facility

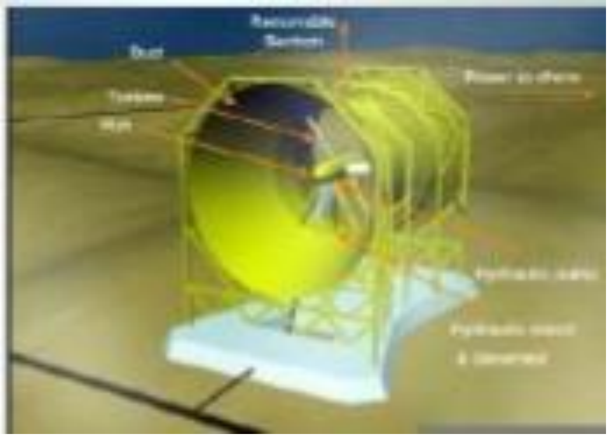
There is an impoundment and water storage facility. Several SHPPs exploit the environmental flow of large dams

Run-off-river

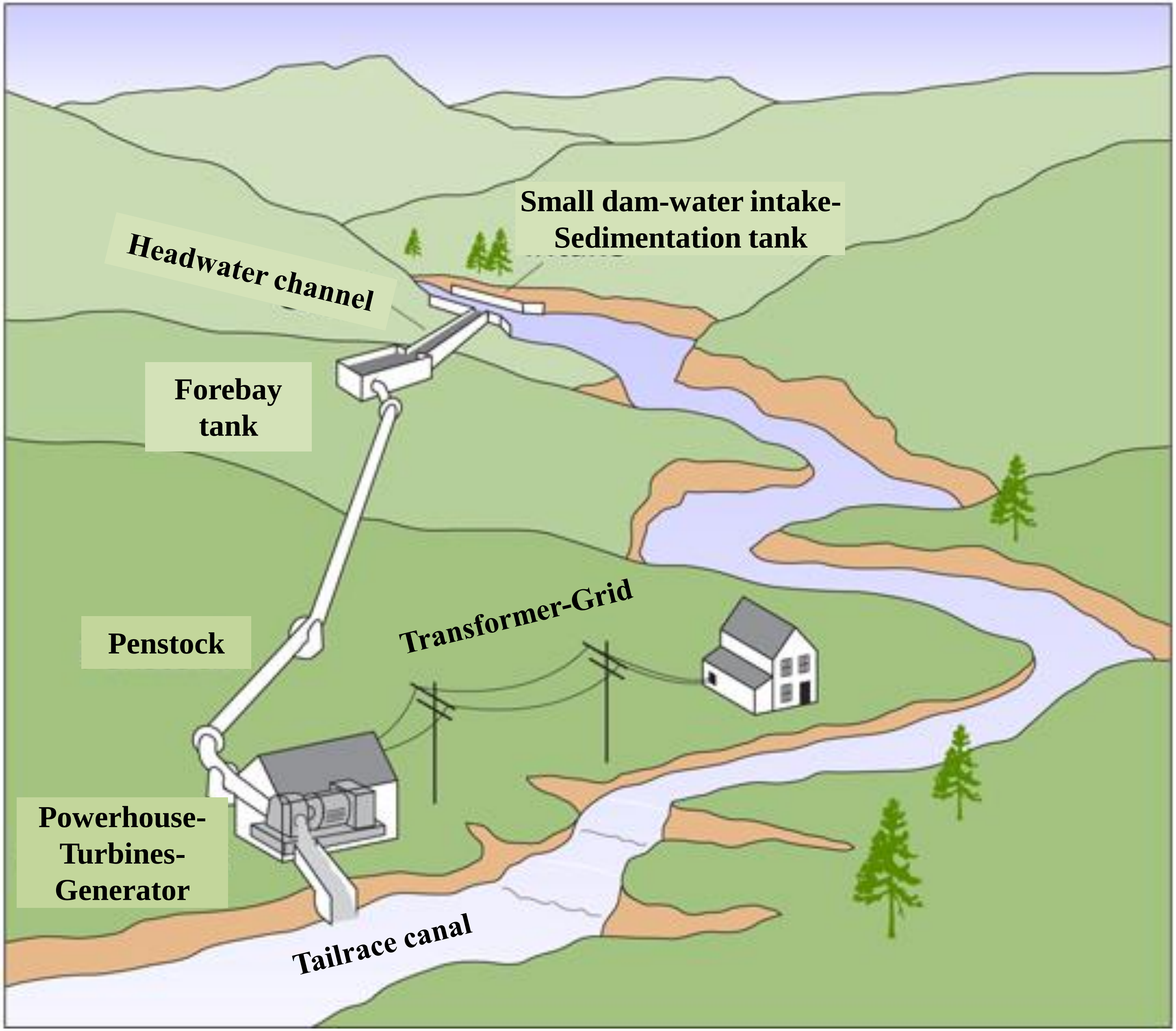
Utilizes the streamflow as it comes, without the ability to store the water. This is the most common SHPP type.

In-stream

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



Components of a typical SHPP



Small dam-water intake-
Sedimentation tank

Headwater channel

Forebay
tank

Penstock

Transformer-Grid

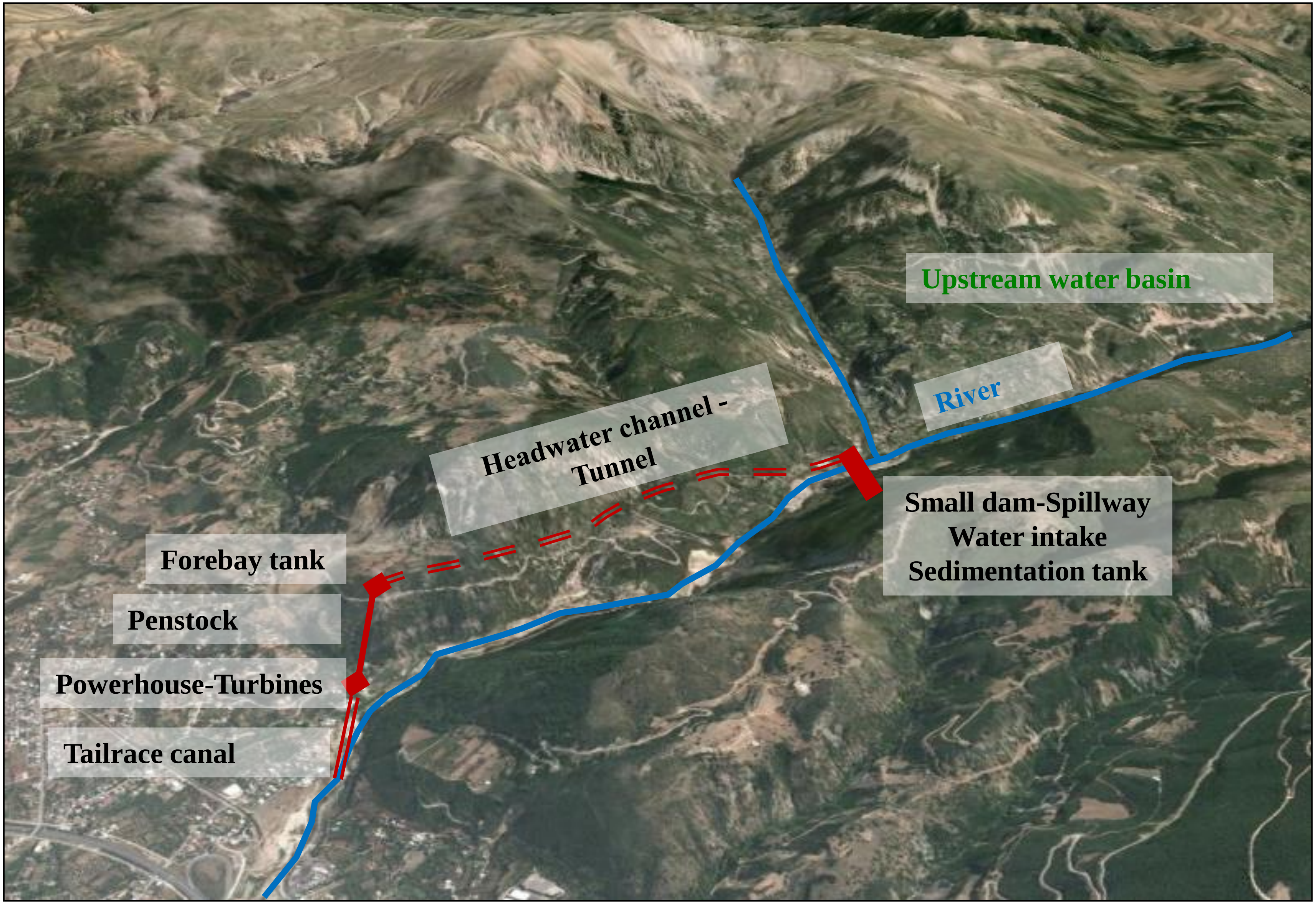
Powerhouse-
Turbines-
Generator

Tailrace canal

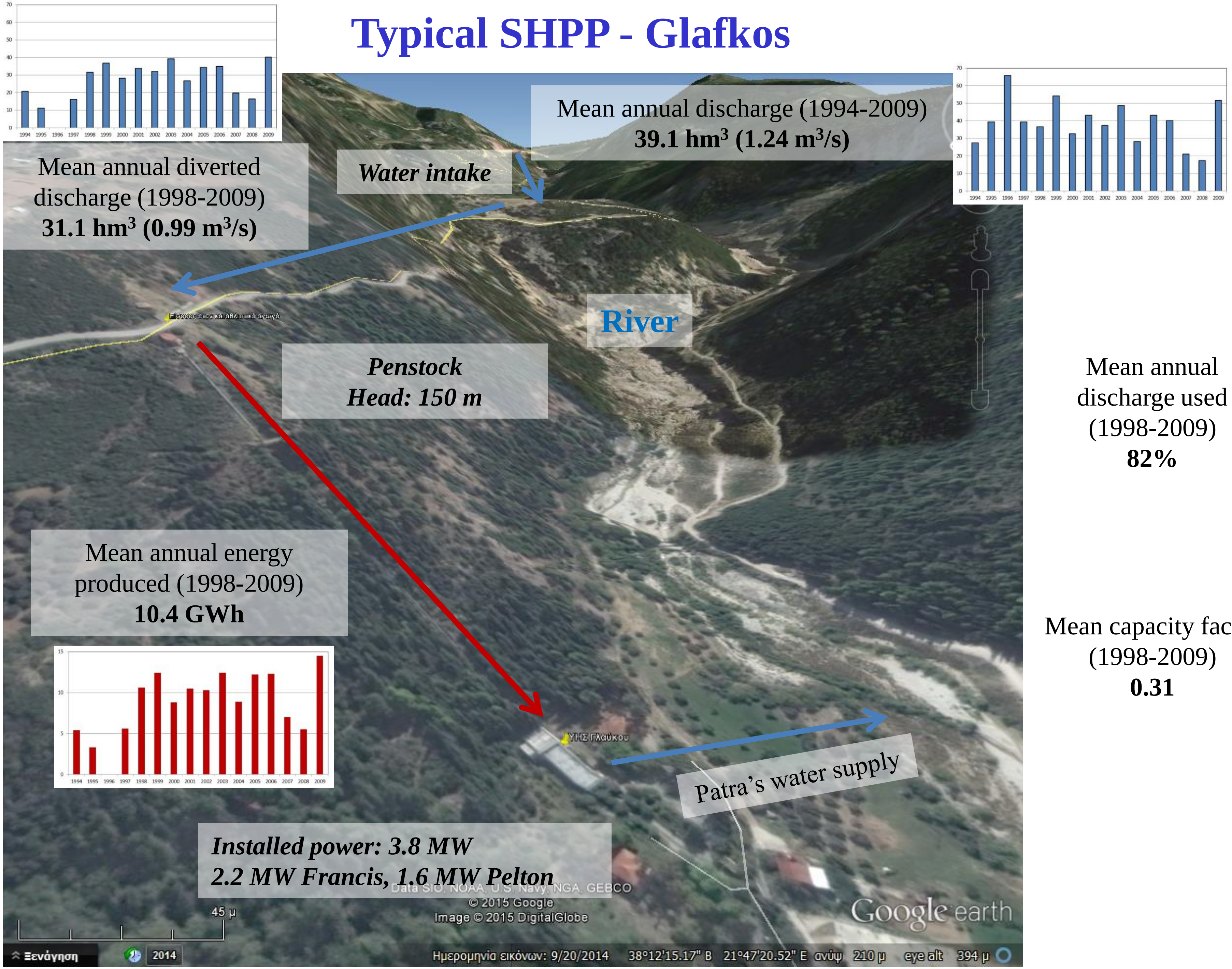
Typical SHPP

Glafkos-Patra, Greece

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



Typical SHPP - Glafkos



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

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

Water intake

River

Penstock
Head: 150 m

Mean annual energy produced (1998-2009)
10.4 GWh

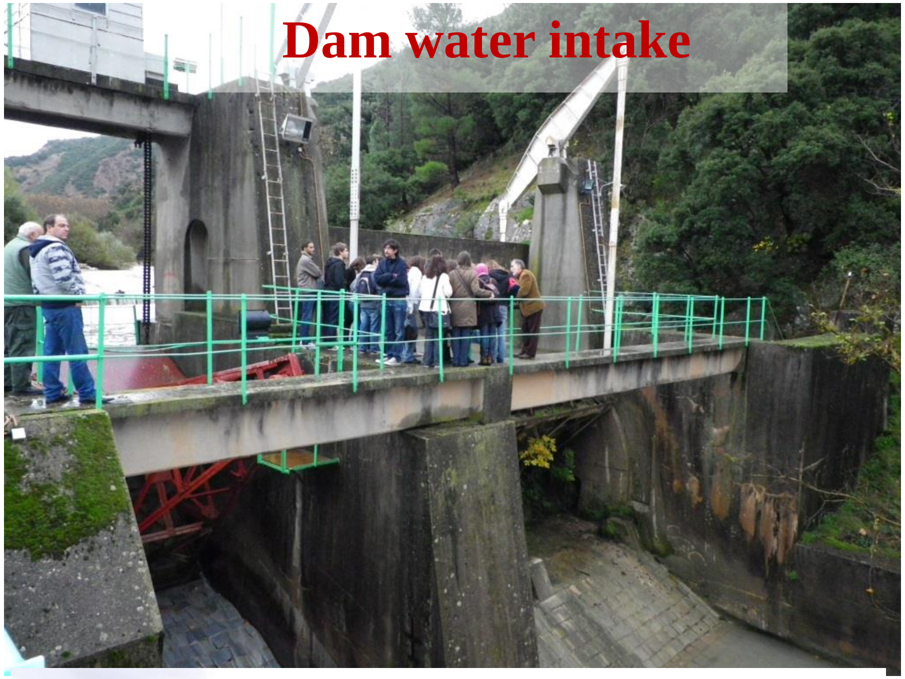
Patra's water supply

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

Mean annual discharge used (1998-2009)
82%

Mean capacity factor (1998-2009)
0.31

Typical SHPP - Glafkos


Dam water intake

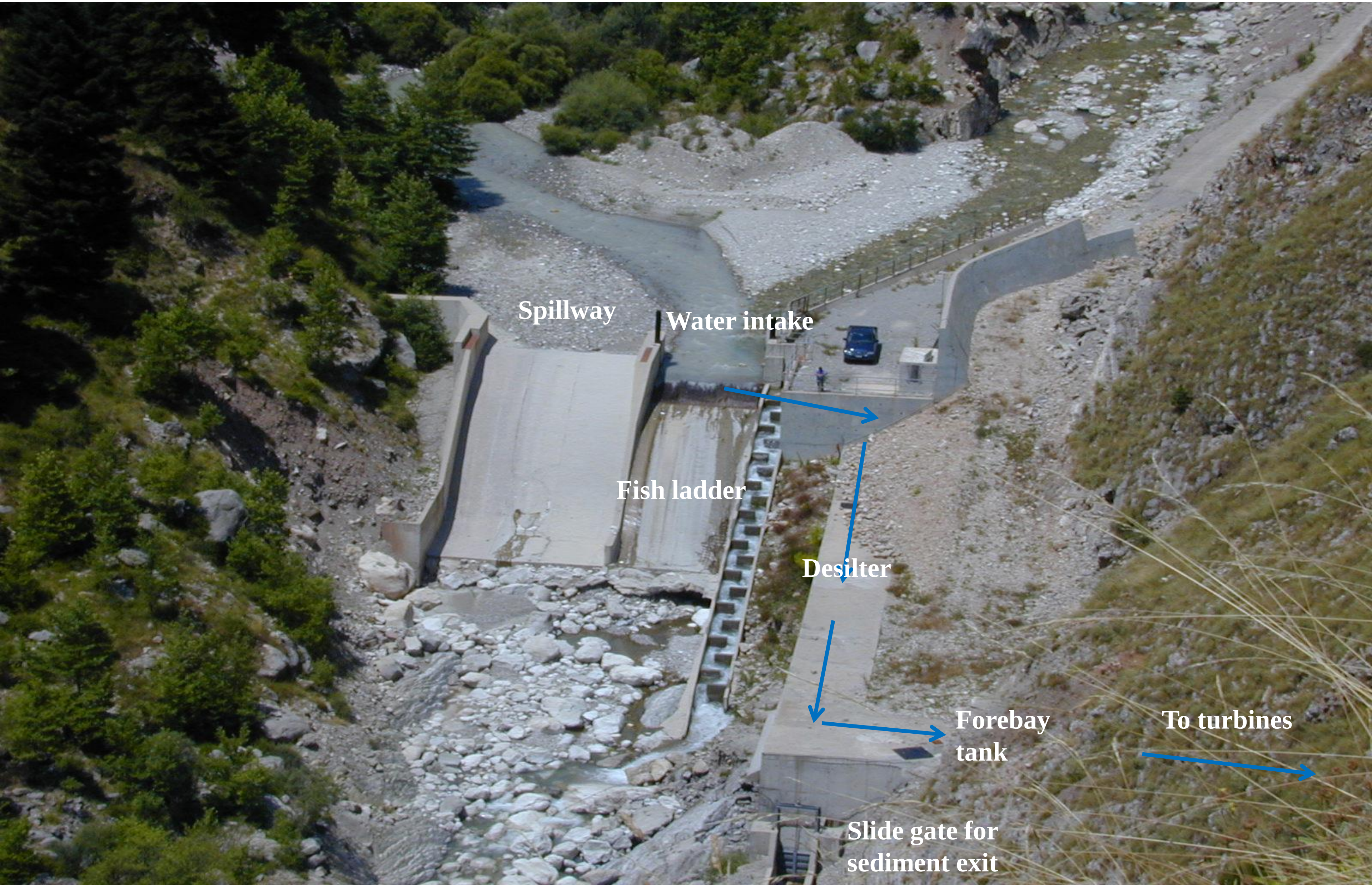

Sand trap – desilter - sedimentation tank


Penstock


Turbines

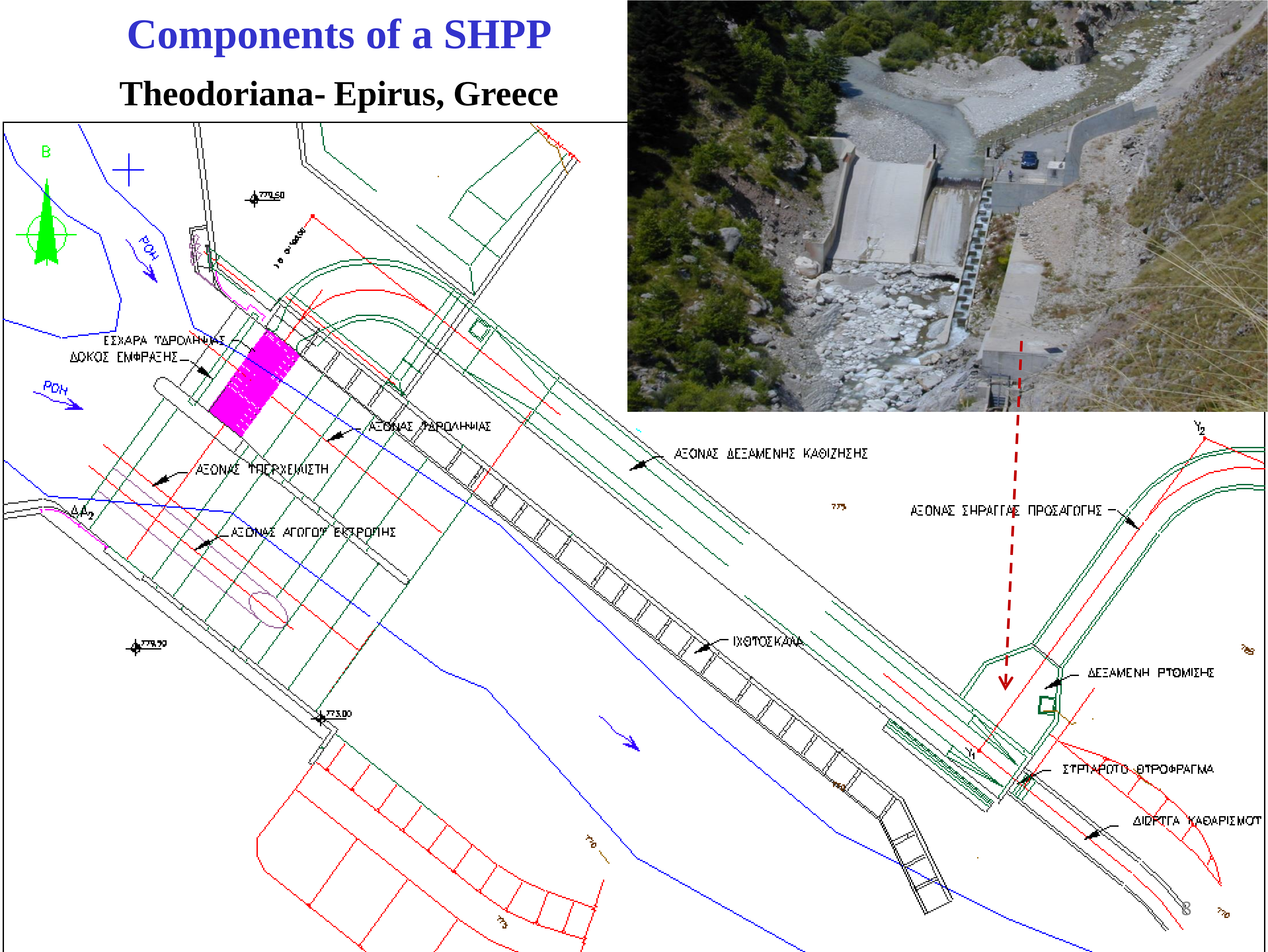
Components of a SHPP

Theodoriana- Epirus, Greece

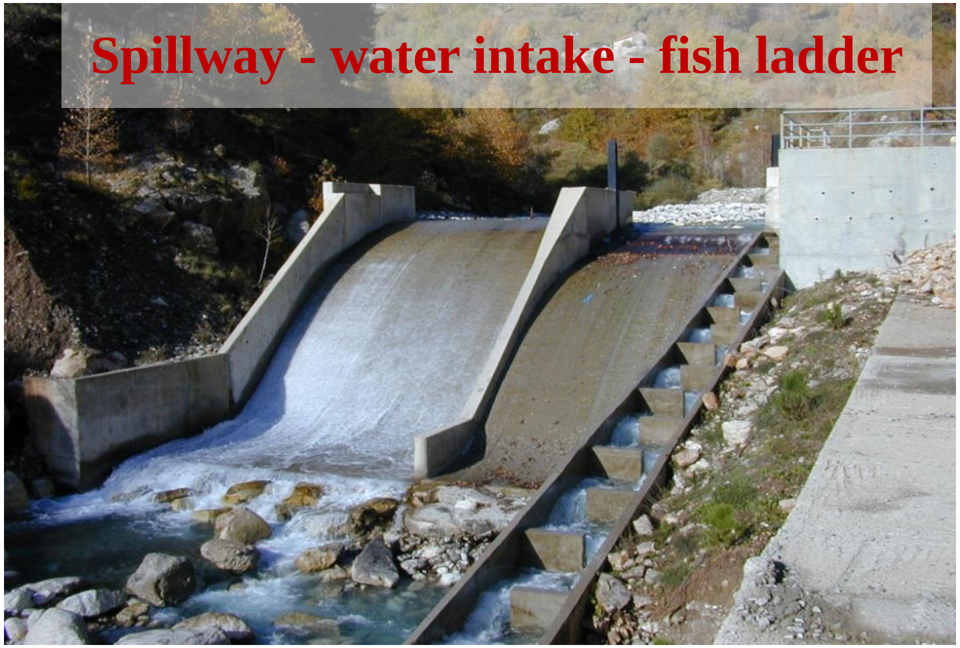


Components of a SHPP

Theodoriana- Epirus, Greece

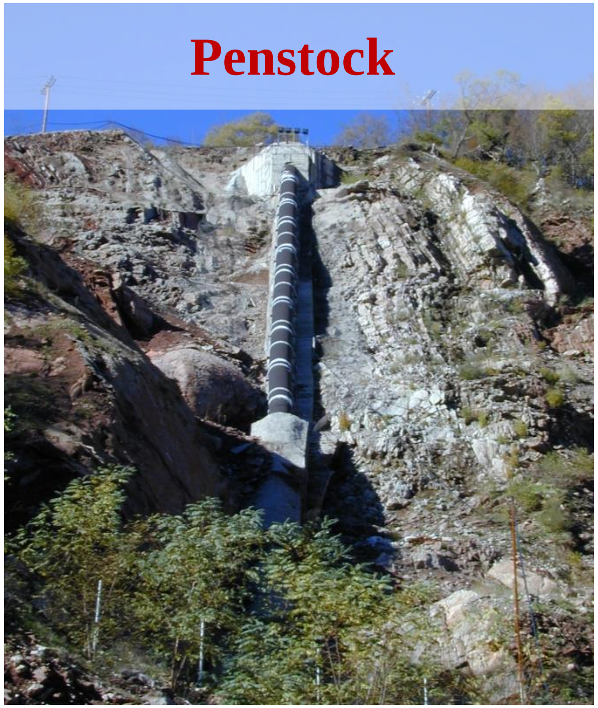


Components of a SHPP



Spillway - water intake - fish ladder

Water intake



Penstock

Powerhouse

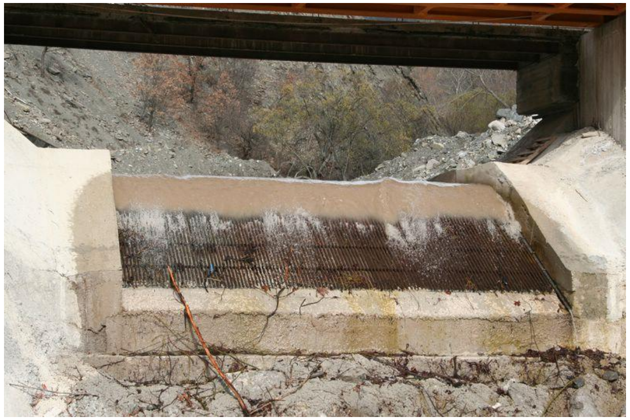
Components of a SHPP

Thermorema - Sterea Hellas

Installed power 1.95 MW, 2003

Desilter (sand traps)

Trash rack of water intake



Headwater channel - sand traps

Forebay tank

Penstock

Photos: ΔΕΛΤΑ Project

SHPPs –Sediment management

Bed load, suspended load and floating sediment

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 that of the water flow. The main movement mechanisms are sliding, rolling or hopping

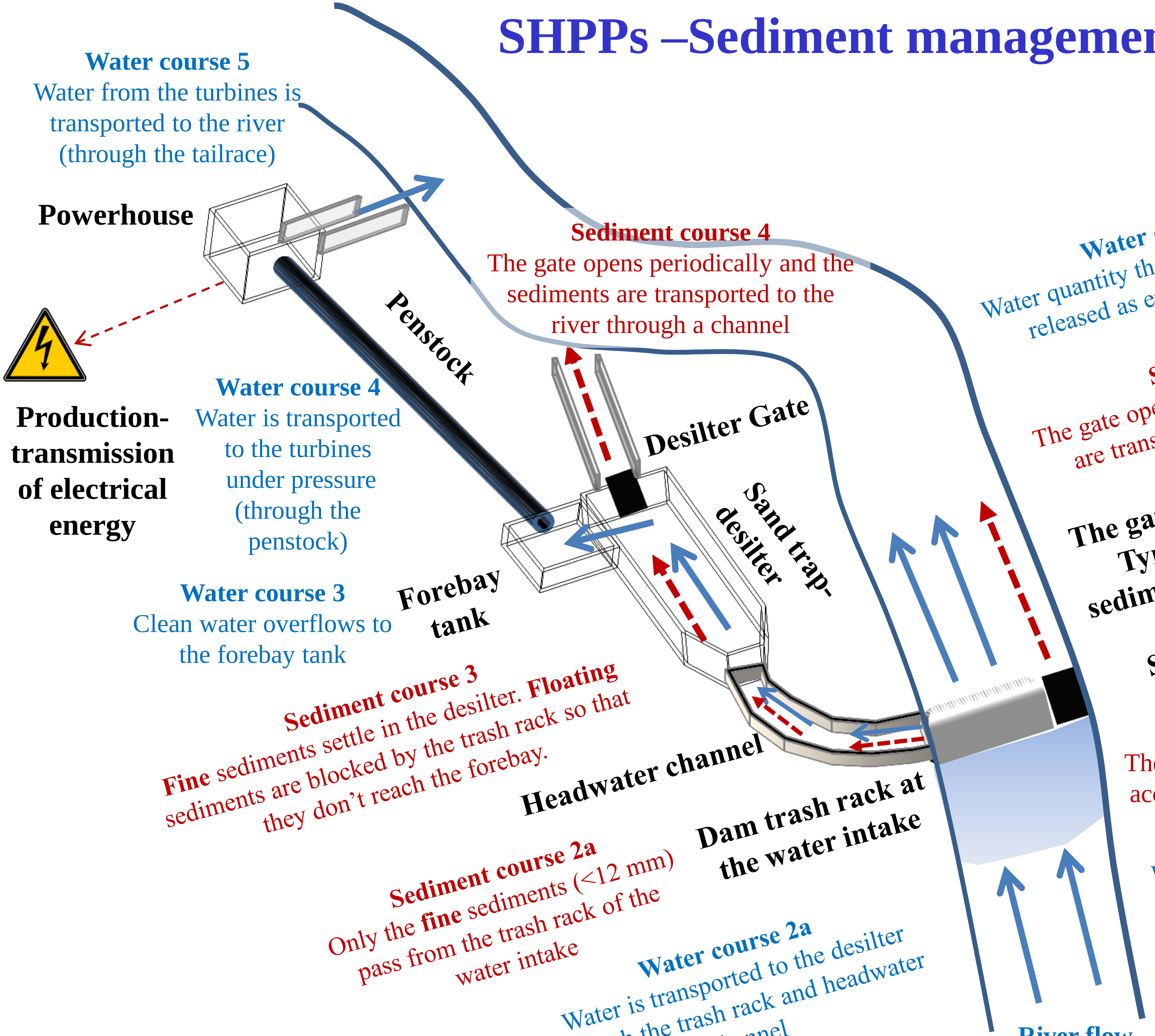
Suspended load

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

Floating sediments

Leaves, branches, debris, garbage etc. that float in the water

SHPPs –Sediment management



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

Powerhouse

Production-transmission of electrical energy

Penstock

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

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

Desilter Gate

Sand trap-desilter

Forebay tank

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.

Headwater channel

Dam trash rack at the water intake

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

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

Sediment sluice gate

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

Water course 1
Water is collected upstream of the dam

River flow

Components of a SHPP

Drop intake - Tyrolean weir - water intake for mountainous regions

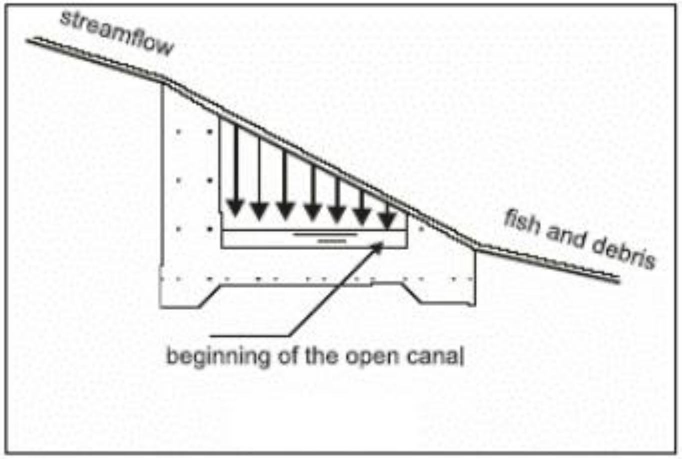
Kerasovo-Epirus

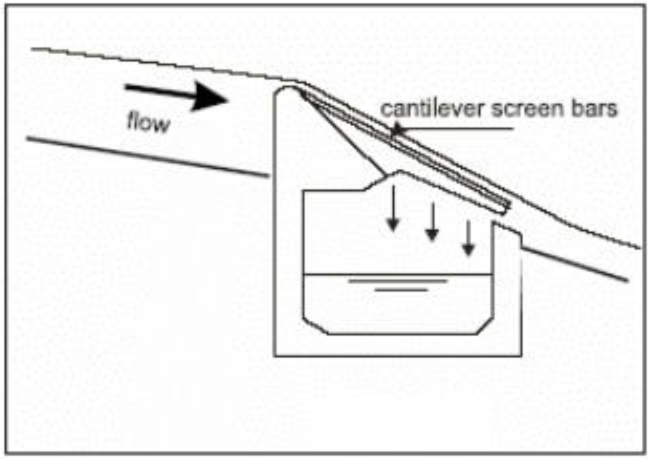
Source: http://www.sofios.gr/projects

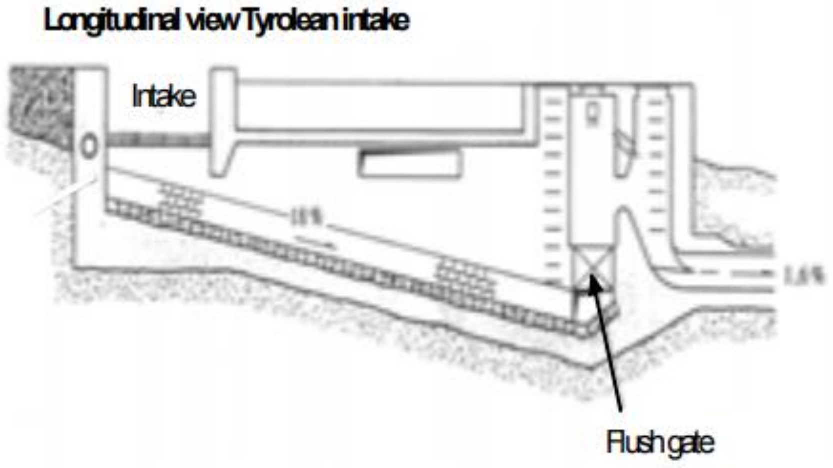
- **Tyrolean weir** is a water intake structure in which water is abstracted from the main flow through a trash rack (screen) over a gutter.
- The gutter is usually made of concrete and built into the river bed.
- The trash rack on the crest should slope downstream (15-30 degrees), to increase flow velocities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

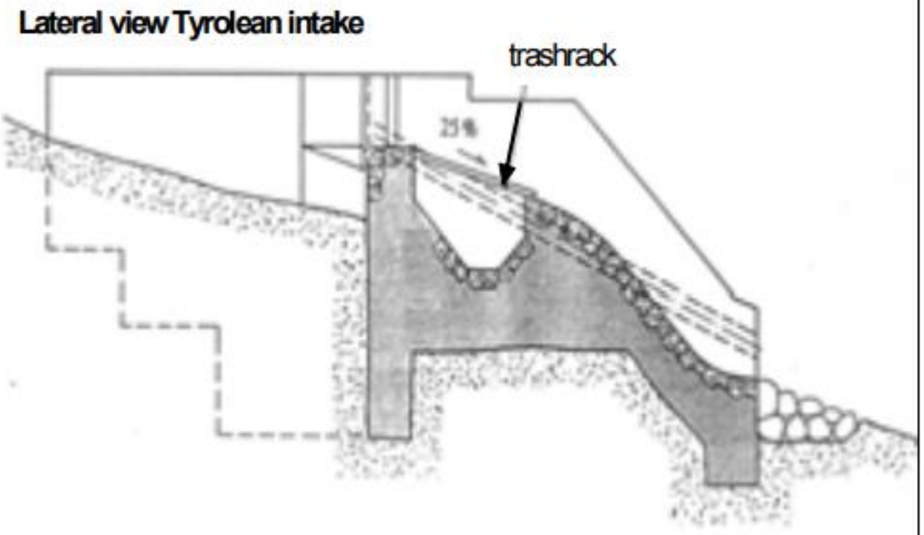
Components of a SHPP

Drop intake - Tyrolean weir - water intake for mountainous regions





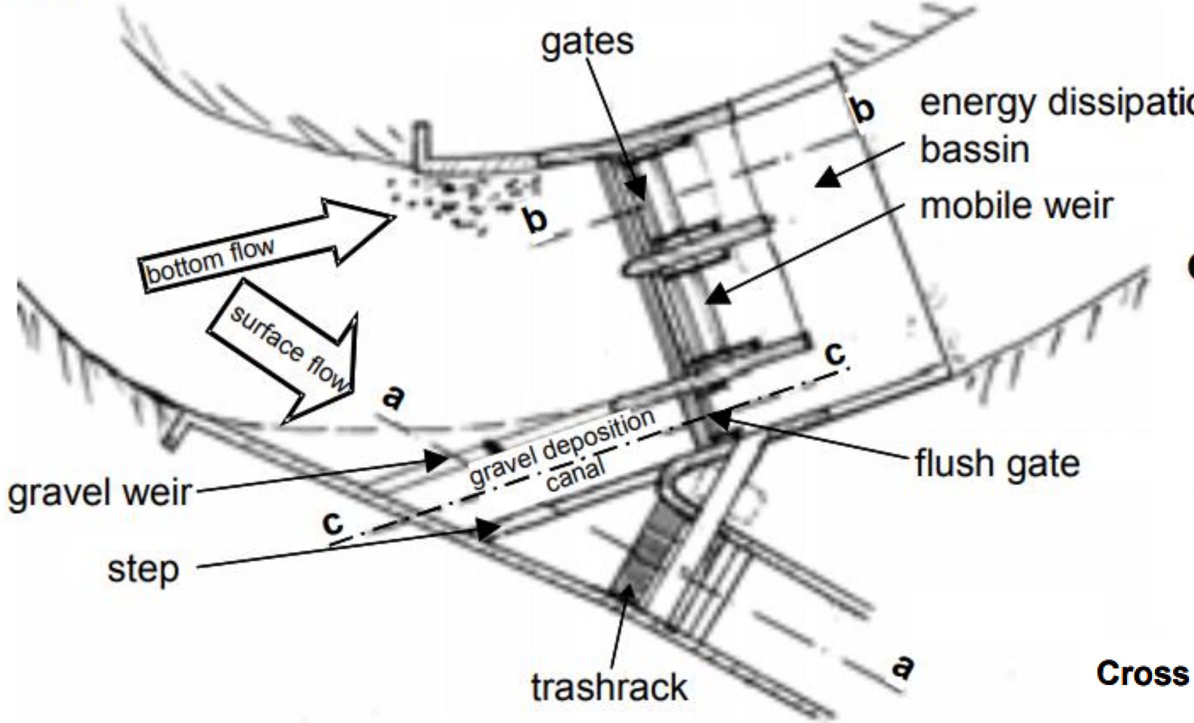




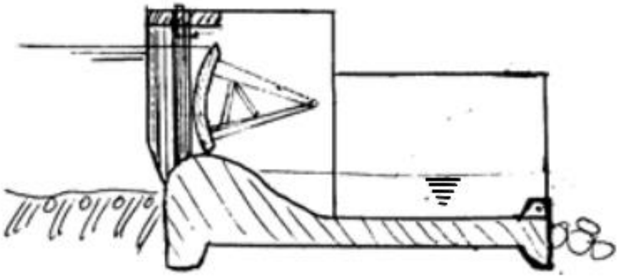
Source: Guide on How to Develop a Small Hydropower Plant, European Small Hydropower Association (ESHA), 2004

SHPPs – Lateral intake - Sediment management

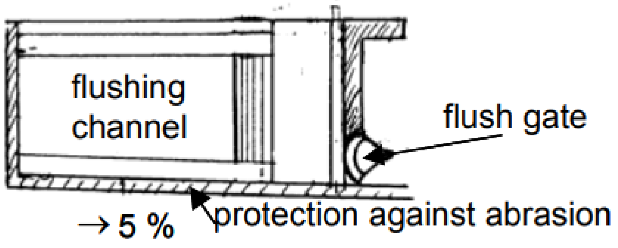
Plan view



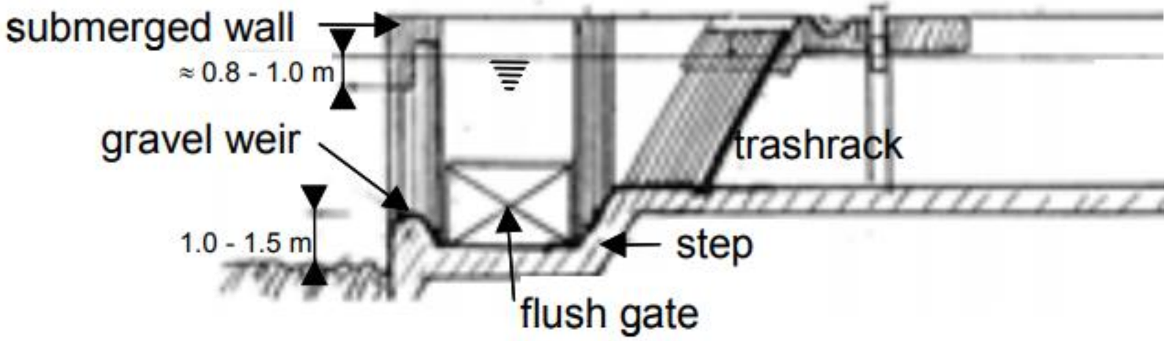
Cross section b - b : Weir /dam



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

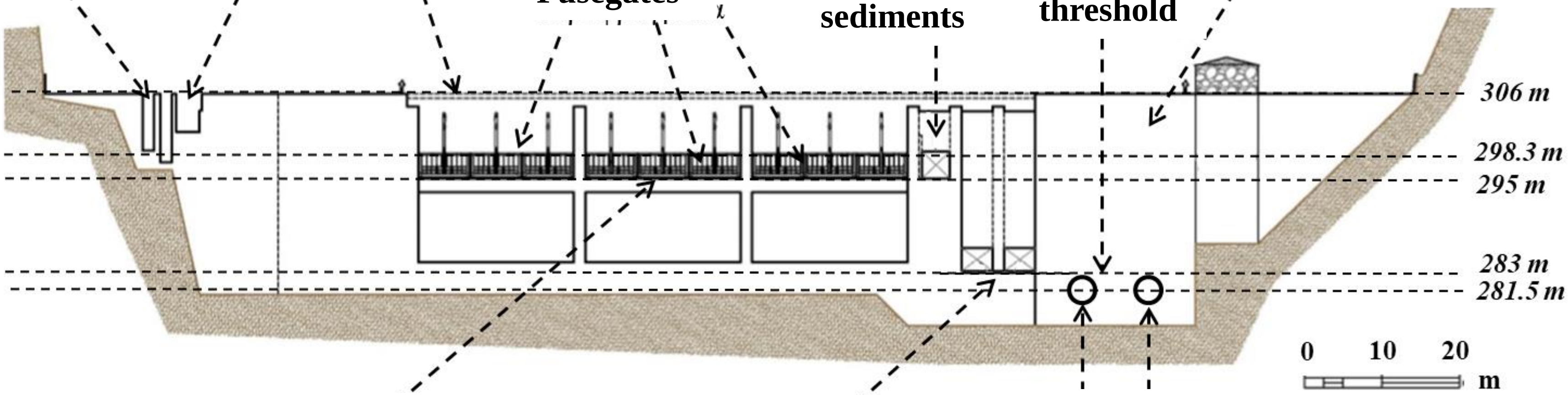
SHPPs –Sediment managment

Dafnozonara

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

Spillway and fusegates

Fish ladder and small boats passage



Fish ladder

Small boat passage

Bridge

Fusegates

Arch gates for removal of floating sediments

Water intake threshold

Powerhouse

Frontal spillway

Arch flushing gates for sediments

Turbines

SHPPs as an additional project

Agia Varvara (0.92 MW)

Thessaloniki water supply 7 m^3/s

Source: PPC Renewables

It has been 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. It operates from 2008 and has mean annual electrical energy production of **4.5 GWh.**

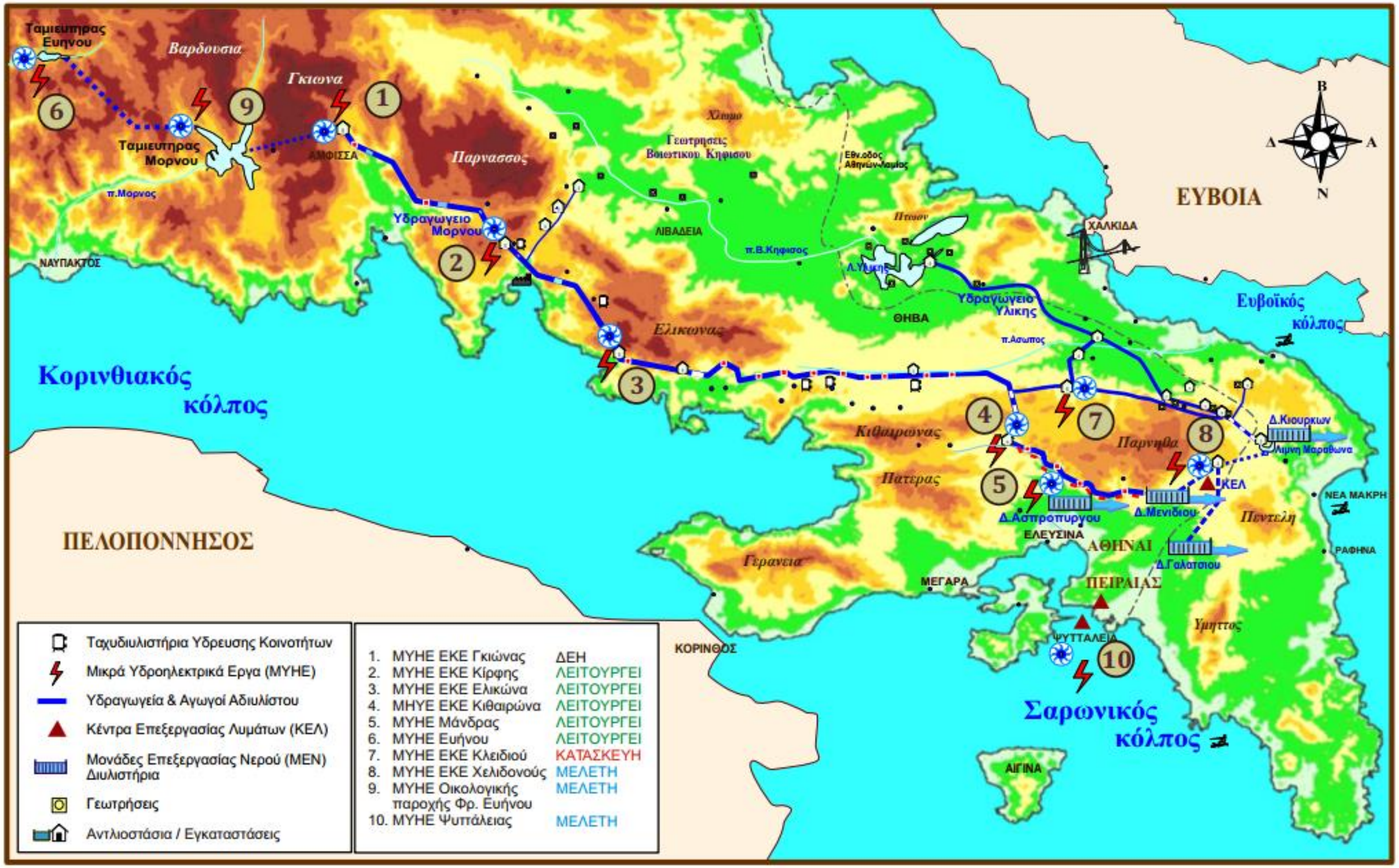
$$I\ (kW) = g * n * H\ (m) * Q\ (m^3/s)$$

$g = 9.81\ m/s^2$ $n = 0.90$ $Q = 4.5\ m^3/s$ $H = 23\ m$ $I = 920\ kW$

SHPPs as an additional project

Aqueducts of the Athens Water Supply System (EYDAP)

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.



⌂	Ταχυδιυλιστήρια Υδρευσης Κοινοτήτων
ϟ	Μικρά Υδροηλεκτρικά Εργα (ΜΥΗΕ)
━	Υδραγωγεία & Αγωγοί Αδιυλίστου
▲	Κέντρα Επεξεργασίας Λυμάτων (ΚΕΛ)
▥	Μονάδες Επεξεργασίας Νερού (ΜΕΝ) Διυλιστήρια
▣	Γεωτρήσεις
⌂	Αντλιοστάσια / Εγκαταστάσεις

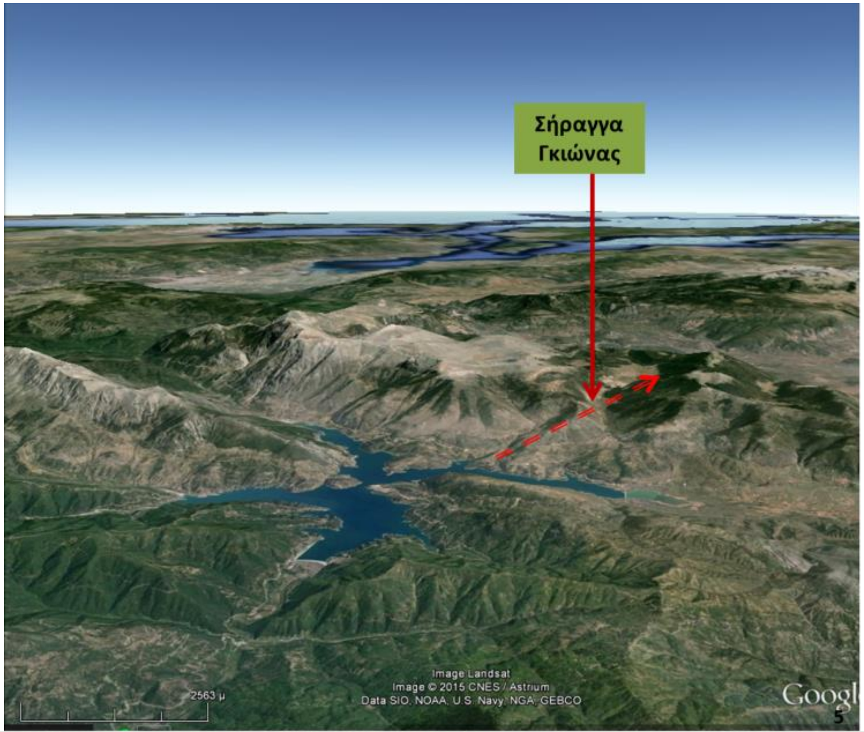
1. ΜΥΗΕ ΕΚΕ Γκιώνας	ΔΕΗ
2. ΜΥΗΕ ΕΚΕ Κίρφης	ΛΕΙΤΟΥΡΓΕΙ
3. ΜΥΗΕ ΕΚΕ Ελικώνα	ΛΕΙΤΟΥΡΓΕΙ
4. ΜΗΥΕ ΕΚΕ Κιθαιρώνα	ΛΕΙΤΟΥΡΓΕΙ
5. ΜΥΗΕ Μάνδρας	ΛΕΙΤΟΥΡΓΕΙ
6. ΜΥΗΕ Ευήνου	ΛΕΙΤΟΥΡΓΕΙ
7. ΜΥΗΕ ΕΚΕ Κλειδιού	ΚΑΤΑΣΚΕΥΗ
8. ΜΥΗΕ ΕΚΕ Χελιδονούς	ΜΕΛΕΤΗ
9. ΜΥΗΕ Οικολογικής παροχής Φρ. Ευήνου	ΜΕΛΕΤΗ
10. ΜΥΗΕ Ψυττάλειας	ΜΕΛΕΤΗ

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

SHPP as an additional project

Aqueducts of the Athens Water Supply System



The most significant SHPP on the Athens aqueduct is Giona that 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 m3/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.

$$\mathbf{I\ (kW) = g * n * H\ (m) * Q\ (m^3/s)}$$

$g = 9.81\ m/s^2$ $n = 0.90$

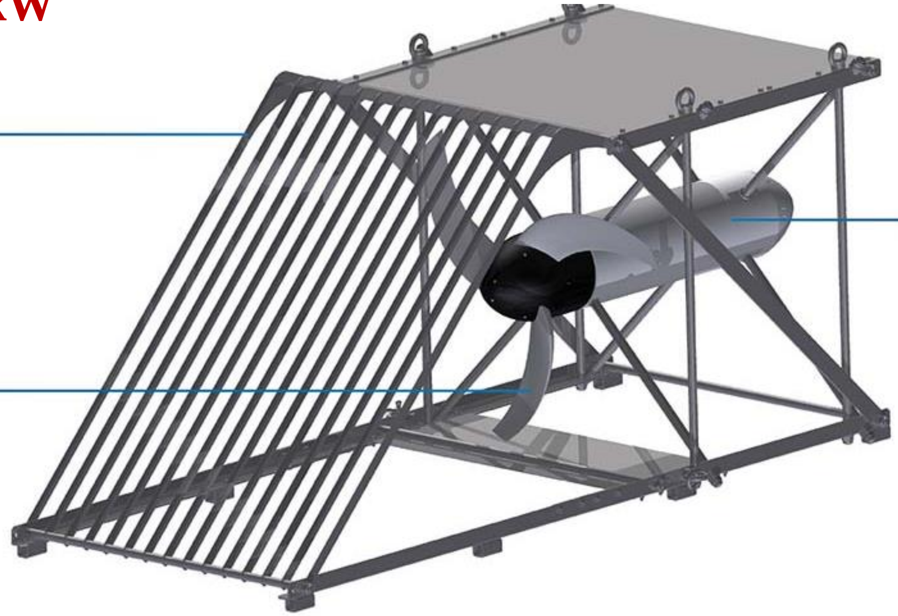
$Q = 14.5\ m^3/s$ $H = 66.1\ m$

I= 8.5 MW

In-stream projects

River current turbines

Smart free stream: **5 kW**



Debris protection
stainless steel cables are carefully designed such that debris neither accumulates nor damages the blades

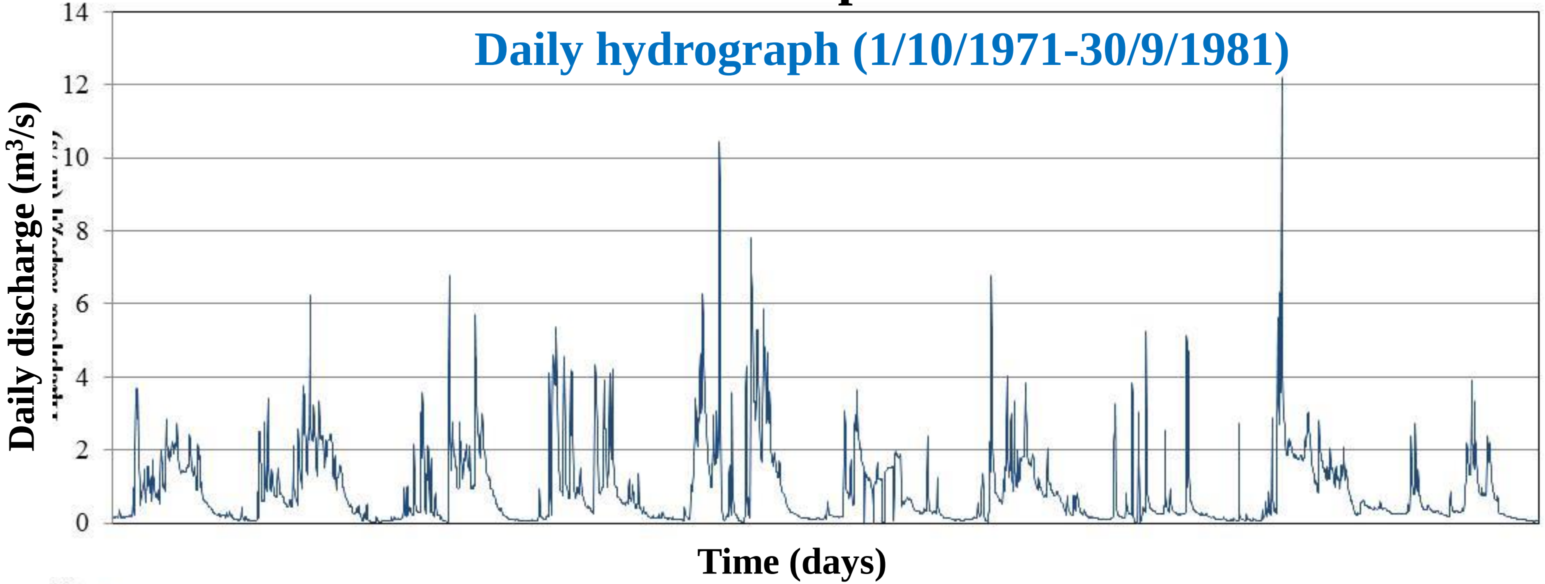
Rotor
slightly curved blades improve performance against debris

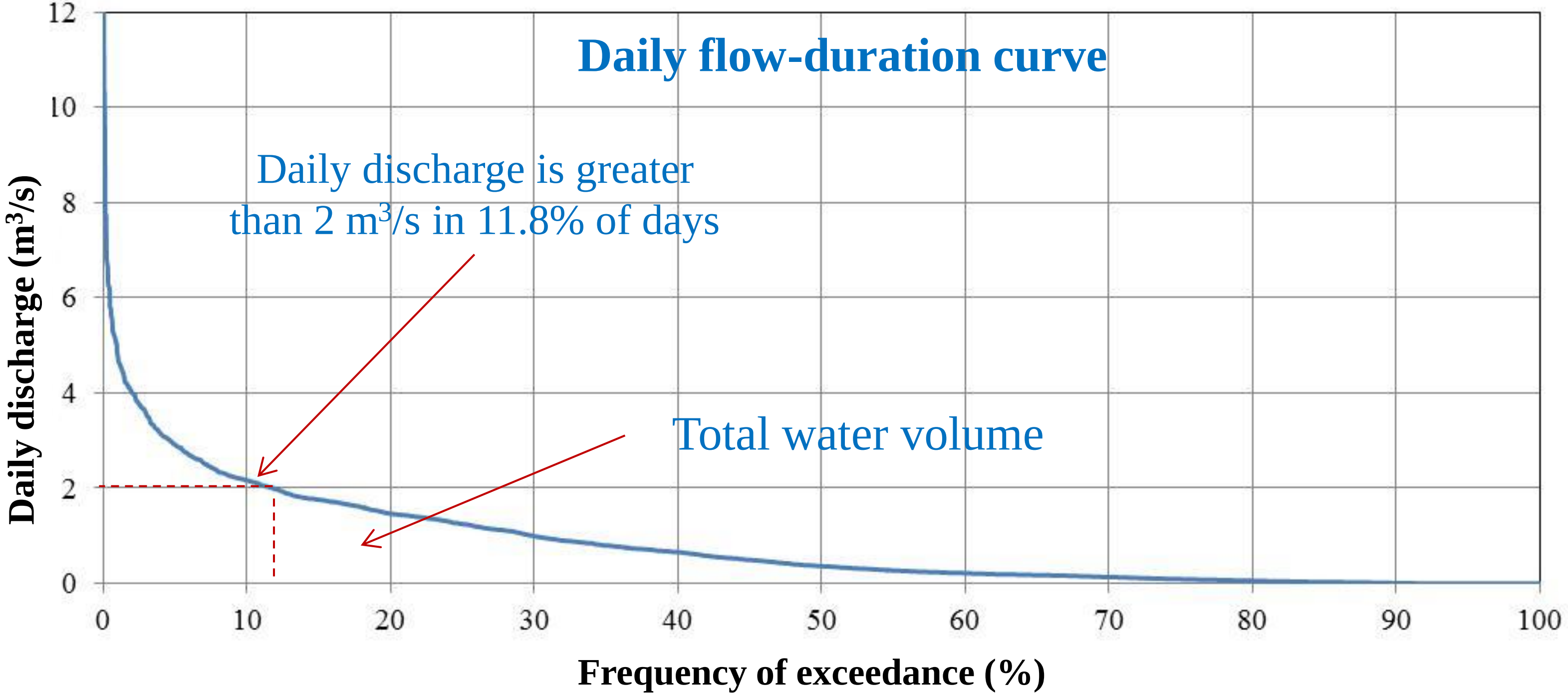
5 kW underwater generator
permanent-magnet generator provides three-phase AC power

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

Design of SHPPs

Water potential


Daily hydrograph (1/10/1971-30/9/1981)


Daily flow-duration curve

Daily discharge is greater than 2 m³/s in 11.8% of days

Total water volume

Design of SHPPs

Environmental flow

The main methodologies for the estimation of environmental flow are based on:

- the historical flows of the river (water flow regime)
- the geometrical characteristics of the river cross sections
- the preservation of the river as (a) habitat for specific species, (b) wetland and (c) natural landscape

Practically, the environmental flow can be estimated considering the:

- statistical characteristics of flow time series (as a percentage of the annual low-flow period or by taking into account the flow duration curve)
- wetted perimeter in specific river cross sections
- required water volumes for the preservation of specific species and wetlands

According to Greek legislation, the minimum environmental flow downstream of SHPPs must be defined as the maximum of the following:

- *30% of the mean discharge of summer months (June, July, August) or*
- *50% of the mean discharge of September or*
- *30 lt/sec in any case.*

The environmental flow must be increased, in case of an important ecosystem downstream

The first known flow regulation rule

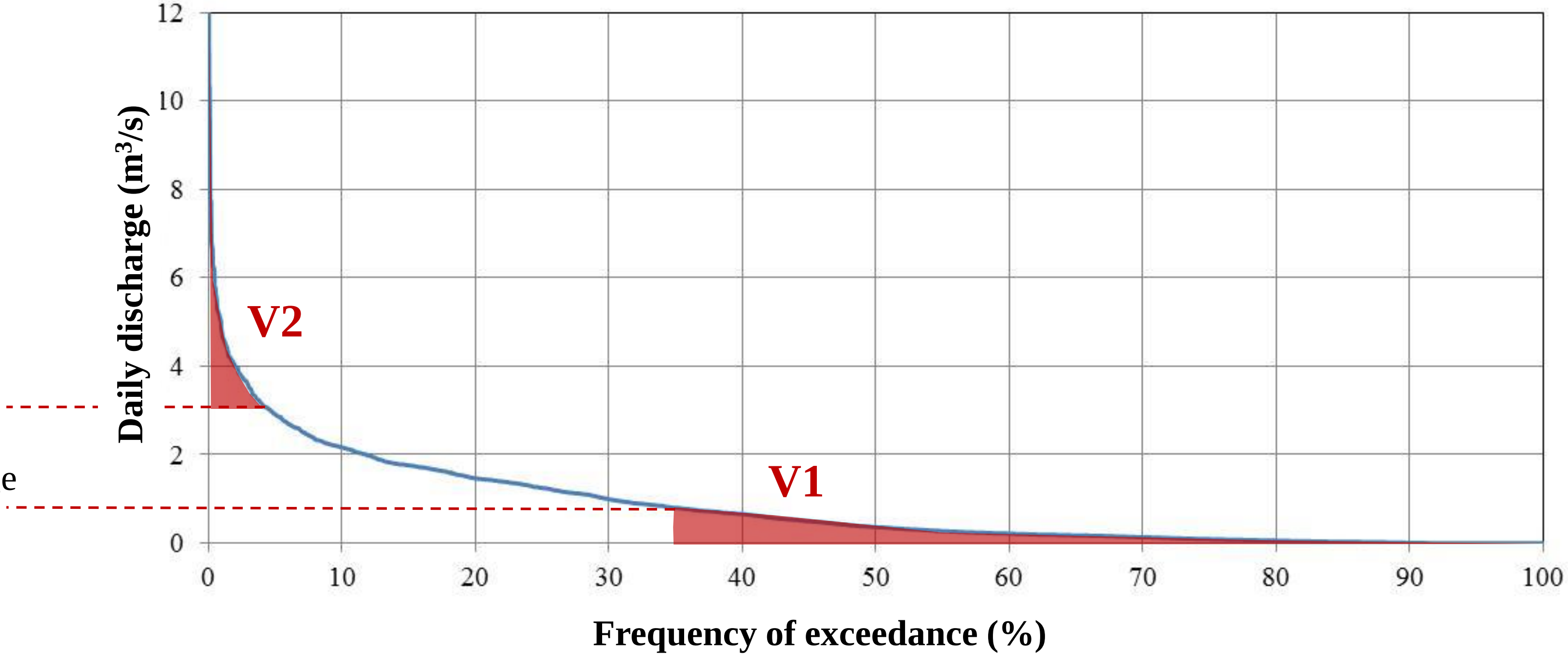
It is saved in an epigraph of the 5th century BC in the ancient city of Gortyn in Crete. The city is crossed by the river Lithaios, which dominates the valley of Messara

Gods. If anyone makes the flow run from the middle of the river towards his own property, it is without penalty for the person so doing. He is to leave the flow as wide as the bridge that the agora holds, or more but no less.

Design of SHPPs

Limitations

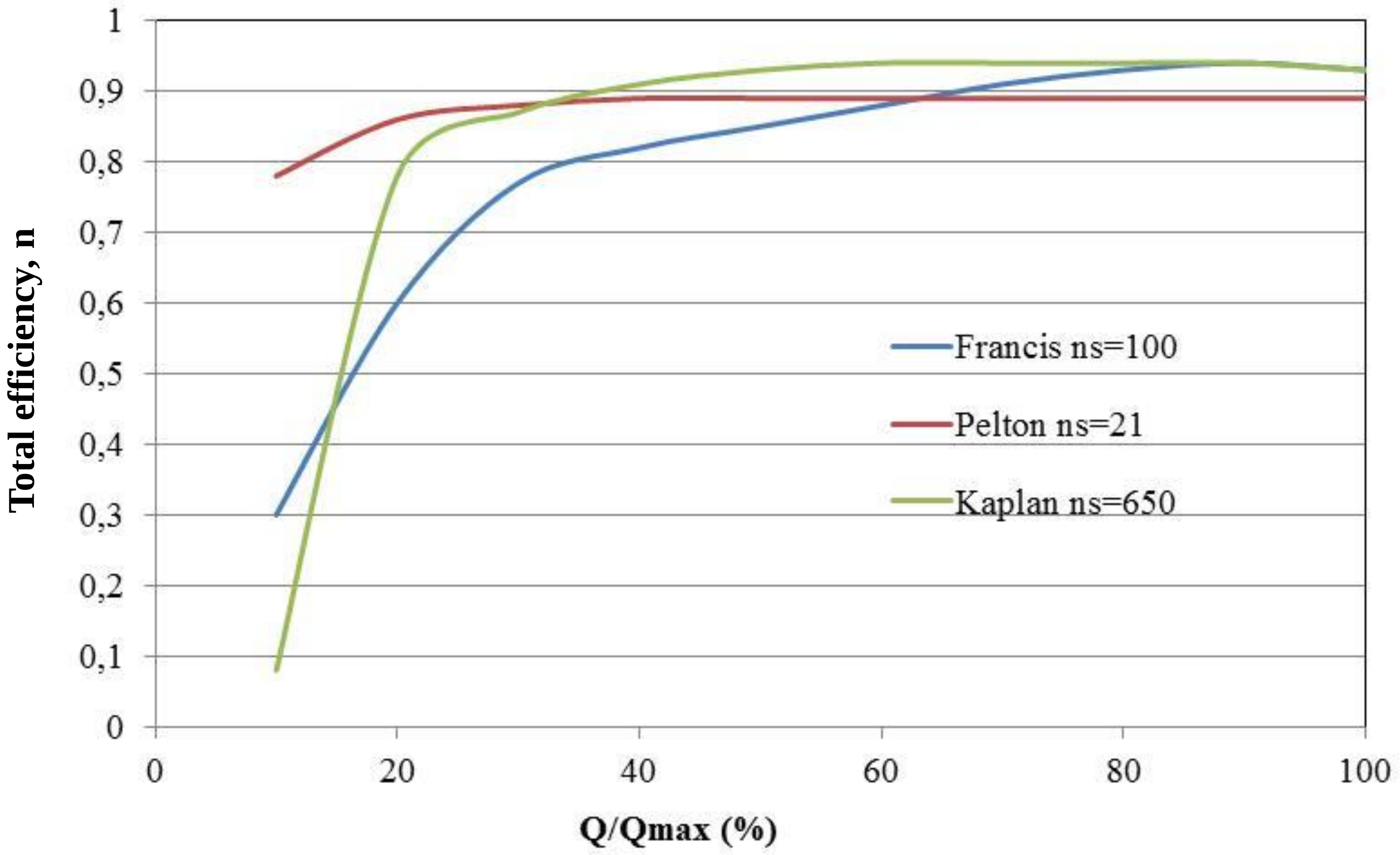
- The turbine exploits a range of discharges between the nominal discharge (maximum) and a minimum discharge that is usually 10% to 30% of the nominal discharge. The exact percentage depends on the type of the turbine (Pelton-Francis-Kaplan)
- The volumes V1 and V2 are not exploited for energy production. The volume V1 depends on the minimum operational discharge of the smallest turbine and volume V2 depends on the maximum operational discharge of the largest turbine
- The minimization of volumes V1 and V2 is achieved with the combination of several turbines with different installed power
- According to Greek legislation the design of SHPPs must ensure: (a) the exploitation of (at least) 75% of the available water volume and (b) an operational time greater than 30%



Operational
discharge range

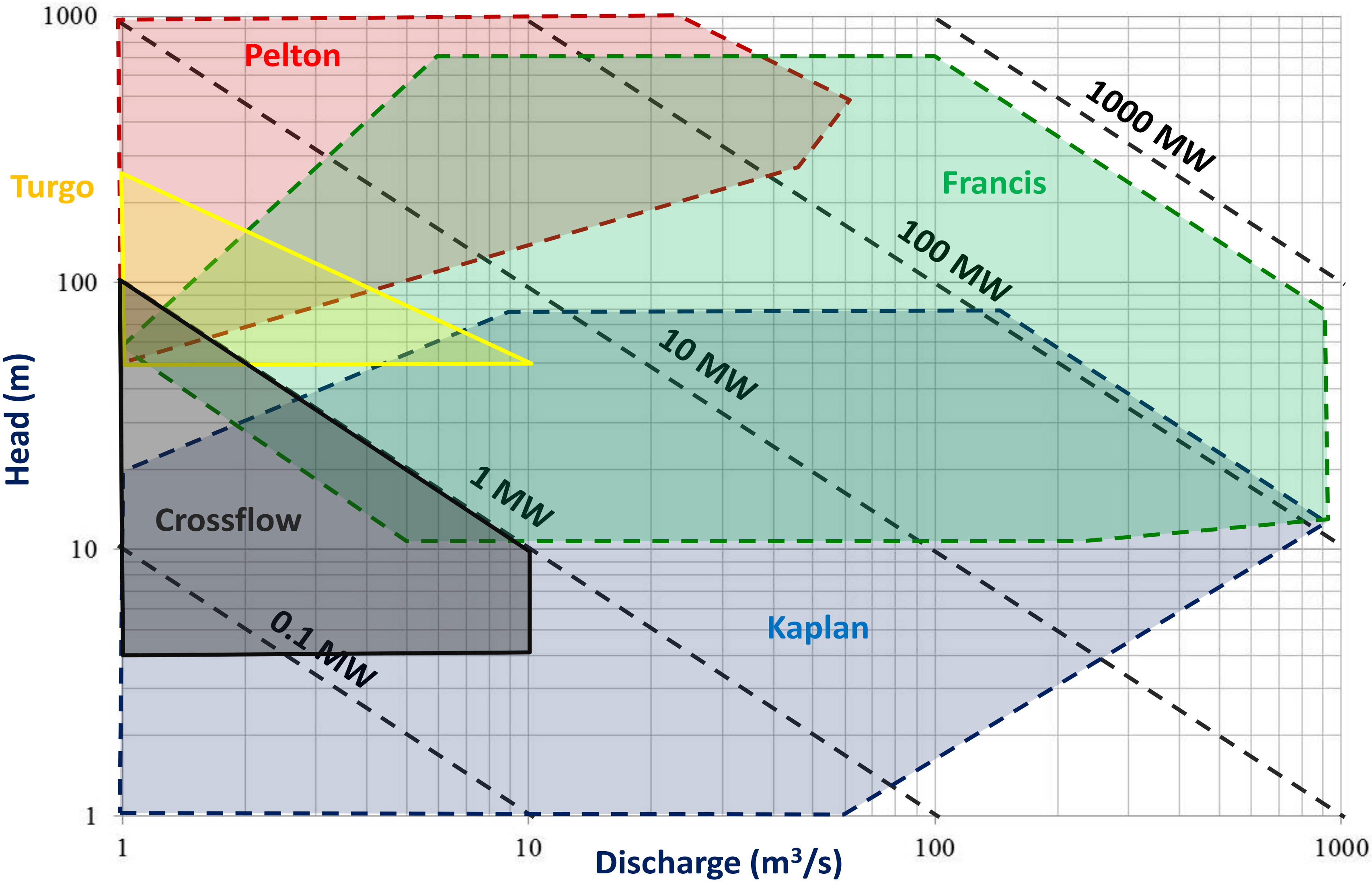
Design of SHPPs

Efficiency curves



Design of SHPPs

Operational ranges of different turbine types



Design of SHPPs

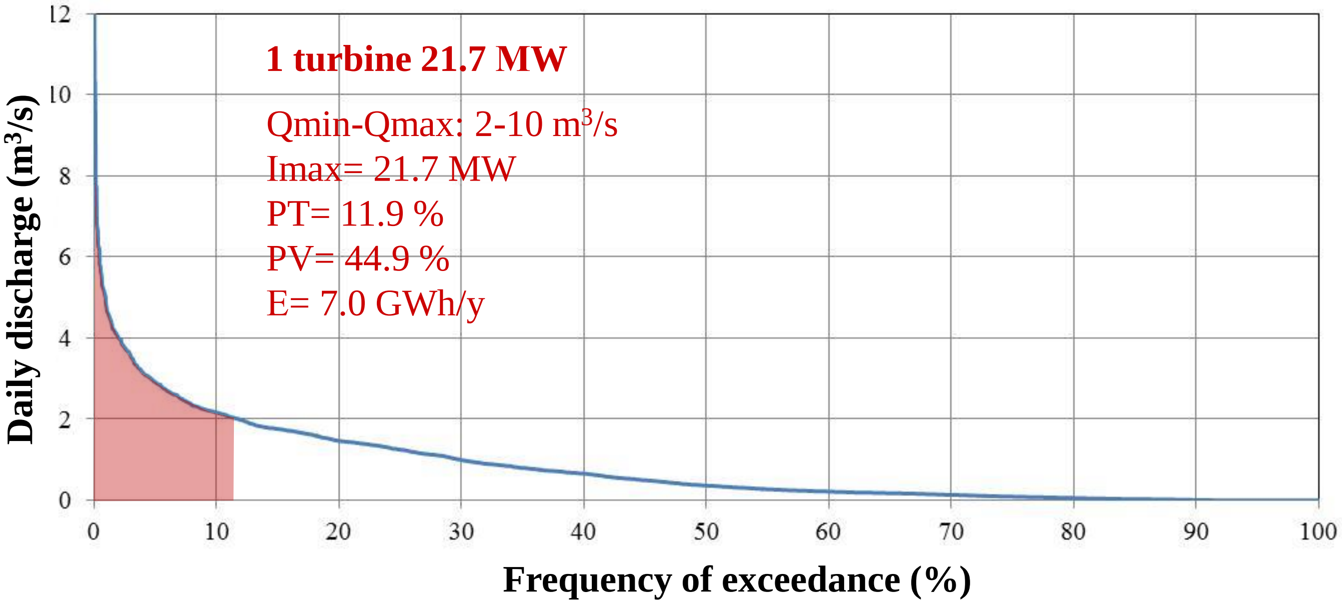
Data

H=260 m
ρ=1000 kg/m^3
g=9.81 m/s^2
n=0.85

Theoretical power for various discharges

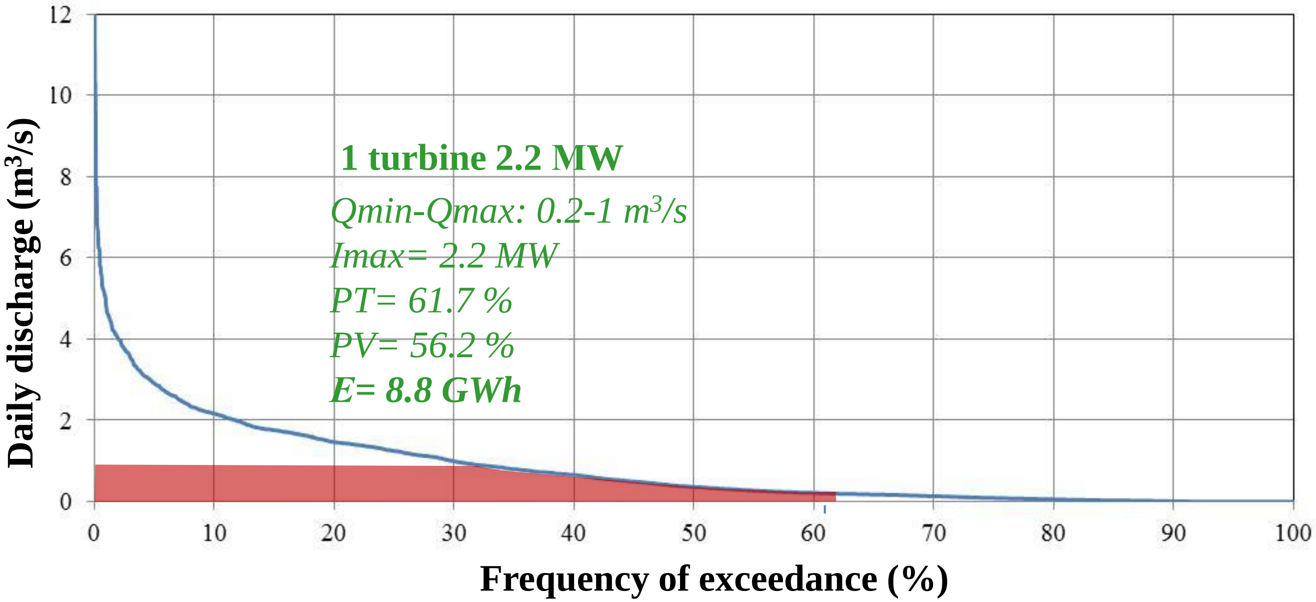
Q (m^3/s)	I (MW)
0.5	1.1
1	2.2
1.5	3.3
2	4.3
2.5	5.4
3	6.5
4	8.7
5	10.8
10	21.7

Turbine Selection



1 turbine 21.7 MW

Qmin-Qmax: 2-10 m^3/s
Imax= 21.7 MW
PT= 11.9 %
PV= 44.9 %
E= 7.0 GWh/y



1 turbine 2.2 MW

Qmin-Qmax: 0.2-1 m^3/s
Imax= 2.2 MW
PT= 61.7 %
PV= 56.2 %
E= 8.8 GWh

Legend

Qmin, Qmax: Minimum, maximum exploitation discharge (m^3/s)

Imax: Power in maximum exploitation discharge (MW)

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

PV: Percentage of water volume used (%)

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

Design of SHPPs

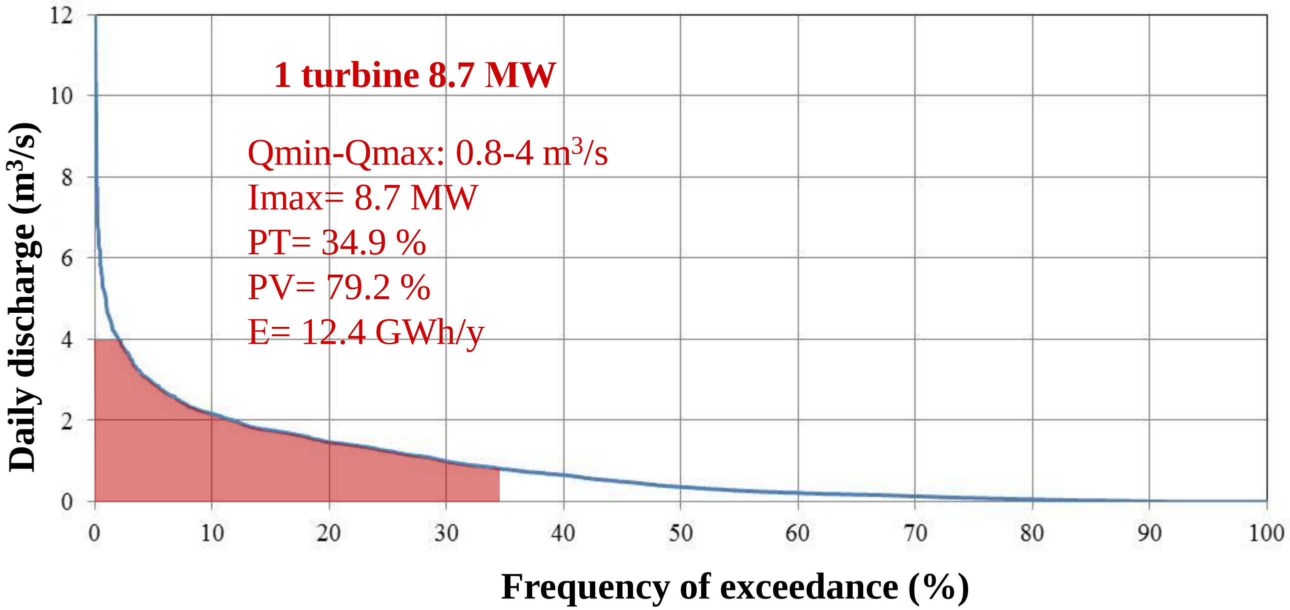
Data

$H=260$ m
$\rho=1000$ kg/m^3
$g=9.81$ m/s^2
$n=0.85$

Theoretical power for various discharges

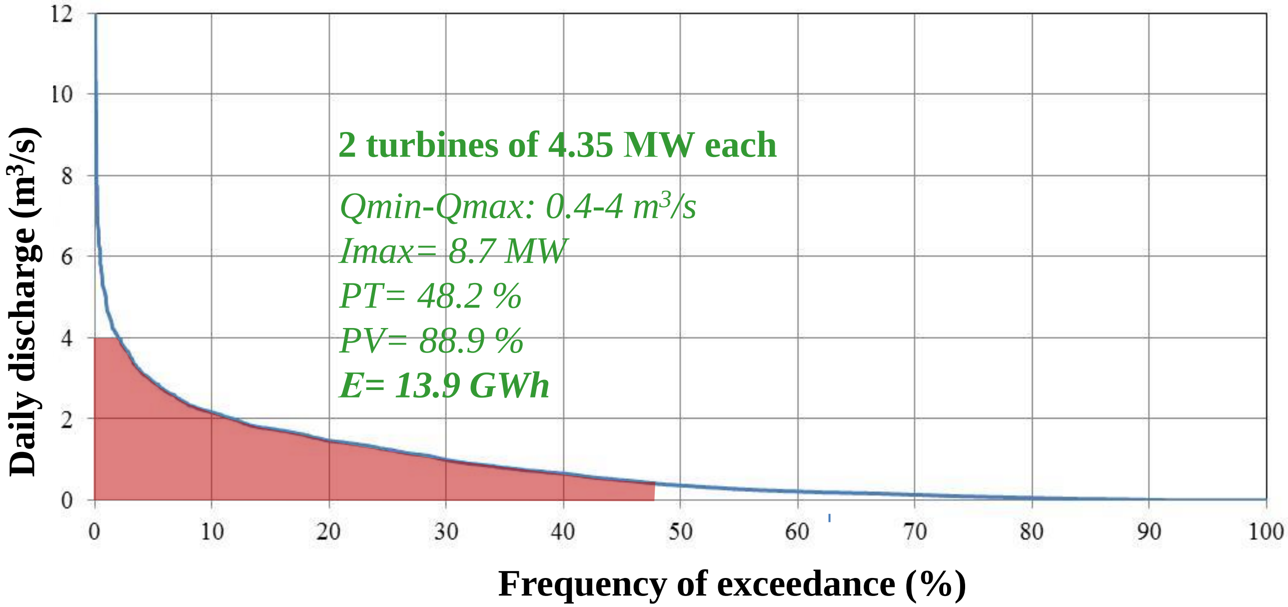
Q (m^3/s)	I (MW)
0.5	1.1
1	2.2
1.5	3.3
2	4.3
2.5	5.4
3	6.5
4	8.7
5	10.8
10	21.7

Selection of turbines



1 turbine 8.7 MW

Qmin-Qmax: 0.8-4 m^3/s
Imax= 8.7 MW
PT= 34.9 %
PV= 79.2 %
E= 12.4 GWh/y



2 turbines of 4.35 MW each

Qmin-Qmax: 0.4-4 m^3/s
Imax= 8.7 MW
PT= 48.2 %
PV= 88.9 %
E= 13.9 GWh

Legend

Qmin, Qmax: Minimum, maximum exploitation discharge (m^3/s)

Imax: Power in maximum exploitation discharge (MW)

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

PV: Percentage of water volume used (%)

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

Design of SHPPs

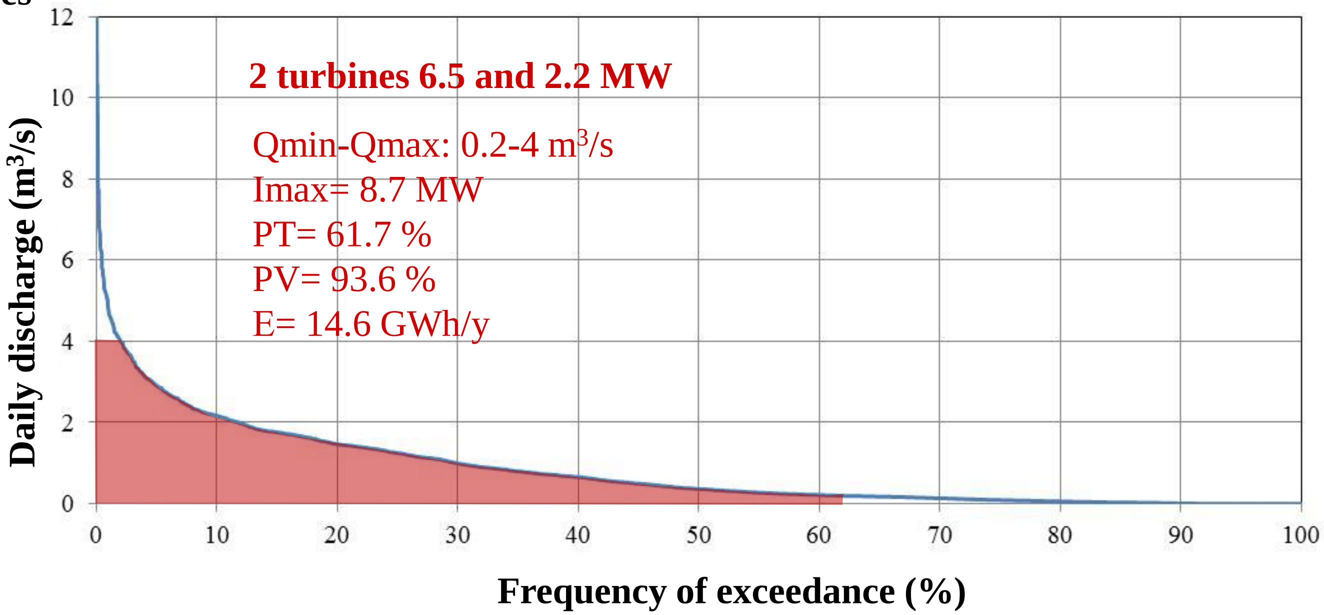
Data

H=260 m
ρ=1000 kg/m^3
g=9.81 m/s^2
n=0.85

Theoretical power for various discharges

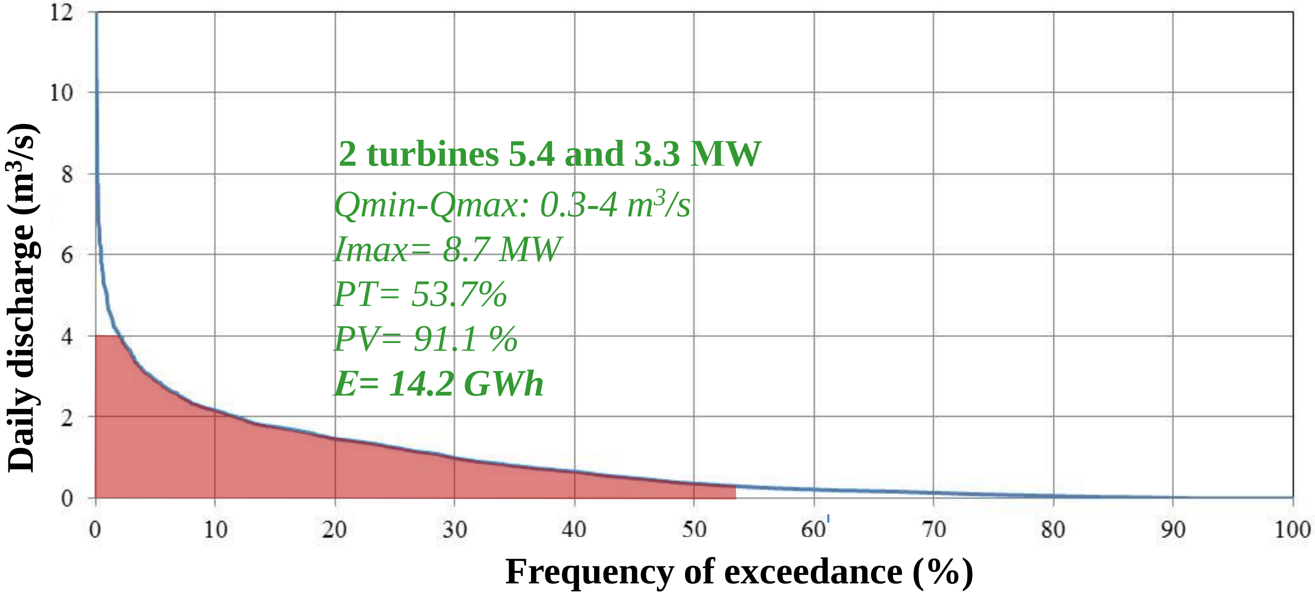
Q (m^3/s)	I (MW)
0.5	1.1
1	2.2
1.5	3.3
2	4.3
2.5	5.4
3	6.5
4	8.7
5	10.8
10	21.7

Selection of turbines



2 turbines 6.5 and 2.2 MW

Qmin-Qmax: 0.2-4 m^3/s
Imax= 8.7 MW
PT= 61.7 %
PV= 93.6 %
E= 14.6 GWh/y



2 turbines 5.4 and 3.3 MW

Qmin-Qmax: 0.3-4 m^3/s
Imax= 8.7 MW
PT= 53.7%
PV= 91.1 %
E= 14.2 GWh

Legend

Qmin, Qmax:
Minimum, maximum exploitation discharge (m^3/s)

Imax: Power in maximum exploitation discharge (MW)

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

PV: Percentage of water volume used (%)

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

Design of SHPPs

Flow duration curve application

$$P(Q) = 1 - F(Q) = (1 + Q/10)^{-5}$$

Q discharge in m^3/s ***P*** probability of exceedance of the value Q ***F*** probability function

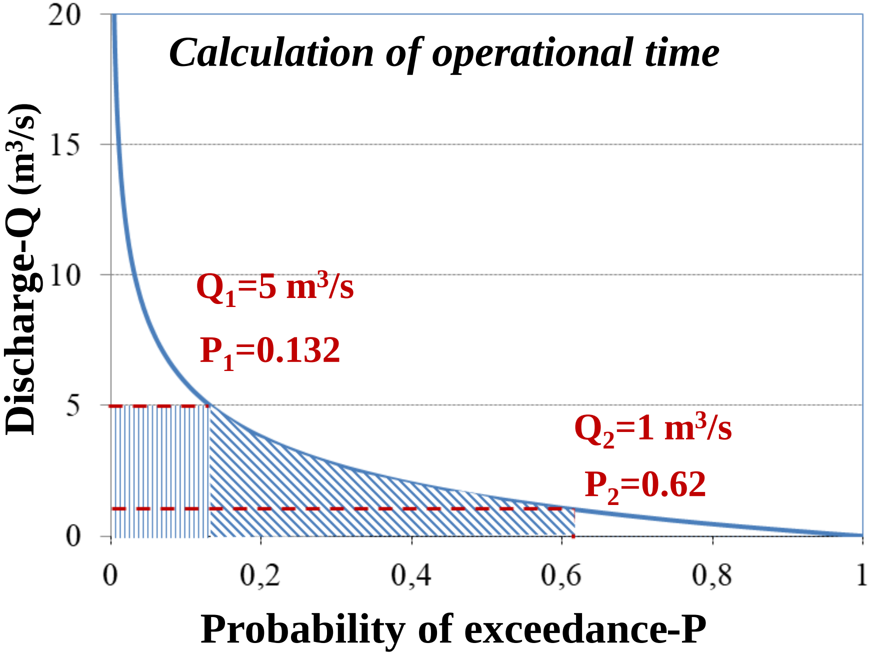
The inverse function is given by the formula:

$$Q(P) = 10(1/P^{0.2} - 1)$$

The integral of the flow duration curve to P is given by the formula:

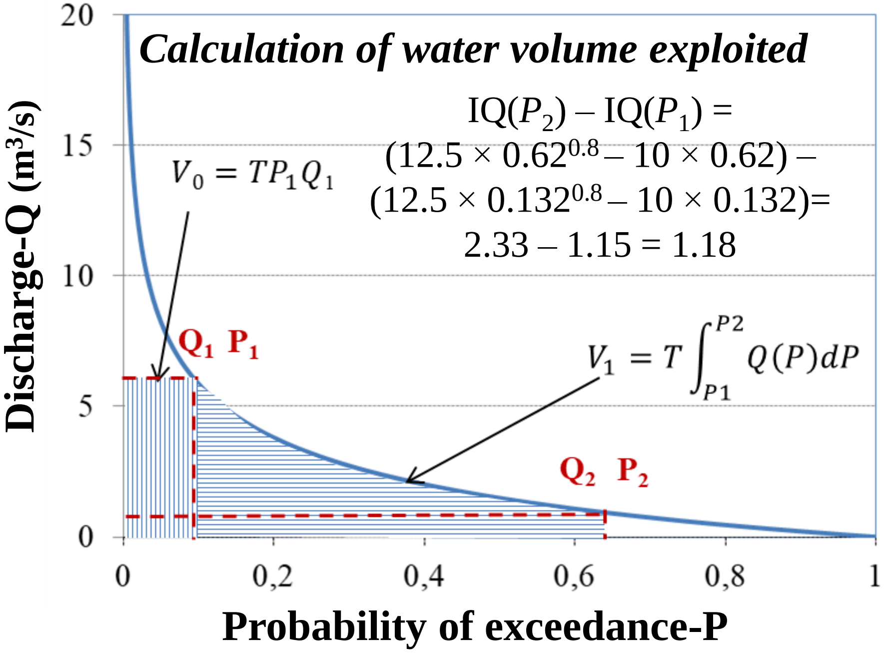
$$\mathrm{IQ} := \int Q(P)\,\mathrm{d}P = 12.5P^{0.8} - 10P$$

A turbine with an operation discharge range of 1 - 5 m^3/s, is examined



Operational time: **62%**

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



$V_0 = TP_1Q_1$

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

$V_1 = T \int_{P1}^{P2} Q(P)dP$

For one-year operation, T =31.56 × 10^6 s

$V_0 = 31.56 \times 0.132 \times 5 = \mathbf{20.8\ hm^3}$

$V_1 = 31.56 \times 1.18 = \mathbf{37.1\ hm^3}$

Exploitation of hydraulic energy

Source: http://www.lifo.gr/guests/viral/56837