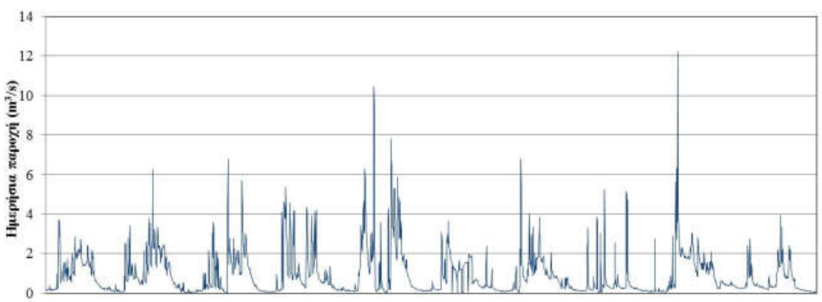
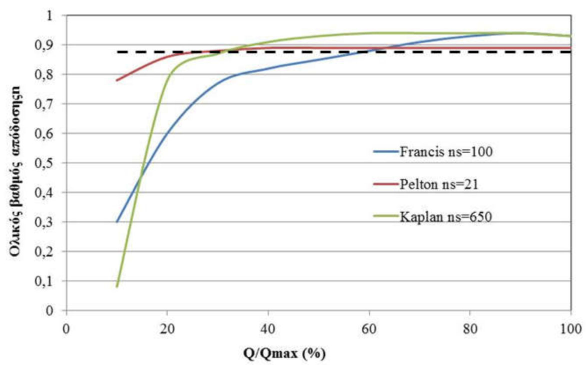
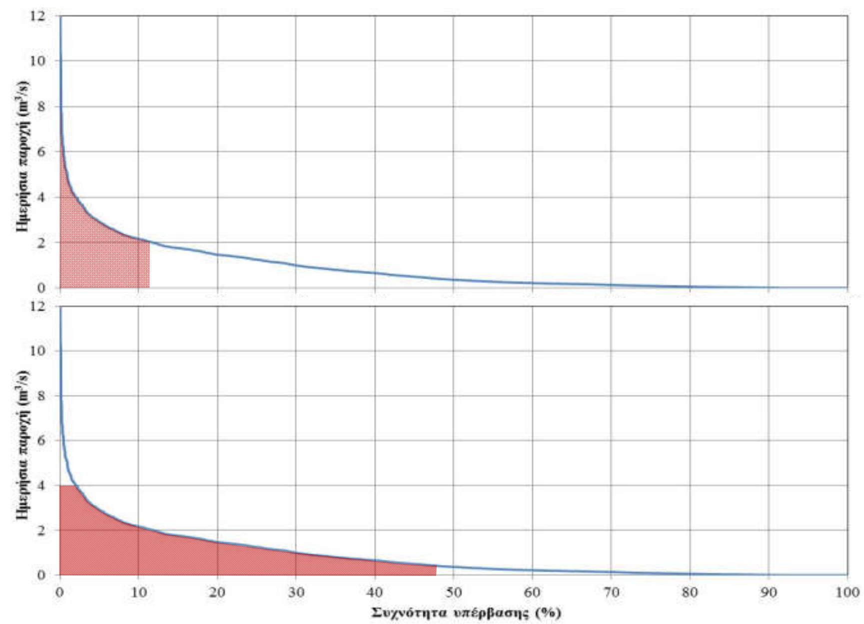
# Postgraduate program:
# Environment and Development
## Course: Energy and Environment

National Technical
University of Athens

# *Exercise instructions: Design of Small Hydroelectric Power Plants*





**Nikos Mamassis, Andreas Efstratiadis,**

**Department of Water Resources & Environmental Engineering,**

**School of Civil Engineering, NTUA**

# Exercise

The construction of a small hydropower plant with a net head of 260 m is considered in a specific river location. Daily flow data are available at the location of the intake for a period of 10 hydrologic years (Excel file), whereas Table 1 contains the corresponding values of the mean monthly flows.

**Table 1 Mean Monthly Flows ($m^3/s$)**

| **Month** | **10** | **11** | **12** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **Annual** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Mean value** | 0.48 | 1.37 | 1.46 | 0.99 | 1.40 | 1.53 | 1.66 | 1.03 | 0.42 | 0.23 | 0.15 | 0.12 | **0.90** |

**Requested:**

1. The estimation of the environmental flow and the timeseries of the daily volume of water exploitable for hydropower production
2. The initial estimation of the mean annual potential electrical energy, assuming a total efficiency of 0.85
3. The development of the exploitable daily flow duration curve
4. The development of a spreadsheet for the simulation of the hydropower plant's daily operation and the calculation of the electricity produced. Assume that the turbine starts operating with a flow higher than 10% of the maximum flow and has a **constant total efficiency** of 0.85. Considering that one turbine is going to be installed, estimate its nominal flow, so that the production of electrical energy is maximised.
5. The development of a spreadsheet for the simulation of the hydropower plant's daily operation and the calculation of the electricity produced. Assume that the turbine has a **variable efficiency** (that can be estimated via the curves supplied), whereas the efficiency of the electromechanical equipment is 0.96. Considering that one turbine is going to be installed, estimate its nominal flow, so that the production of electrical energy is maximised. Use the performance curves of the three turbine types (Francis, Pelton, Kaplan), which are supplied in the Excel file. Assume that the following conditions will need to apply: a) the volume of water utilised, after the deduction of the environmental flow, needs to be at least 75% of the total, and b) the exploitation index of the plant needs to be at least 30%
6. Investigate the installation of two turbines. Calculate the electrical energy produced from different turbine combinations and identify the most efficient ones in terms of electricity production
7. The final selection of **two** turbines, after taking into account other factors besides the maximisation of electrical energy production

# 1. Environmental flow estimation

| | A | B | C | D | E | F | G | H | I | J | K | L | M | N | O |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | | | | | | | | | | | | | | | |
| 2 | Έκταση | 42.8 | km2 | | | | | | | | | | | | |
| 3 | Απορροή | 28.4 | hm3 | | | | | | | | | | | | |
| 4 | Απορροή | 663.3 | mm | | | | | | | | | | | | |
| 5 | | | | | | | | | | | | | | | |
| 6 | | | | | | | | | | | | | | | |
| 7 | | **10** | **11** | **12** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **Έτος** | |
| 8 | 1971-72 | 0.18 | 0.77 | 1.32 | 1.02 | 1.73 | 1.78 | 1.55 | 1.00 | 0.31 | 0.21 | 0.13 | 0.08 | **0.84** | |
| 9 | 1972-73 | 1.20 | 1.17 | 0.59 | 1.43 | 2.61 | 2.14 | 1.74 | 0.91 | 0.28 | 0.11 | 0.05 | 0.09 | **1.03** | |
| 10 | 1973-74 | 0.32 | 0.81 | 1.13 | 0.20 | 1.89 | 1.71 | 2.17 | 1.57 | 0.42 | 0.11 | 0.07 | 0.17 | **0.88** | |
| 11 | 1974-75 | 0.90 | 2.81 | 1.57 | 0.76 | 1.54 | 1.92 | 1.06 | 0.67 | 0.43 | 0.15 | 0.15 | 0.09 | **1.00** | |
| 12 | 1975-76 | 0.77 | 3.45 | 2.22 | 1.11 | 0.44 | 2.45 | 3.62 | 2.18 | 0.76 | 0.22 | 0.12 | 0.12 | **1.45** | |
| 13 | 1976-77 | 0.22 | 0.94 | 1.99 | 1.05 | 0.87 | 1.45 | 0.99 | 0.42 | 0.49 | 0.32 | 0.11 | 0.08 | **0.74** | |
| 14 | 1977-78 | 0.18 | 1.19 | 0.89 | 1.80 | 1.95 | 1.40 | 0.98 | 0.72 | 0.39 | 0.40 | 0.14 | 0.11 | **0.85** | |
| 15 | 1978-79 | 0.57 | 0.63 | 0.82 | 0.39 | 0.53 | 0.31 | 1.28 | 0.26 | 0.16 | 0.09 | 0.26 | 0.10 | **0.45** | |
| 16 | 1979-80 | 0.15 | 0.80 | 3.67 | 1.88 | 2.13 | 1.49 | 1.37 | 1.32 | 0.42 | 0.48 | 0.41 | 0.30 | **1.20** | |
| 17 | 1980-81 | 0.28 | 1.16 | 0.40 | 0.28 | 0.34 | 0.61 | 1.80 | 1.28 | 0.57 | 0.18 | 0.10 | 0.05 | **0.59** | |
| 18 | **Μέση τιμή** | **0.48** | **1.37** | **1.46** | **0.99** | **1.40** | **1.53** | **1.66** | **1.03** | **0.42** | **0.23** | **0.15** | **0.12** | **0.90** | |
| 19 | | | | | | | | | | | | | | | |
| 20 | ΟΙΚΟΛΟΓΙΚΗ 1 | | 0.08 | | | | | | | | | | | | |
| 21 | ΟΙΚΟΛΟΓΙΚΗ 2 | | 0.06 | | | | | | | | | | | | |
| 22 | ΟΙΚΟΛΟΓΙΚΗ 3 | | 0.03 | | | | | | | | | | | | |
| 23 | | | | | | | | | | | | | | | |
| 24 | **ΟΙΚΟΛΟΓΙΚΗ** | | **0.08** | | | | | | | | | | | | |
| 25 | V hm3 | | 25.9 | | | | | | | | | | | | |
| 26 | 75%*V | | 19.4 | | | | | | | | | | | | |
| 27 | | | | | | | | | | | | | | | |
| 28 | | 0.90 | 0.08 | 0.82 | | | ΚΑΜΠΥΛΗ ΔΙΑΡΚΕΙΑΣ | | | | | | | | |
| 29 | | | ΟΙΚΟΛΟΓΙ | ΕΚΜΕΤΑΛΛΕΥΣΗ | | | ΣΥΧΝΟΤΗΤΑ | ΕΚΜΕΤΑΛΛΕΥΣΗ | | | | | | | |
| 30 | 1/10/1971 | 0.17 | 0.08 | 0.09 | | 1 | 0.03 | 12.10 | | | | | | | |
| 31 | 2/10/1971 | 0.17 | 0.08 | 0.09 | | 2 | 0.05 | 10.36 | | | | | | | |
| 32 | 3/10/1971 | 0.17 | 0.08 | 0.09 | | 3 | 0.08 | 10.32 | | | | | | | |
| 33 | 4/10/1971 | 0.15 | 0.08 | 0.07 | | 4 | 0.11 | 9.31 | | | | | | | |
| 34 | 5/10/1971 | 0.12 | 0.08 | 0.04 | | 5 | 0.14 | 7.81 | | | | | | | |

***Estimation of environmental flow as the maximum of:***

*1. 30% of the mean discharge of summer months (June, July, August) or*

*2. 50% of the mean discharge of September or*

*3. 30 lt/sec in any case.*

***Flow duration curve*** SB1

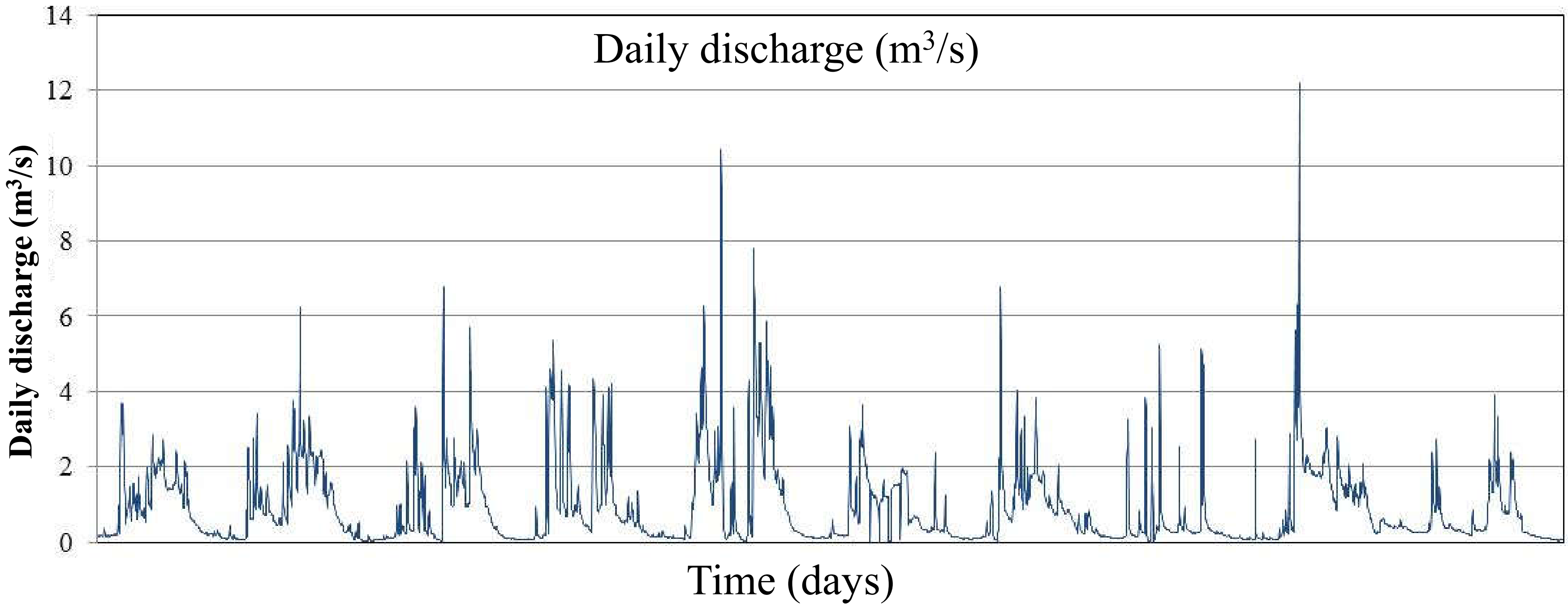
1. Ranking daily discharges in descending order
2. Calculation of empirical probability of exceedance

**Slide 3**

---

**SB1** "Flow duration curve" instead of "duration curve" or "Flow duration curve for hydropower production"
Sandra Baki, 28-Mar-19

# 2.Initial estimations




*Mean discharge available for hydropower exploitation:* ***0.82 m/s*** ***(the envrinomental flow has been abstracted)***

*Mean annual water volume available for hydropower exploitation:* ***25.9 hm³***

Assuming:

$\rho$ *1000 kg/m³*
$g$ *9.81 m/s²*
$H$ *260 m*
$n$ *0.85*

Potential values assuming complete exploitation:

Mean annual energy produced: **15 624 MWh**

Installed power for continuous operation: **1.8 MW**

Installed power for operation of 3000 h: **5.2 MW**

# 2. Initial estimations

*Mean discharge available for exploitation:* ***0.82 m/s***

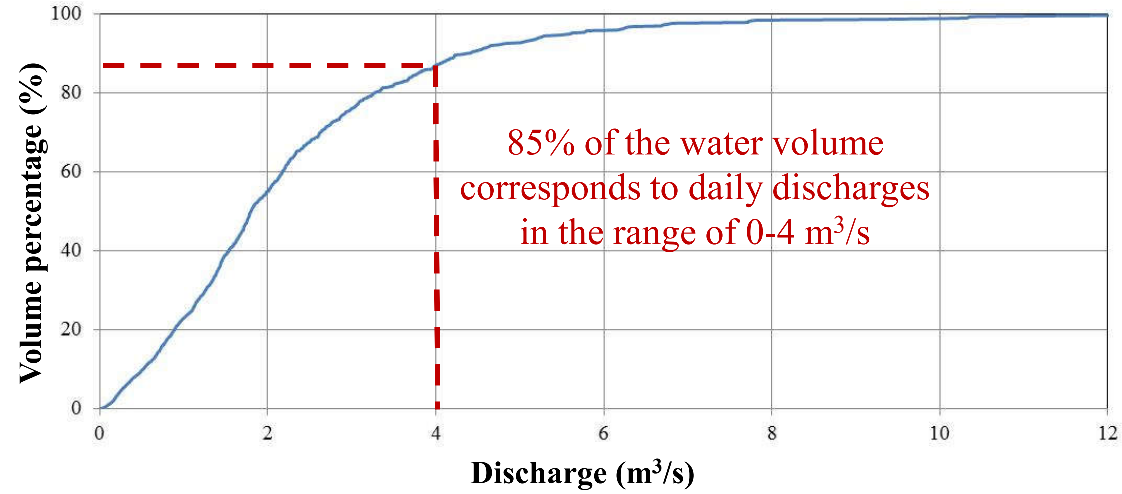
*Mean annual water volume available for exploitation:* ***25.9 hm³***

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

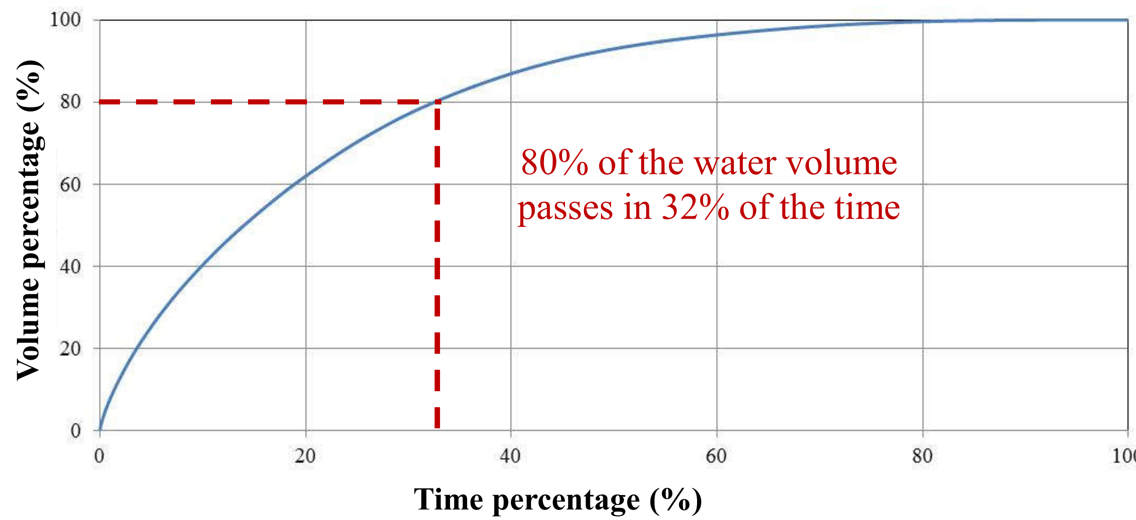
**Discharge–installed power relationship**

| $Q\ (m^3/s)$ | $I\ (MW)$ |
|---|---|
| 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 |

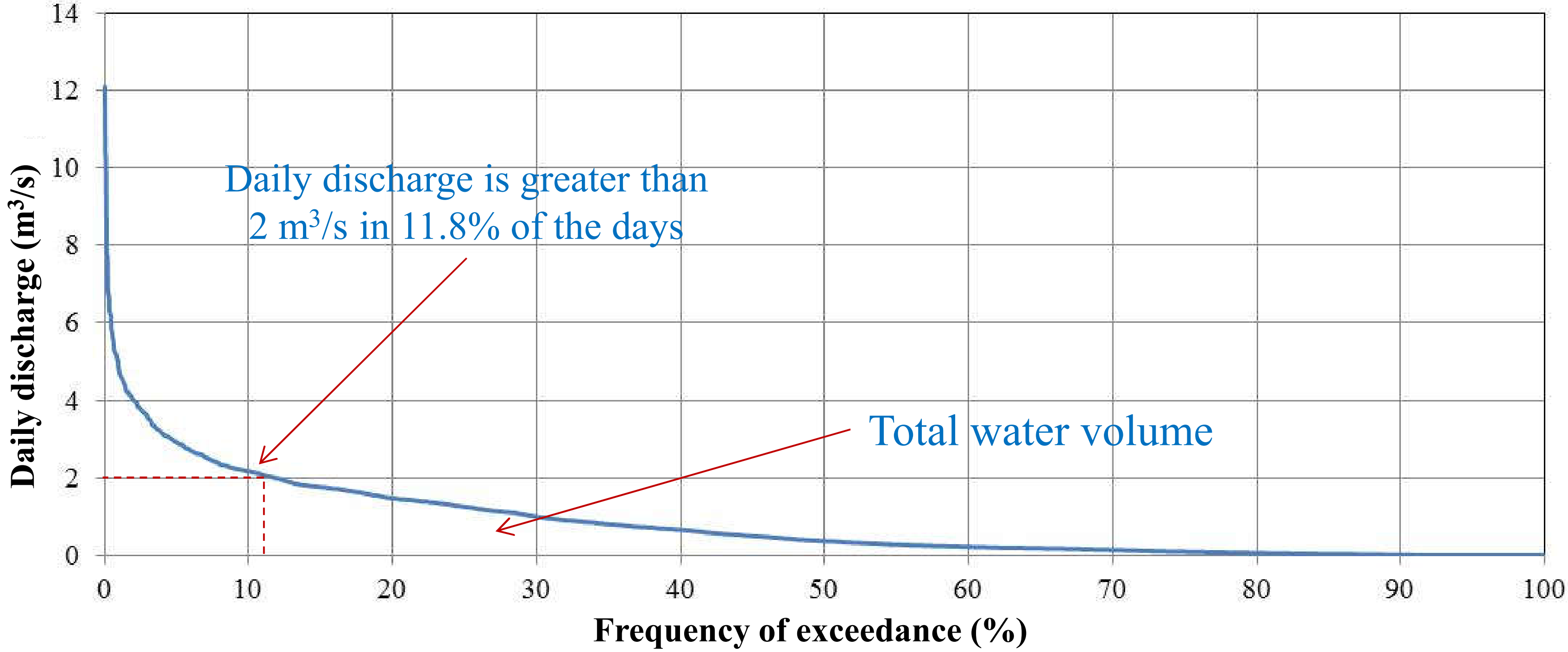
**Volume percentage-discharge relationship**

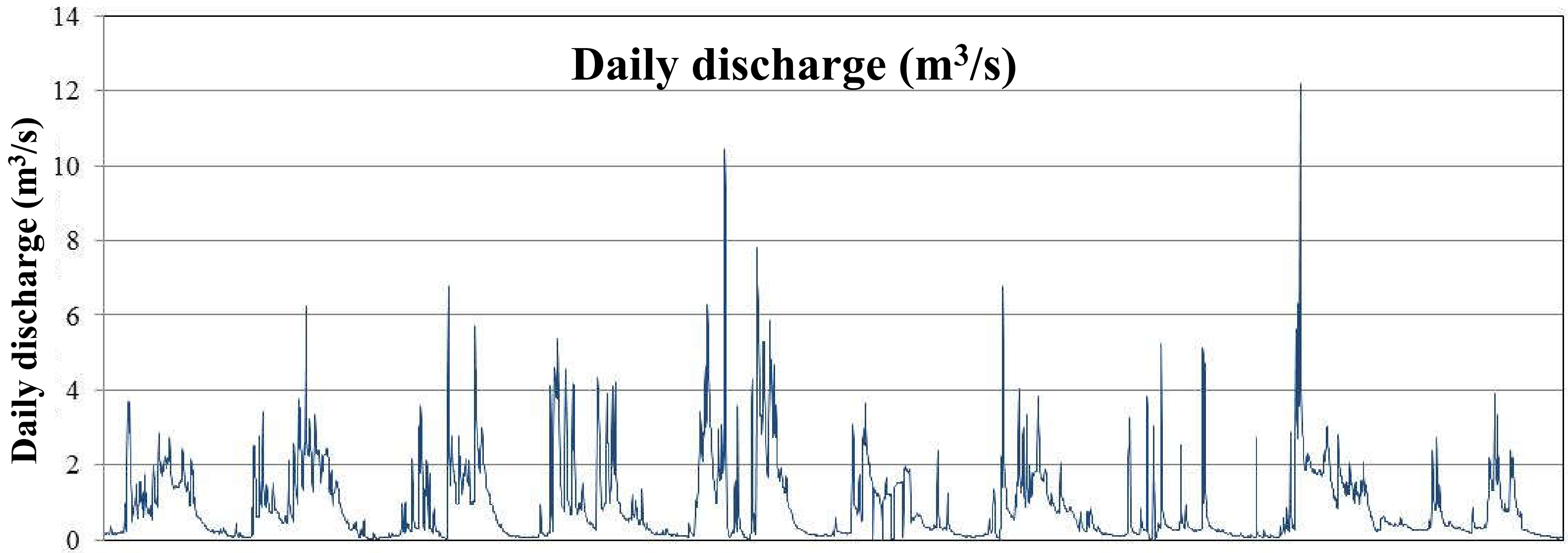



**Volume-time percentage relationship**



# 3. Daily flow duration curve



# 4. Examples with 1 turbine (n=0.85, Qmin=0.2*Qmax)

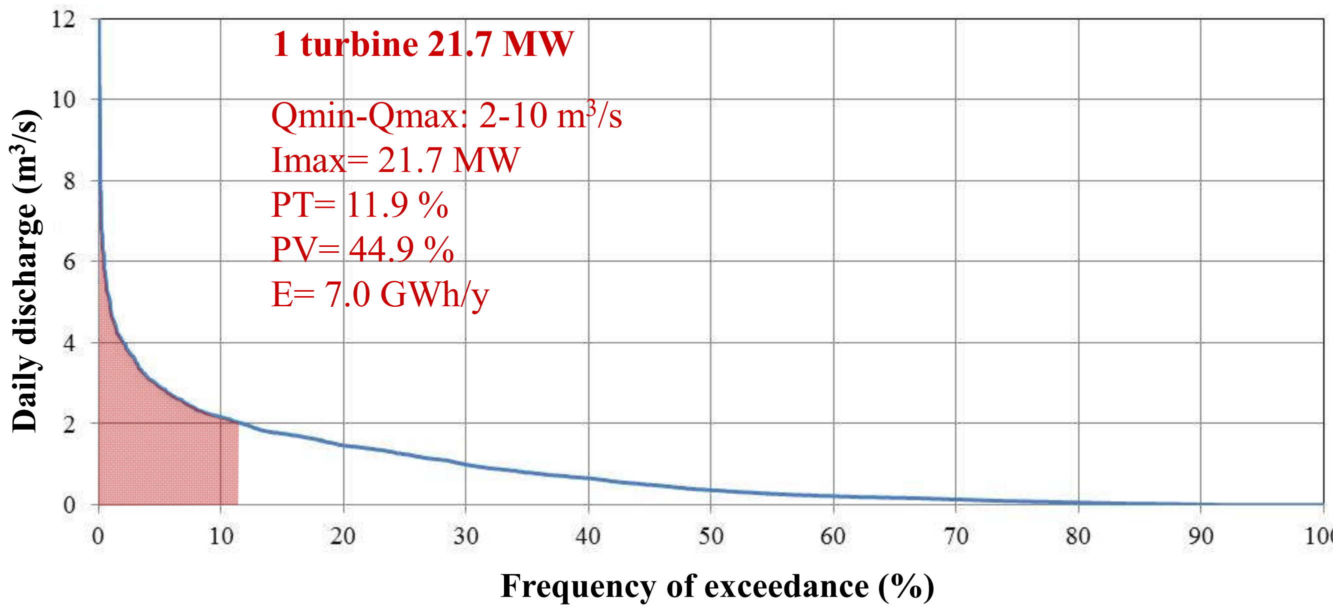
**Warning: In exercise Qmin=0.1*Qmax**

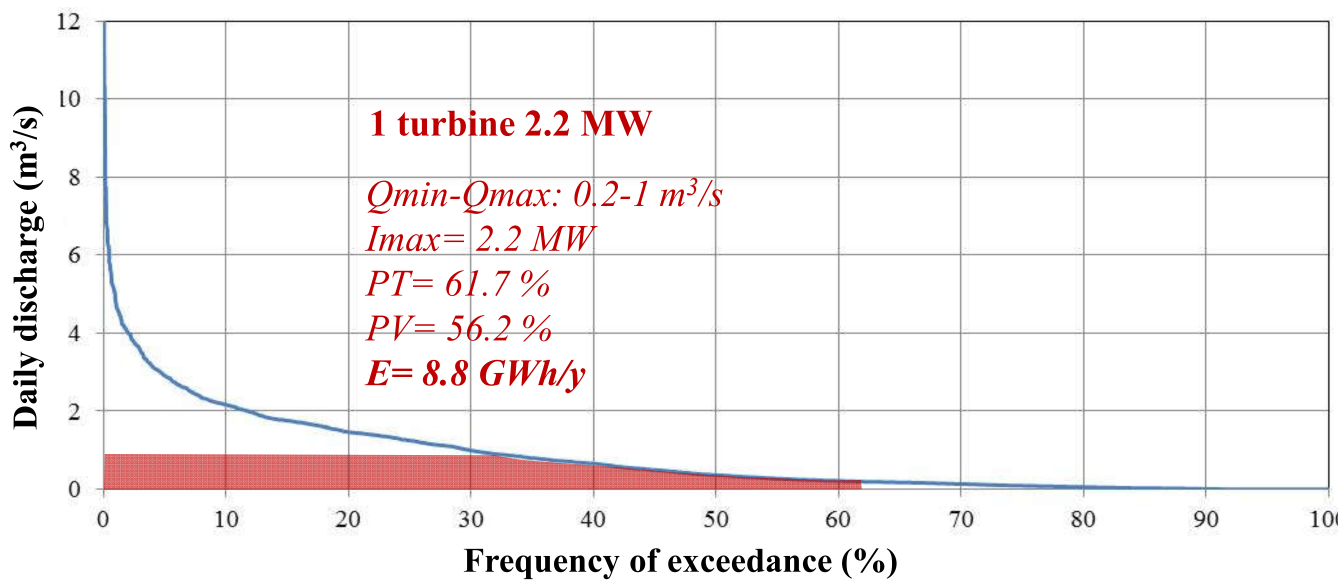
**Data**

H=260 m
ρ=1000 kg/m³
g=9.81 m/s²
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 |




**Legend**

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

**Imax:** Power at 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)

# 4. Calculations for 1 turbine

Data-Constants

| | A | B | C | D | E | F | G | H | I |
|---|---|---|---|---|---|---|---|---|---|
| 1 | | | | | | | | | |
| 2 | | | | Daily timeseries statistics (a) discharge, (b) water volume, (c) potential | | | | | |
| 3 | | | | energy and (d) required power | | | | | |
| 4 | H | 260 | | For 10 years | $m^3/s$ | $m^3/day$ | kWh | kW | |
| 5 | ρ | 1000 | | Maximum | 12.1 | 1045256.9 | 629479.8 | 26228.3 | |
| 6 | g | 9.81 | | Minimum | 0 | 0 | 0 | 0 | |
| 7 | n | 0.85 | | Mean | 0.822 | 71029.3 | 42775.6 | 1782.3 | |
| 8 | | | | | | | | | |
| 9 | | | | | | $hm^3$ | GWh | | |
| 10 | | | | Total | | 259.5 | 156.3 | | |
| 11 | | | | Total days | 3653 | | | | |
| 12 | | | | **Mean annual** | | 25.9 | 15.6 | | |
| 13 | | | **Daily electrical energy E(kWh)=g*n*H(m)*V($m^3$)/3600** | | | | | | |
| 14 | | | =$B$6*$B$7*$B$4*C25/3600 | | | | | | |
| 15 | | | | | | | | | |
| 16 | **Max-Min exploitation discharge ($m^3/s$)** | | | | | Qmax (m3/s) | 10 | 5 | 2 |
| 17 | | | | | | Qmin (m3/s) | 1 | 0.5 | 0.2 |
| 18 | **Power at max exploitation discharge (MW)** | | | | | Imax (MW) | 21.7 | 10.8 | 4.3 |
| 19 | **Percentage of operational time per year (%)** | | | | | PT (%) | 29.9 | 44.7 | 61.7 |
| 20 | **Percentage of water volume used (%)** | | | | | PV (%) | 76.9 | 88.6 | 80.6 |
| 21 | **Total electrical energy (GWh)** | | | | | E (GWh) | 120.2 | 138.4 | 126.0 |
| 22 | | | | | | E (GWh/y) | 12.0 | 13.8 | 12.6 |
| 23 | | | | | | ΣΔ | 0.06 | 0.15 | 0.33 |
| 24 | | m3/s | m3/day | kWh | kW | | kWh/d | kWh/d | kWh/d |
| 25 | 1/10/1971 | 0.094 | 8153.6 | 4910.3 | 204.6 | | 0 | 0 | 0 |
| 26 | 2/10/1971 | 0.094 | 8153.6 | 4910.3 | 204.6 | | 0 | 0 | 0 |
| 27 | 3/10/1971 | 0.094 | 8153.6 | 4910.3 | 204.6 | | 0 | 0 | 0 |
| 28 | 4/10/1971 | 0.069 | 5941.2 | 3577.9 | 149.1 | | 0 | 0 | 0 |

Data-daily discharge timeseries

**Daily volume ($m^3$)** =B25*86400

=D25/24 **Daily power I(kW)=E(kWh)/24h**

# 4. Calculations for 1 turbine

- If the daily discharge is within the operational range (minimum-maximum discharge), then the **daily energy** is calculated using the formula **E(kWh)**=g*n*H(m)*V(m³)/3600=g*n*H(m)*Q(m³/s)*86400/3600= **g*n*H(m)*Q(m³/s)*24**
- If the daily discharge is greater than the nominal (maximum) one, then the **daily energy** is calculated with a discharge equal to the nominal one.
- If the daily discharge is lower than the minimum operational, then the **daily energy is equal to zero**

=IF(AND($B25>G$17,$B25<G$16),$B$4*$B$6*$B$7*$B25*24,IF($B25>G$16,$B$4*$B$6*$B$7*G$16*24,0))

**Min and max operational discharge are defined by the user**

| | A | B | C | D | E | F | G | H | I |
|---|---|---|---|---|---|---|---|---|---|
| 4 | H | 260 | | | | | | | |
| 5 | ρ | 1000 | | | | | | | |
| 6 | g | 9.81 | | | | | | | |
| 7 | n | 0.85 | | | | | | | |
| 16 | **Max-Min exploitation discharge (m³/s)** | | | | | Qmax (m3/s) | 10 | 5 | 2 |
| 17 | | | | | | Qmin (m3/s) | 1 | 0.5 | 0.2 |
| 18 | **Power at max exploitation discharge (MW)** | | | | | Imax (MW) | 21.7 | 10.8 | 4.3 |
| 19 | **Percentage of operational time per year (%)** | | | | | PT (%) | 29.9 | 44.7 | 61.7 |
| 20 | **Percentage of water volume used (%)** | | | | | PV (%) | 76.9 | 88.6 | 80.6 |
| 21 | **Total electrical energy (GWh)** | | | | | E (GWh) | 120.2 | 138.4 | 126.0 |
| 22 | | | | | | E (GWh/y) | 12.0 | 13.8 | 12.6 |
| 23 | | | | | | ΣΔ | 0.06 | 0.15 | 0.33 |
| 24 | | m3/s | m3/day | kWh | kW | | kWh/d | kWh/d | kWh/d |
| 25 | 1/10/1971 | 0.094 | 8153.6 | 4910.3 | 204.6 | | 0 | 0 | 0 |
| 26 | 2/10/1971 | 0.094 | 8153.6 | 4910.3 | 204.6 | | 0 | 0 | 0 |
| 27 | 3/10/1971 | 0.094 | 8153.6 | 4910.3 | 204.6 | | 0 | 0 | 0 |
| 28 | 4/10/1971 | 0.069 | 5941.2 | 3577.9 | 149.1 | | 0 | 0 | 0 |

# 4. Calculations for 1 turbine

**Calculation of the water volume percentage exploited**

- The energy produced is summed
- The daily water volume is calculated (and summed for the entire time period) using the formula: $V(m^3)=Q\ (m^3/s)*t\ (hr)*3600=E(kWh)/[g*n*H(m)]\Rightarrow$ $\mathbf{V(m^3)=E(kWh)/[g*n*H(m)*3600]}$
- This is divided by the total water volume and the percentage is calculated

`=(SUM(G25:G3677)*3600/($B$4*$B$6*$B$7))/($F$10*1000000)*100`

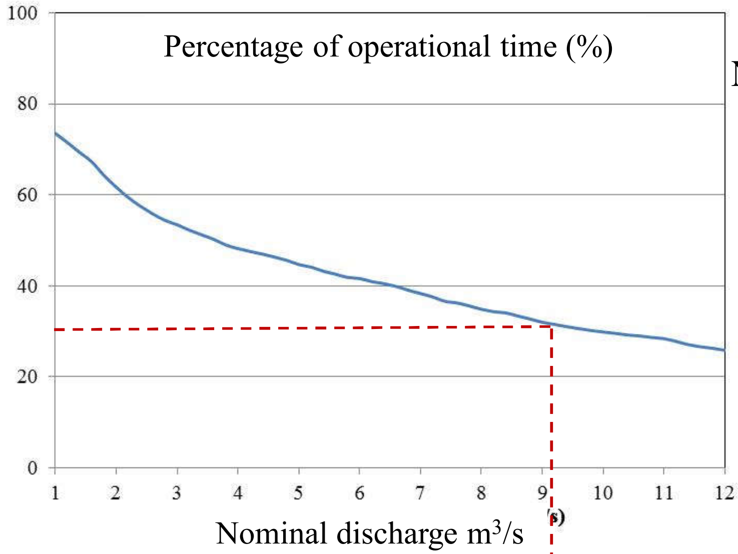
**Calculation of the operational time in the year**

The days in which energy was produced are counted and the percentage is calculated considering the total number of days

`=COUNTIF(G25:G3677,">0")/$E$11*100`

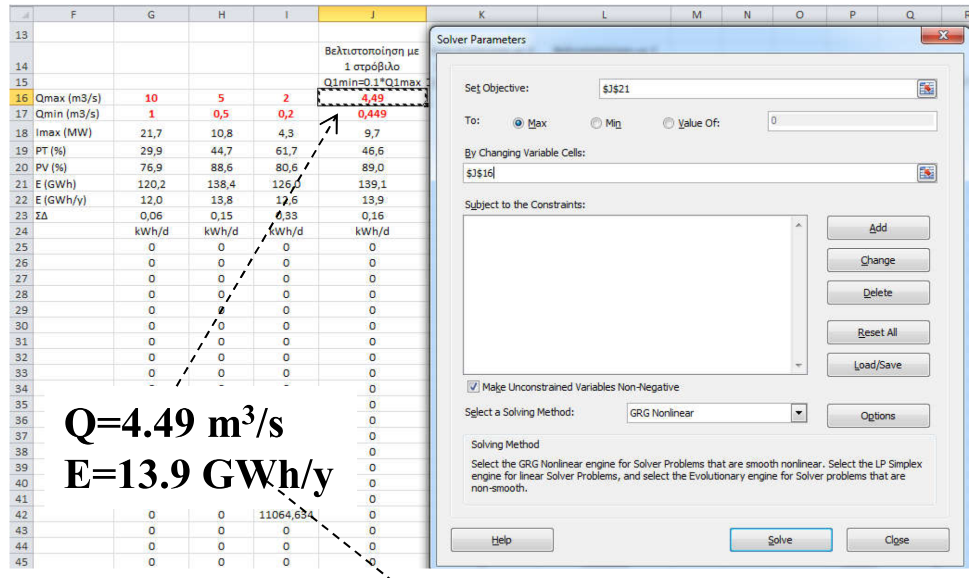
| | A | B | C | D | E | F | G | H | I |
|---|---|---|---|---|---|---|---|---|---|
| 1 | | | | | | | | | |
| 2 | | | | | | | | | |
| 3 | | | | | | | | | |
| 4 | H | 260 | | | | | | | |
| 5 | ρ | 1000 | | | | | | | |
| 6 | g | 9.81 | | | | | | | |
| 7 | n | 0.85 | | | | | | | |
| 8 | | | | | | | | | |
| 9 | | | | | | $hm^3$ | GWh | | |
| 10 | | | | ΑΘΡΟΙΣΜΑ | | 259.5 | | | |
| 11 | | | | Total number of days | 3653 | | | | |
| 12 | | | | Mean annual | | 25.9 | | | |
| 13 | | | | | | | | | |
| 14 | | | | | | | | | |
| 15 | | | | | | | | | |
| 16 | **Max-Min exploitation discharge ($m^3/s$)** | | | | | Qmax (m3/s) | 10 | 5 | 2 |
| 17 | | | | | | Qmin (m3/s) | 1 | 0.5 | 0.2 |
| 18 | **Power at max exploitation discharge (MW)** | | | | | Imax (MW) | 21.7 | 10.8 | 4.3 |
| 19 | **Percentage of operational time per year (%)** | | | | | PT (%) | 29.9 | 44.7 | 61.7 |
| 20 | **Percentage of water volume used (%)** | | | | | PV (%) | 76.9 | 88.6 | 80.6 |
| 21 | **Total electrical energy (GWh)** | | | | | E (GWh) | 120.2 | 138.4 | 126.0 |
| 22 | | | | | | E (GWh/y) | 12.0 | 13.8 | 12.6 |
| 23 | | | | | | ΣΔ | 0.06 | 0.15 | 0.33 |
| 24 | | m3/s | m3/day | kWh | kW | | kWh/d | kWh/d | kWh/d |
| 25 | 1/10/1971 | 0.094 | 8153.6 | 4910.3 | 204.6 | | 0 | 0 | 0 |
| 26 | 2/10/1971 | 0.094 | 8153.6 | 4910.3 | 204.6 | | 0 | 0 | 0 |
| 27 | 3/10/1971 | 0.094 | 8153.6 | 4910.3 | 204.6 | | 0 | 0 | 0 |
| 28 | 4/10/1971 | 0.069 | 5941.2 | 3577.9 | 149.1 | | 0 | 0 | 0 |

# 4. Examples with 1 turbine (n=0.85, Qmin=0.1*Qmax)

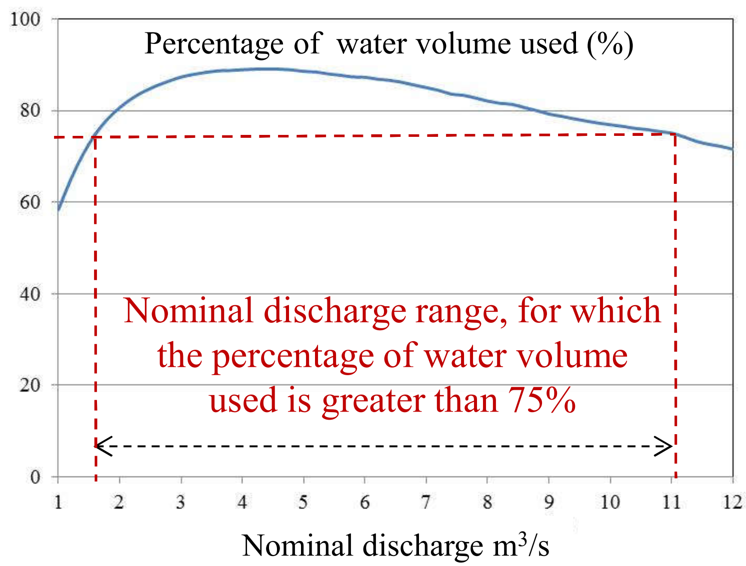



Nominal discharge range, for which the percentage of operational time is greater than 30%

**Nominal operational discharge for maximization of the produced energy**
**(use of solver)**

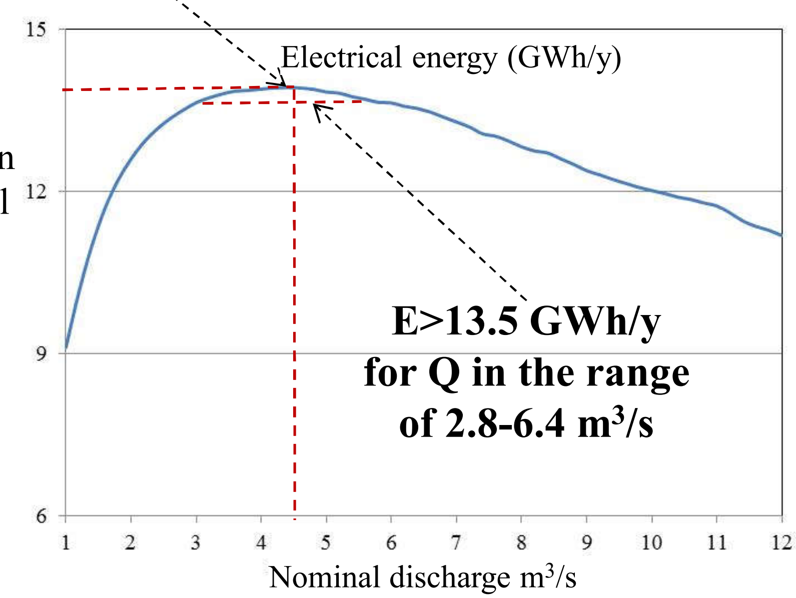



**Q=4.49 m³/s**
**E=13.9 GWh/y**




Nominal discharge range, for which the percentage of water volume used is greater than 75%

Energy production curve for nominal discharge in the range 1-12 m³/s

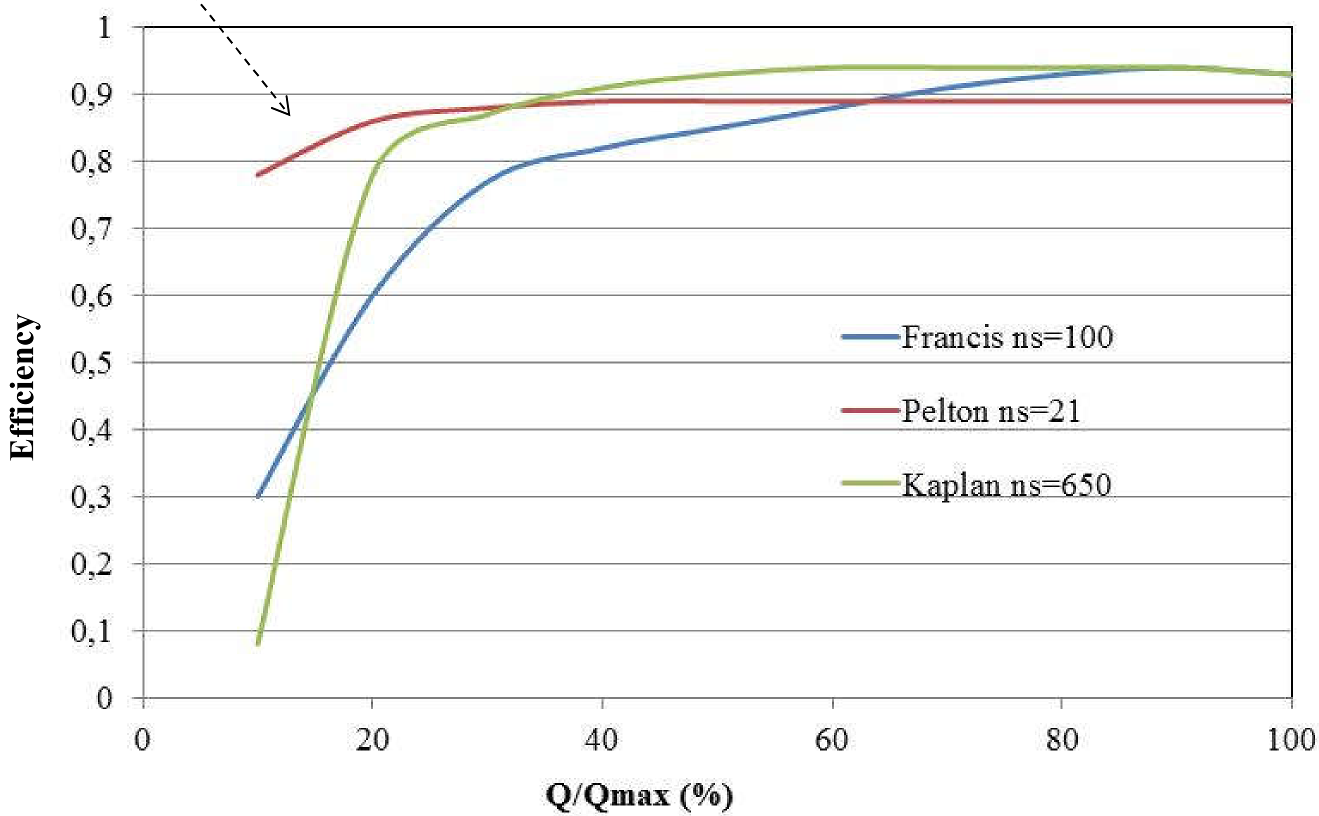



**E>13.5 GWh/y for Q in the range of 2.8-6.4 m³/s**

# 5. Turbine efficiency curves

- Assuming an efficiency for the electromechanical equipment of **0.96**,
- the total efficiency of **0.85** corresponds to:
- a turbine efficiency of 0.85/0.96=**0.885**

| Q/Qmax | Francis ns=100 | Pelton ns=21 | Kaplan ns=650 |
|---|---|---|---|
| 10 | 0,3 | 0,78 | 0,08 |
| 20 | 0,6 | 0,86 | 0,78 |
| 30 | 0,77 | 0,88 | 0,87 |
| 40 | 0,82 | 0,89 | 0,91 |
| 50 | 0,85 | 0,89 | 0,93 |
| 60 | 0,88 | 0,89 | 0,94 |
| 70 | 0,91 | 0,89 | 0,94 |
| 80 | 0,93 | 0,89 | 0,94 |
| 90 | 0,94 | 0,89 | 0,94 |
| 100 | 0,93 | 0,89 | 0,93 |




| | Francis ns=100 | | Pelton ns=21 | | Kaplan ns=650 |
|---|---|---|---|---|---|
| 0 | | 0 | | 0 | |
| 1 | | 1 | | 1 | |
| 2 | | 2 | | 2 | |
| 3 | | 3 | | 3 | |
| 4 | | 4 | | 4 | |
| 5 | | 5 | | 5 | |
| 6 | | 6 | | 6 | |
| 7 | | 7 | | 7 | |
| 8 | | 8 | | 8 | |
| 9 | | 9 | | 9 | |
| 10 | 0,3 | 10 | 0,78 | 10 | 0,08 |
| 11 | 0,33 | 11 | 0,788 | 11 | 0,15 |
| 12 | 0,36 | 12 | 0,796 | 12 | 0,22 |
| 13 | 0,39 | 13 | 0,804 | 13 | 0,29 |
| 14 | 0,42 | 14 | 0,812 | 14 | 0,36 |
| 15 | 0,45 | 15 | 0,82 | 15 | 0,43 |
| 16 | 0,48 | 16 | 0,828 | 16 | 0,5 |
| 17 | 0,51 | 17 | 0,836 | 17 | 0,57 |
| 18 | 0,54 | 18 | 0,844 | 18 | 0,64 |
| 19 | 0,57 | 19 | 0,852 | 19 | 0,71 |
| 20 | 0,6 | 20 | 0,86 | 20 | 0,78 |
| 21 | 0,617 | 21 | 0,862 | 21 | 0,789 |
| 22 | 0,634 | 22 | 0,864 | 22 | 0,798 |
| 23 | 0,651 | 23 | 0,866 | 23 | 0,807 |
| 24 | 0,668 | 24 | 0,868 | 24 | 0,816 |
| 25 | 0,685 | 25 | 0,87 | 25 | 0,825 |
| 26 | 0,702 | 26 | 0,872 | 26 | 0,834 |
| 27 | 0,719 | 27 | 0,874 | 27 | 0,843 |
| 28 | 0,736 | 28 | 0,876 | 28 | 0,852 |
| 29 | 0,753 | 29 | 0,878 | 29 | 0,861 |
| 30 | 0,77 | 30 | 0,88 | 30 | 0,87 |
| 31 | 0,775 | 31 | 0,881 | 31 | 0,874 |
| 32 | 0,78 | 32 | 0,882 | 32 | 0,878 |
| 33 | 0,785 | 33 | 0,883 | 33 | 0,882 |
| 34 | 0,79 | 34 | 0,884 | 34 | 0,886 |
| 35 | 0,795 | 35 | 0,885 | 35 | 0,89 |
| 36 | 0,8 | 36 | 0,886 | 36 | 0,894 |
| 37 | 0,805 | 37 | 0,887 | 37 | 0,898 |
| 38 | 0,81 | 38 | 0,888 | 38 | 0,902 |
| 39 | 0,815 | 39 | 0,889 | 39 | 0,906 |
| 40 | 0,82 | 40 | 0,89 | 40 | 0,91 |
| 41 | 0,823 | 41 | 0,89 | 41 | 0,912 |
| 42 | 0,826 | 42 | 0,89 | 42 | 0,914 |
| 43 | 0,829 | 43 | 0,89 | 43 | 0,916 |
| 44 | 0,832 | 44 | 0,89 | 44 | 0,918 |
| 45 | 0,835 | 45 | 0,89 | 45 | 0,92 |
| 46 | 0,838 | 46 | 0,89 | 46 | 0,922 |
| 47 | 0,841 | 47 | 0,89 | 47 | 0,924 |
| 48 | 0,844 | 48 | 0,89 | 48 | 0,926 |
| 49 | 0,847 | 49 | 0,89 | 49 | 0,928 |
| 50 | 0,85 | 50 | 0,89 | 50 | 0,93 |
| 51 | 0,853 | 51 | 0,89 | 51 | 0,931 |
| 52 | 0,856 | 52 | 0,89 | 52 | 0,932 |
| 53 | 0,859 | 53 | 0,89 | 53 | 0,933 |
| 54 | 0,862 | 54 | 0,89 | 54 | 0,934 |
| 55 | 0,865 | 55 | 0,89 | 55 | 0,935 |
| 56 | 0,868 | 56 | 0,89 | 56 | 0,936 |
| 57 | 0,871 | 57 | 0,89 | 57 | 0,937 |
| 58 | 0,874 | 58 | 0,89 | 58 | 0,938 |
| 59 | 0,877 | 59 | 0,89 | 59 | 0,939 |
| 60 | 0,88 | 60 | 0,89 | 60 | 0,94 |
| 61 | 0,883 | 61 | 0,89 | 61 | 0,94 |
| 62 | 0,886 | 62 | 0,89 | 62 | 0,94 |
| 63 | 0,889 | 63 | 0,89 | 63 | 0,94 |
| 64 | 0,892 | 64 | 0,89 | 64 | 0,94 |
| 65 | 0,895 | 65 | 0,89 | 65 | 0,94 |
| 66 | 0,898 | 66 | 0,89 | 66 | 0,94 |
| 67 | 0,901 | 67 | 0,89 | 67 | 0,94 |
| 68 | 0,904 | 68 | 0,89 | 68 | 0,94 |
| 69 | 0,907 | 69 | 0,89 | 69 | 0,94 |
| 70 | 0,91 | 70 | 0,89 | 70 | 0,94 |
| 71 | 0,912 | 71 | 0,89 | 71 | 0,94 |
| 72 | 0,914 | 72 | 0,89 | 72 | 0,94 |
| 73 | 0,916 | 73 | 0,89 | 73 | 0,94 |
| 74 | 0,918 | 74 | 0,89 | 74 | 0,94 |
| 75 | 0,92 | 75 | 0,89 | 75 | 0,94 |
| 76 | 0,922 | 76 | 0,89 | 76 | 0,94 |
| 77 | 0,924 | 77 | 0,89 | 77 | 0,94 |
| 78 | 0,926 | 78 | 0,89 | 78 | 0,94 |
| 79 | 0,928 | 79 | 0,89 | 79 | 0,94 |
| 80 | 0,93 | 80 | 0,89 | 80 | 0,94 |
| 81 | 0,931 | 81 | 0,89 | 81 | 0,94 |
| 82 | 0,932 | 82 | 0,89 | 82 | 0,94 |
| 83 | 0,933 | 83 | 0,89 | 83 | 0,94 |
| 84 | 0,934 | 84 | 0,89 | 84 | 0,94 |
| 85 | 0,935 | 85 | 0,89 | 85 | 0,94 |
| 86 | 0,936 | 86 | 0,89 | 86 | 0,94 |
| 87 | 0,937 | 87 | 0,89 | 87 | 0,94 |
| 88 | 0,938 | 88 | 0,89 | 88 | 0,94 |
| 89 | 0,939 | 89 | 0,89 | 89 | 0,94 |
| 90 | 0,94 | 90 | 0,89 | 90 | 0,94 |
| 91 | 0,939 | 91 | 0,89 | 91 | 0,939 |
| 92 | 0,938 | 92 | 0,89 | 92 | 0,938 |
| 93 | 0,937 | 93 | 0,89 | 93 | 0,937 |
| 94 | 0,936 | 94 | 0,89 | 94 | 0,936 |
| 95 | 0,935 | 95 | 0,89 | 95 | 0,935 |
| 96 | 0,934 | 96 | 0,89 | 96 | 0,934 |
| 97 | 0,933 | 97 | 0,89 | 97 | 0,933 |
| 98 | 0,932 | 98 | 0,89 | 98 | 0,932 |
| 99 | 0,931 | 99 | 0,89 | 99 | 0,931 |
| 100 | 0,93 | 100 | 0,89 | 100 | 0,93 |

# 5. Example with 1 turbine (with efficiency curve)

| | A | B | C | D | E | F | G | H | I | J |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | H | 260 | | I (kW) = 9.81 * Q ($m^3$/s) * H (m) * n | | | | | Turbine efficiency curve | |
| 2 | ρ | 1000 | | | | | | | Francis ns=100 | |
| 3 | g | 9,81 | | | | | | | Q/Qmax | n |
| 4 | n | 0,96 | Efficiency of the electromechanical equipment | | | | | | 0 | |
| 5 | | | | | | | | | 1 | |
| 6 | | | | | | | | | 2 | |
| 7 | | | | | | | | | 3 | |
| 8 | | | | | | | | | 4 | |
| 9 | | | | | | | | | 5 | |
| 10 | | | | | | | | | 6 | |
| 11 | | | | | | | | | 7 | |
| 12 | | | | | | | | | 8 | |
| 13 | | | | | | | | | 9 | |
| 14 | | | | | | | | | 10 | 0,3 |
| 15 | | | | | | | | | 11 | 0,33 |
| 16 | | | | | | Francis ns=100 | | | 12 | 0,36 |
| 17 | Max-Min exploitation discharge ($m^3$/s) | | | | Qmax (m3/s) | 3,00 | | | 13 | 0,39 |
| 18 | | | | | Qmin (m3/s) | 0,30 | | | 14 | 0,42 |
| 19 | Power at max exploitation discharge | | | | Imax (MW) | 7,3 | | | 15 | 0,45 |
| 20 | Percentage of operational time per year | | | | PT (%) | 53,4 | | | 16 | 0,48 |
| 21 | Percentage of water volume used | | | | PV (%) | 87,3 | | | 17 | 0,51 |
| 22 | Total electrical energy (GWh) | | | | E (GWh) | 128,5 | | | 18 | 0,54 |
| 23 | | | | | E (GWh/y) | 12,9 | | | 19 | 0,57 |
| 24 | | | | | ΣΔ | 0,20 | | | 20 | 0,6 |
| 25 | | | | | | | | | 21 | 0,617 |
| 26 | | m3/s | m3/day | | kWh/d | Q/Qmax | Efficiency | kWh/d | 22 | 0,634 |
| 99 | 12/12/1971 | 0,620 | 53561,1 | | 36430,1 | 20 | 0,60 | 21858,1 | 95 | 0,935 |
| 100 | 13/12/1971 | 0,708 | 61146,6 | | 41589,5 | 23 | 0,65 | 27074,7 | 96 | 0,934 |
| 101 | 14/12/1971 | 0,794 | 68626,7 | | 46677,1 | 26 | 0,70 | 32767,4 | 97 | 0,933 |
| 102 | 15/12/1971 | 0,860 | 74315,8 | | 50546,6 | 28 | 0,74 | 37202,3 | 98 | 0,932 |

1. The energy is calculated by taking into account the efficiency of the electromechanical equipment. It will later be corrected with the efficiency of the turbines that corresponds to the daily discharge by taking into account the turbine efficiency curves

=IF(AND($B99>F$18;$B99<F$17);$B$1*$B$3*$B$4*$B99*24;IF($B99>F$17;$B$1*$B$3*$B$4*F$17*24;0))

2. The percentage of the daily discharge to the nominal one, is calculated

=MAX(INT(100*B99/F$17);1)

3. According to the percentage of the daily discharge to the nominal one, the corresponding efficiency is located in the efficiency curve

=LOOKUP(F99;$I$5:$J$104)

4. The daily energy is corrected according to the turbine efficiency

=G99*E99

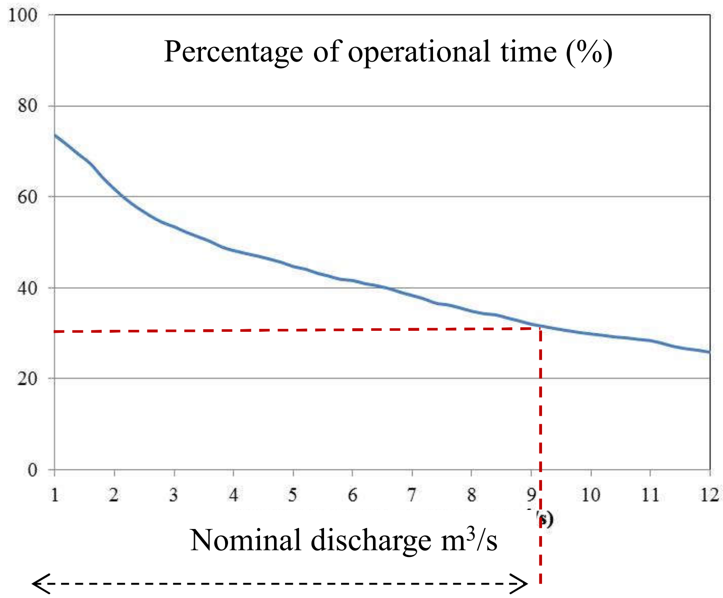
**WARNING:** The calculation of the percentage of the used water volume changes. Initially, the efficiency of the turbines is calculated as the quotient of the final energy to the initial energy that was calculated by taking into account the efficiency of the electromechanical equipment.

SUM(H27:H3679)/SUM(E27:E3679)

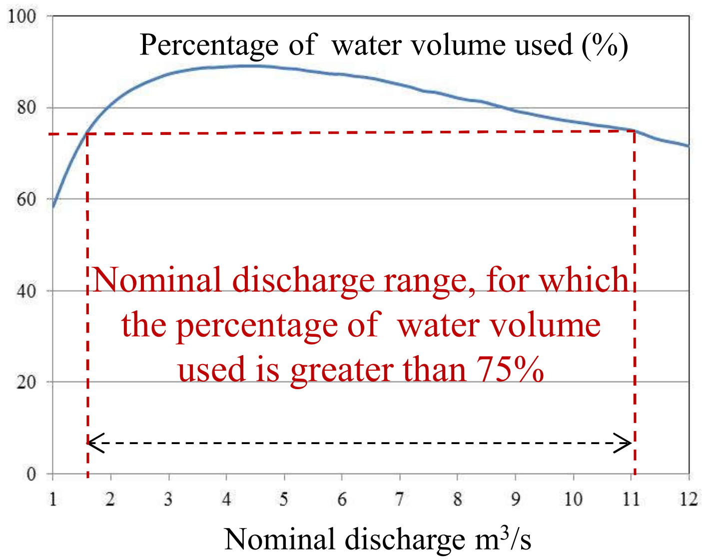
**The new formula incorporates the efficiency of the turbines**

=(SUM(H27:H3679)*3600/($B$1*$B$3*$B$4***SUM(H27:H3679)/SUM(E27:E3679)**)/($C$12*1000000)*100)

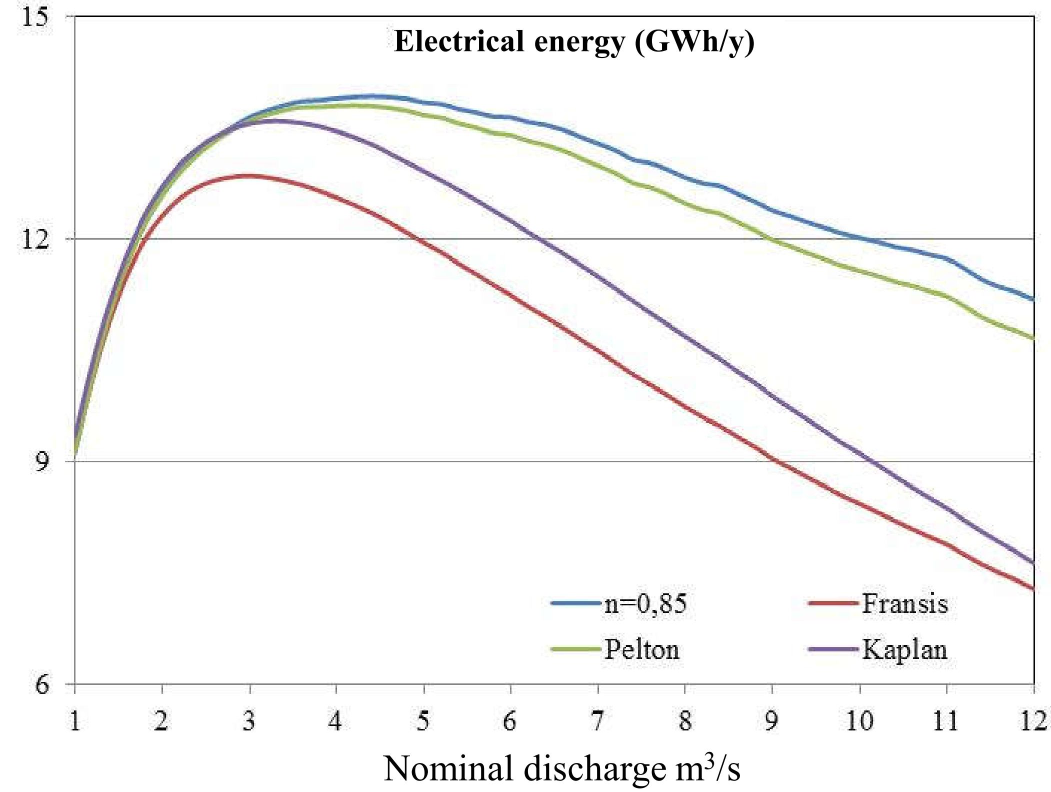
# 5. Example with 1 turbine (with efficiency




Nominal discharge range, for which the percentage of operational time is greater than 30%




**Energy production curve for nominal discharge in the range 1-12 m³/s**




| | | |
|---|---|---|
| **Constant efficiency n=0.85** | Q=4.4 m³/s | E=13.9 GWh/y |
| **Pelton** | Q=4.2 m³/s | E=13.8 GWh/y |
| **Kaplan** | Q=3.4 m³/s | E=13.6 GWh/y |
| **Francis** | Q=3.0 m³/s | E=12.8 GWh/y |

# 6. Examples with 2 turbines (n=0.85, Qmin=0.2*Qmax)

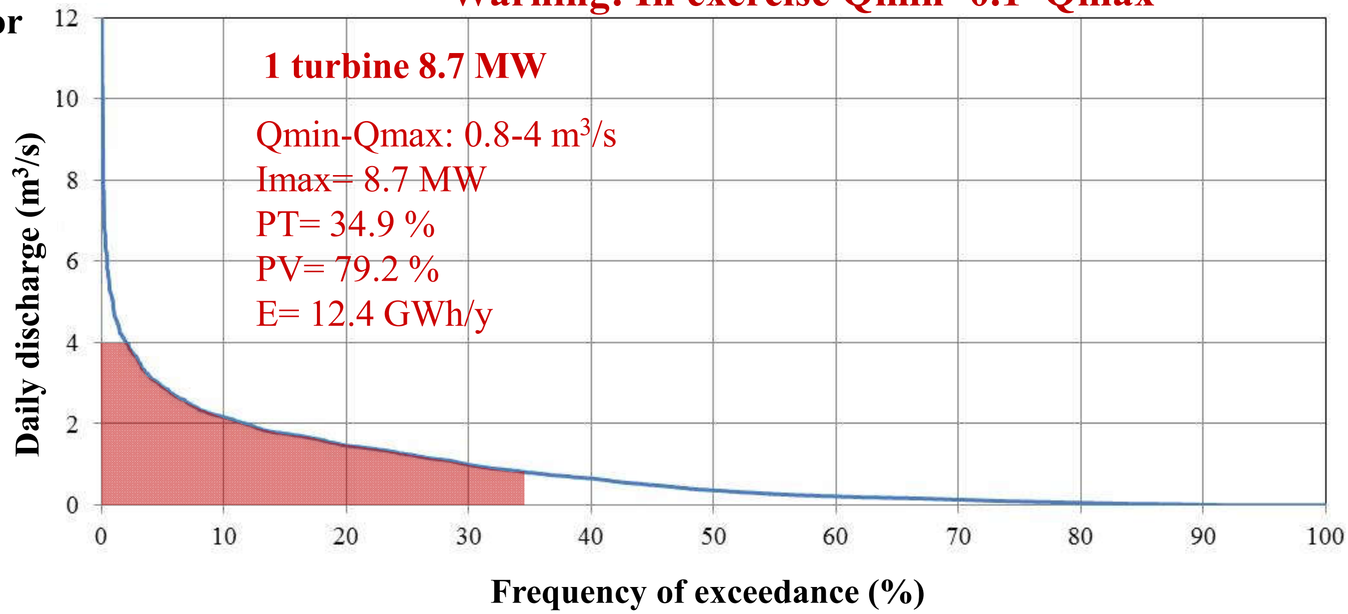
**Warning: In exercise Qmin=0.1*Qmax**

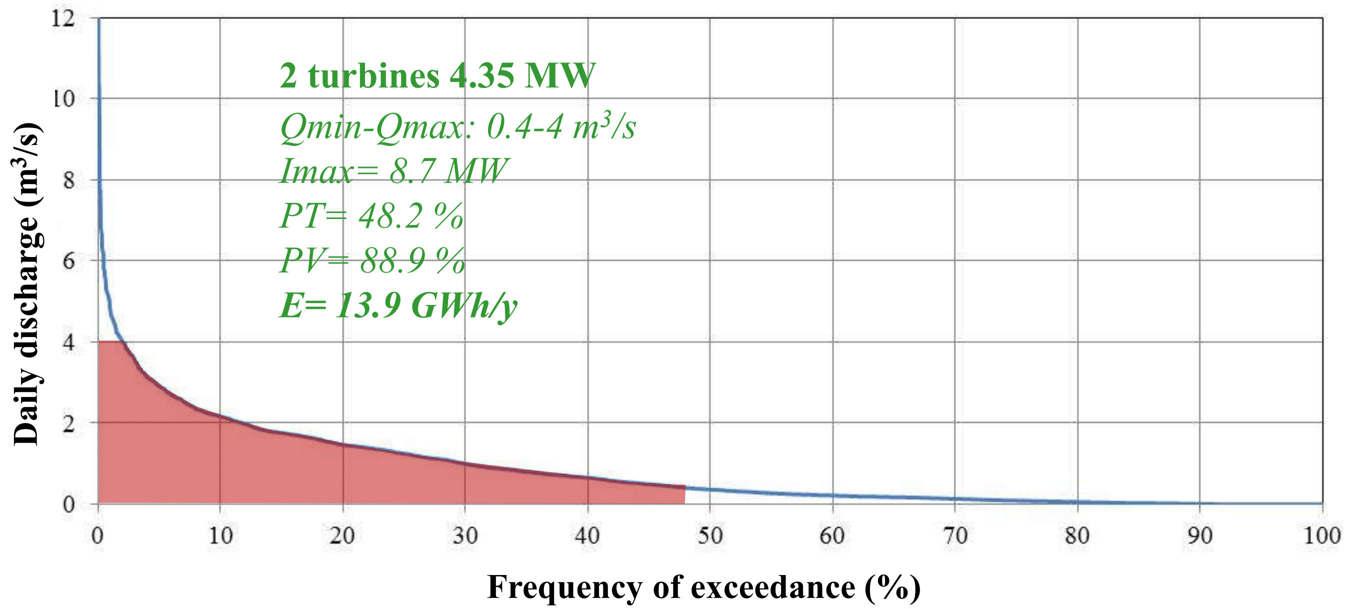
**Data**

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 |




**Legend**

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

**Imax:** Power at 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)

# 6. Examples with 2 turbines (n=0.85, Qmin=0.2*Qmax)

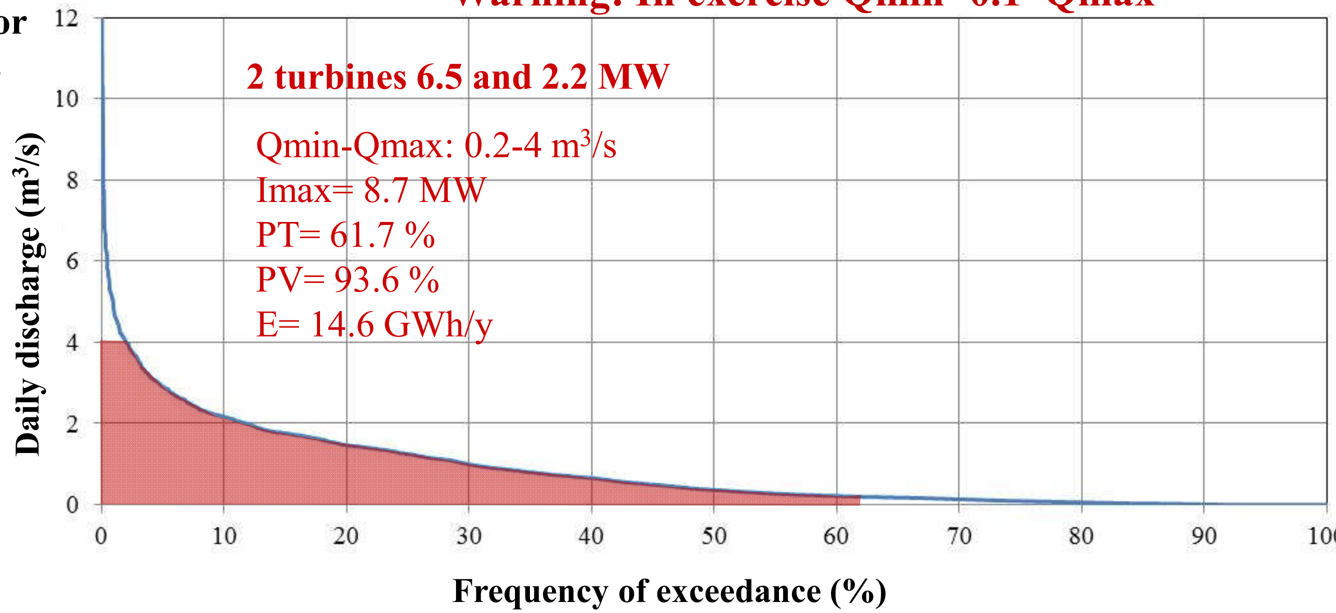
**Warning: In exercise Qmin=0.1*Qmax**

## 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 |




**Legend**

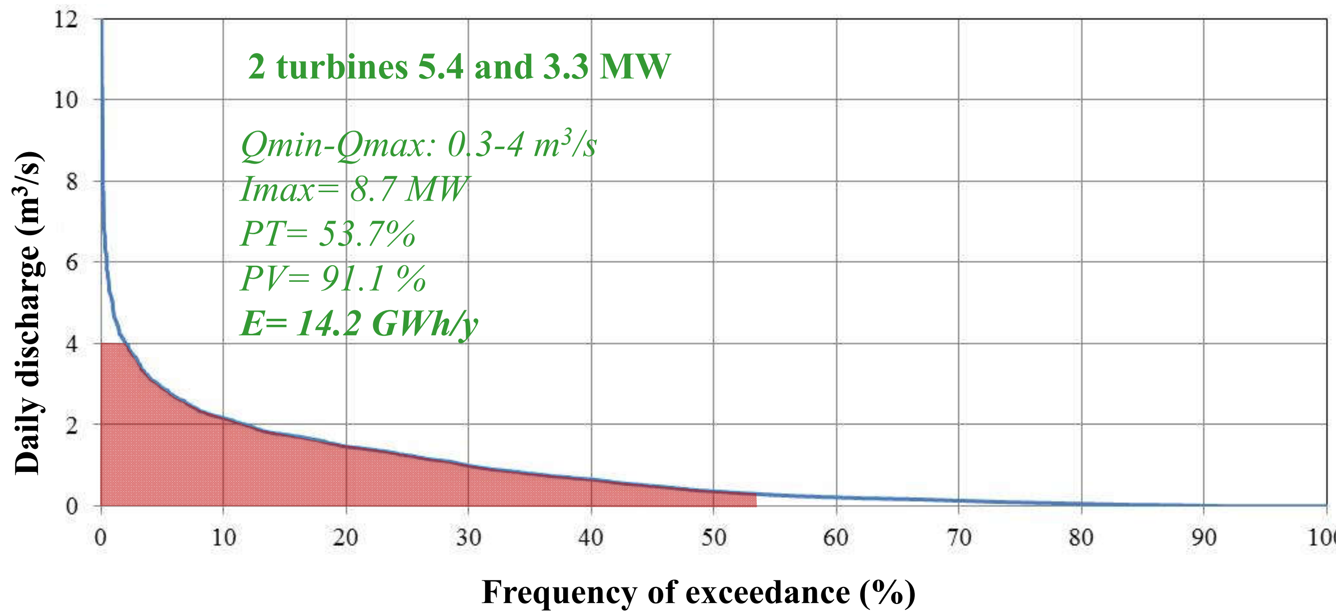
**Qmin, Qmax:** Minimum, maximum exploitation discharge (m$^3$/s)

**Imax:** Power at 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)



# 6. Optimization with 2 turbines (n=0.85 for Qmin=0.1*Qmax)

| | Optimization with 1 turbine | Optimization with 2 same turbines | Optimization with 2 sequential turbines | |
|---|---|---|---|---|
| | Q1min=0.1*Q1max | Q1min=0.1*(Q2max/2) | Q1min=0.1*0.1*Q2max | |
| Qmax (m3/s) | 4,49 | 5,08 | 8,71 | =Q1max+Q2max |
| Qmin (m3/s) | 0,45 | 0,25 | 0,09 | =Q1min |
| Imax (MW) | 9,7 | 11,0 | 18,9 (16.9 and 2 MW) | |
| PT (%) | 46,6 | 56,4 | 75,8 | |
| PV (%) | 89,0 | 93,8 | 99,0 | |
| E (GWh) | 139,1 | 146,6 | 154,7 | |
| E (GWh/y) | 13,9 | 14,7 | 15,5 | |
| ΣΔ | 0,16 | 0,15 | 0,09 | |

**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 |

# 6. Optimization with 2 turbines (considering efficiency curves)

We make the assumption, that initially the first turbine starts operating and in the case that the discharge is out of its operational range, then the flow is routed to the second turbine

| | A | B | C | D | E | F | G | H | I | J | K | L | M | N | O | P | Q | R |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | H | 260 | | | | | | | | | | | | | | | | |
| 2 | ρ | 1000 | | | | | Καμπύλη 1 | | Καμπύλη 2 | | | | | | | | | |
| 3 | g | 9,81 | | | | | Q/Qmax | n | Q/Qmax | n | | | | | | | | |
| 4 | n | 0,96 | ΣΑ Ηλεκτρομηχανολογικού εξοπλισμού | | | | 0 | | 0 | | | | | | | | | |
| 5 | | | | | | | 1 | | 1 | | | | | | | | | |
| 6 | Για 10 έτη | m3/s | | | | | 2 | | 2 | | | | | | | | | |
| 7 | ΜΕΓΙΣΤΟ | 12,1 | | | | | 3 | | 3 | | | | | | | | | |
| 8 | ΕΛΑΧΙΣΤΟ | 0 | | | | | 4 | | 4 | | | | | | | | | |
| 9 | ΜΕΣΟ | 0,822 | | | | | 5 | | 5 | | | | | | | | | |
| 10 | | | | | | | 6 | | 6 | | | Σύνολο | | | | | | |
| 11 | | | hm3 | | | | 7 | | 7 | | | Qmax (m3/s) | | 3,80 | | | | |
| 12 | ΑΘΡΟΙΣΜΑ | 259,5 | | 229,2 | 30,3 | 19,9 | 8 | | 8 | | | Qmin (m3/s) | | 0,04 | | | | |
| 13 | Σύνολο ημερών | 3653 | | | | | 9 | | 9 | | | E (GWh/y) | | 13,9 | | | | |
| 14 | | | | | | | 10 | 0,3 | 10 | 0,3 | | | | | | | | |
| 15 | **Μέσο ετήσιο** | 25,9 | | | | | 11 | 0,33 | 11 | 0,33 | | | | | | | | |
| 16 | | | | Στρόβιλος 1 | | Στρόβιλος 2 | 12 | 0,36 | 12 | 0,36 | | | Στρόβιλος 1 | | | | Στρόβιλος 2 | |
| 17 | | | Qmax (m3/s) | 3,40 | | 0,40 | 13 | 0,39 | 13 | 0,39 | | Qmax (m3/s) | 3,40 | | | | 0,40 | |
| 18 | | | Qmin (m3/s) | 0,34 | | 0,04 | 14 | 0,42 | 14 | 0,42 | | Qmin (m3/s) | 0,34 | | | | 0,04 | |
| 19 | | | | | | | 15 | 0,45 | 15 | 0,45 | | E (GWh) | 12,8 | | | | 1,1 | |
| 20 | | | | | | | 16 | 0,48 | 16 | 0,48 | | | | | | | | |
| 21 | | | | | | | 17 | 0,51 | 17 | 0,51 | | | | | | | | |
| 22 | | | | | | | 18 | 0,54 | 18 | 0,54 | | | | | | | | |
| 23 | | | | | | | 19 | 0,57 | 19 | 0,57 | | | | | | | | |
| 24 | | | | | | | 20 | 0,6 | 20 | 0,6 | | | | | | | | |
| 25 | | | | Παροχές Σ1 | Υπόλοιπο | Παροχές Σ2 | 21 | 0,617 | 21 | 0,617 | | | | | | | | |
| 26 | | **m3/s** | | **m3/s** | **m3/s** | **m3/s** | 22 | 0,634 | 22 | 0,634 | | **kWh/d** | **Q/Qmx** | **ΣΑ** | **kWh/d** | | **kWh/d** | **Q/Qmx** |
| 27 | 1/10/1971 | 0,094 | | 0,000 | 0,094 | 0,094 | 23 | 0,651 | 23 | 0,651 | | 0,0 | 1 | 0,00 | 0,0 | | 5545,8 | 23 |
| 28 | 2/10/1971 | 0,094 | | 0,000 | 0,094 | 0,094 | 24 | 0,668 | 24 | 0,668 | | 0,0 | 1 | 0,00 | 0,0 | | 5545,8 | 23 |
| 29 | 3/10/1971 | 0,094 | | 0,000 | 0,094 | 0,094 | 25 | 0,685 | 25 | 0,685 | | 0,0 | 1 | 0,00 | 0,0 | | 5545,8 | 23 |

=B27-D27

=$B$1*$B$3*$B$4*$D27*24

Allocation of discharge to 2 turbines

=IF(AND($E27>F$18;$E27<F$17);$E27;IF($E27>F$17;F$17;0))

=IF(AND($B27>D$18;$B27<D$17);$B27;IF($B27>D$17;D$17;0))

=$B$1*$B$3*$B$4*$F27*24

# 7. Optimization with 2 turbines (considering efficiency curves)

We make the assumption, that initially the first turbine starts operating and in the case that the discharge is out of its operational range, then the flow is routed to the second turbine

## 2 Pelton turbines

| **Qmax ($m^3/s$)** | **4,2** | **4,2** | | **4,2** | | **4,2** | |
|---|---|---|---|---|---|---|---|
| **E (GWh/y)** | **13,8** | **14,6** | | **14,9** | | **15,1** | |
| | | Σ1 | Σ2 | Σ1 | Σ2 | Σ1 | Σ2 |
| $Q_{1,2}max$ ($m^3/s$) | | 2,1 | 2,1 | 3,0 | 1,2 | 3,8 | 0,4 |
| $E_{1,2}$ (GWh/y) | | 12,7 | 1,8 | 13,6 | 1,3 | 13,8 | 1,3 |

## 2 Francis turbines

| **Qmax ($m^3/s$)** | **3,0** | **3,0** | | **3,0** | | **3,0** | |
|---|---|---|---|---|---|---|---|
| **E (GWh/y)** | **12,9** | **14,2** | | **14,0** | | **13,9** | |
| | | Σ1 | Σ2 | Σ1 | Σ2 | Σ1 | Σ2 |
| $Q_{1,2}max$ ($m^3/s$) | | 1,5 | 1,5 | 2,0 | 1,0 | 2,7 | 0,3 |
| $E_{1,2}$ (GWh/y) | | 11,2 | 3,0 | 12,3 | 1,7 | 12,8 | 1,0 |

## Pelton-Francis Combination

| **Qmax ($m^3/s$)** | **3,0** | | **3,0** | | **3,0** | | **3,0** | | **3,0** | | **3,0** | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **E (GWh/y)** | **14,3** | | **14,1** | | **14,2** | | **14,1** | | **14,4** | | **14,0** | |
| | Pelton | Francis | Francis | Pelton | Pelton | Francis | Francis | Pelton | Pelton | Francis | Francis | Pelton |
| $Q_{1,2}max$ ($m^3/s$) | 1,5 | 1,5 | 1,5 | 1,5 | 2,0 | 1,0 | 2,0 | 1,0 | 2,5 | 0,5 | 2,5 | 0,5 |
| $E_{1,2}$ (GWh/y) | 11,4 | 3,0 | 11,2 | 2,9 | 12,6 | 1,7 | 12,3 | 1,7 | 13,2 | 1,1 | 12,7 | 1,2 |