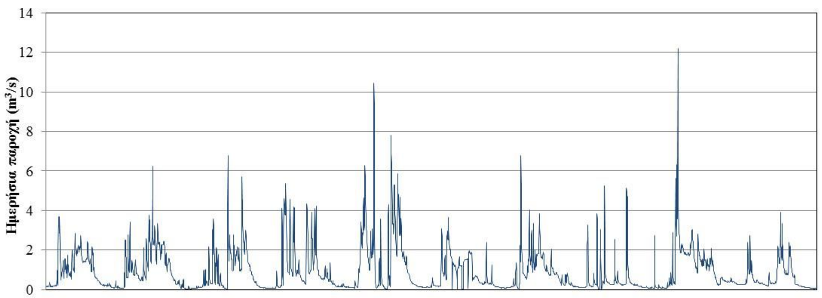
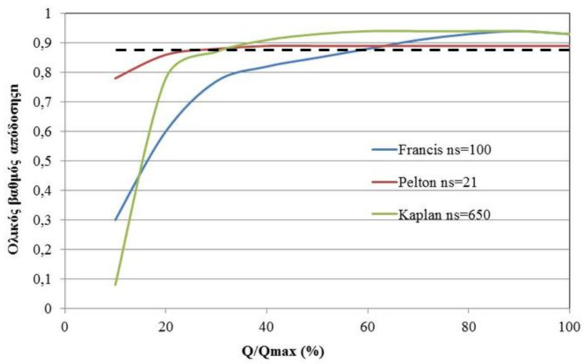
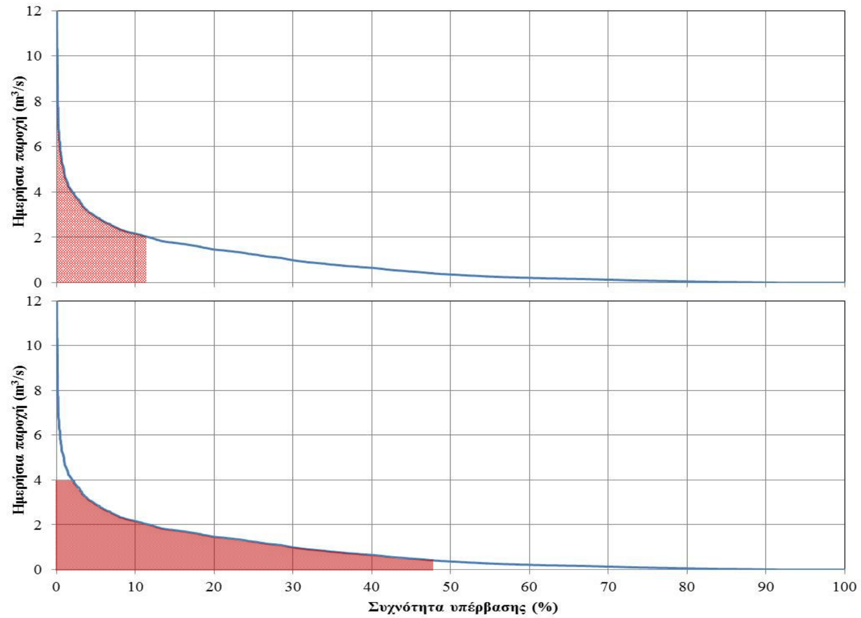
Renewable Energy & Hydroelectric Works

Exercise instructions: Design of Small Hydroelectric Power Plants







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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.

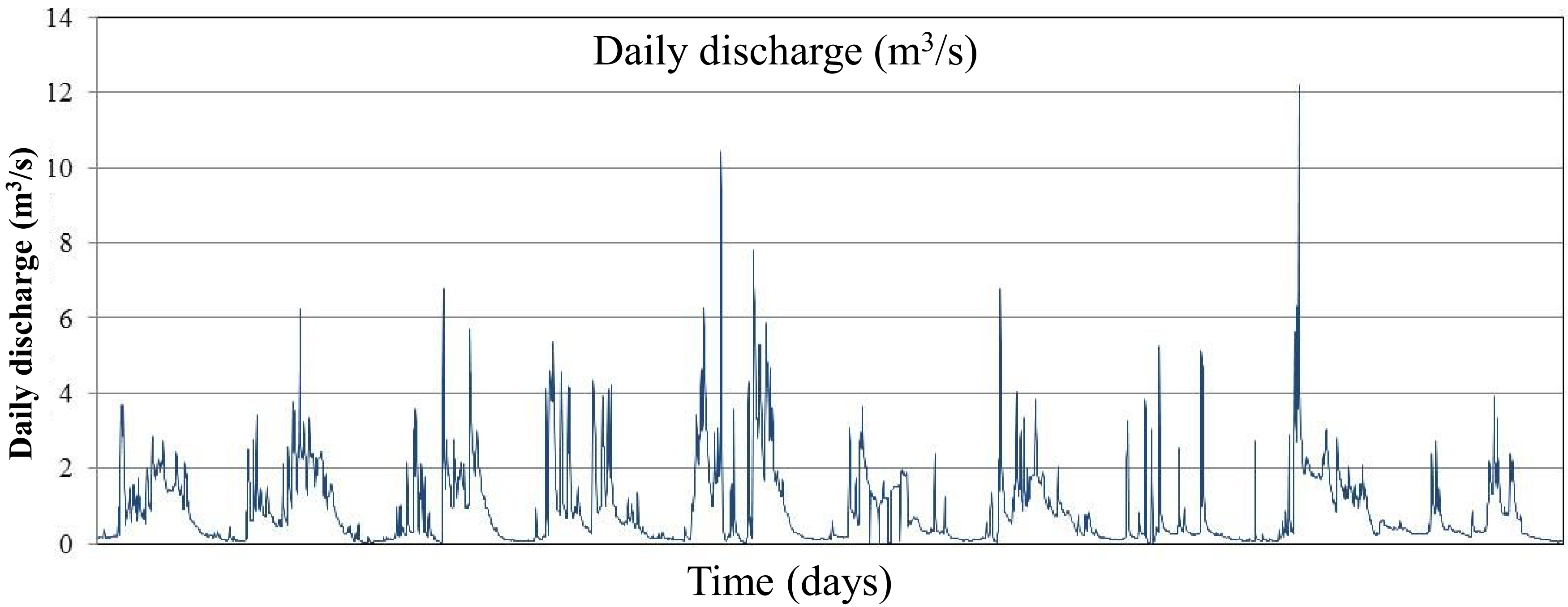
Flow duration curve SB1

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, 28/3/2019

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:

ρ *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**

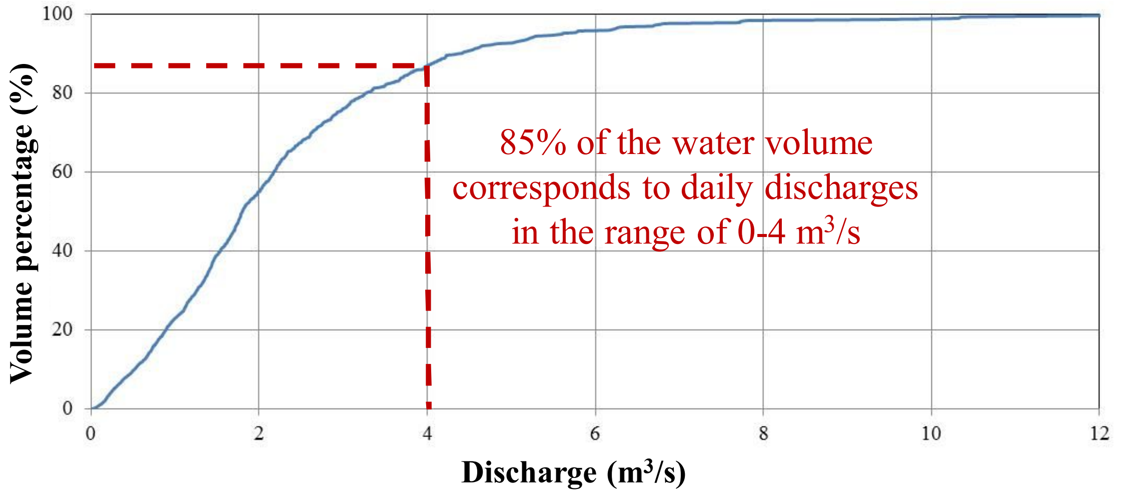
Mean annual water volume available for exploitation: **25.9 hm^3**

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

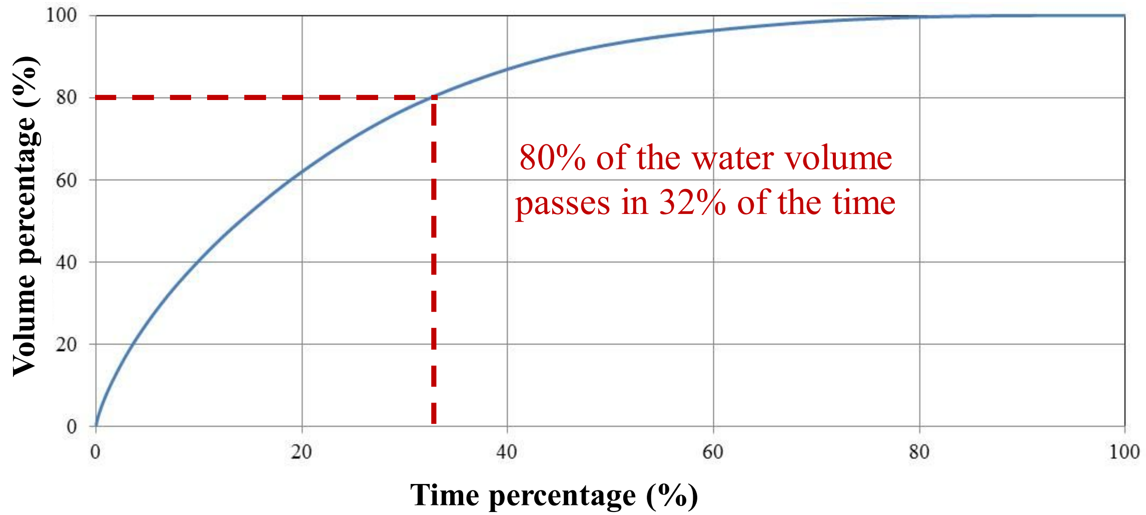
Discharge–installed power relationship

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

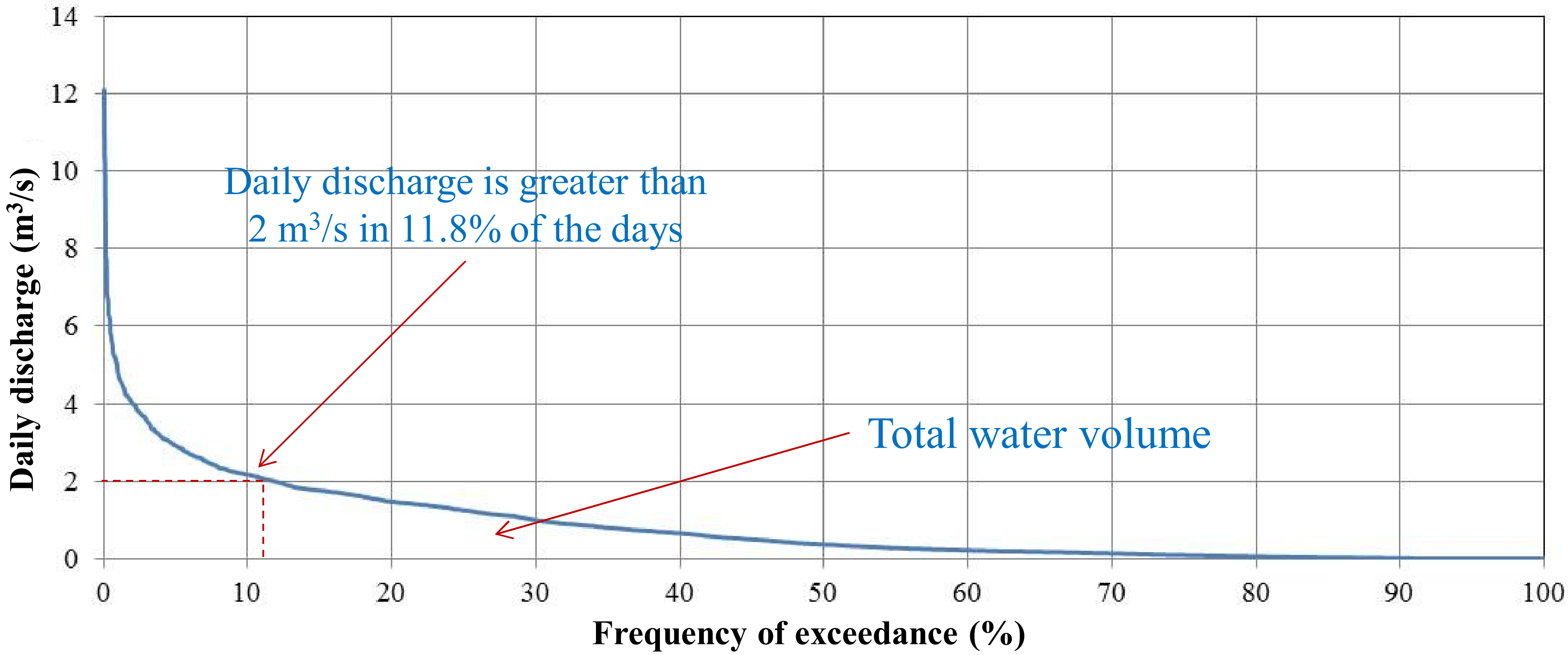
Volume percentage-discharge relationship

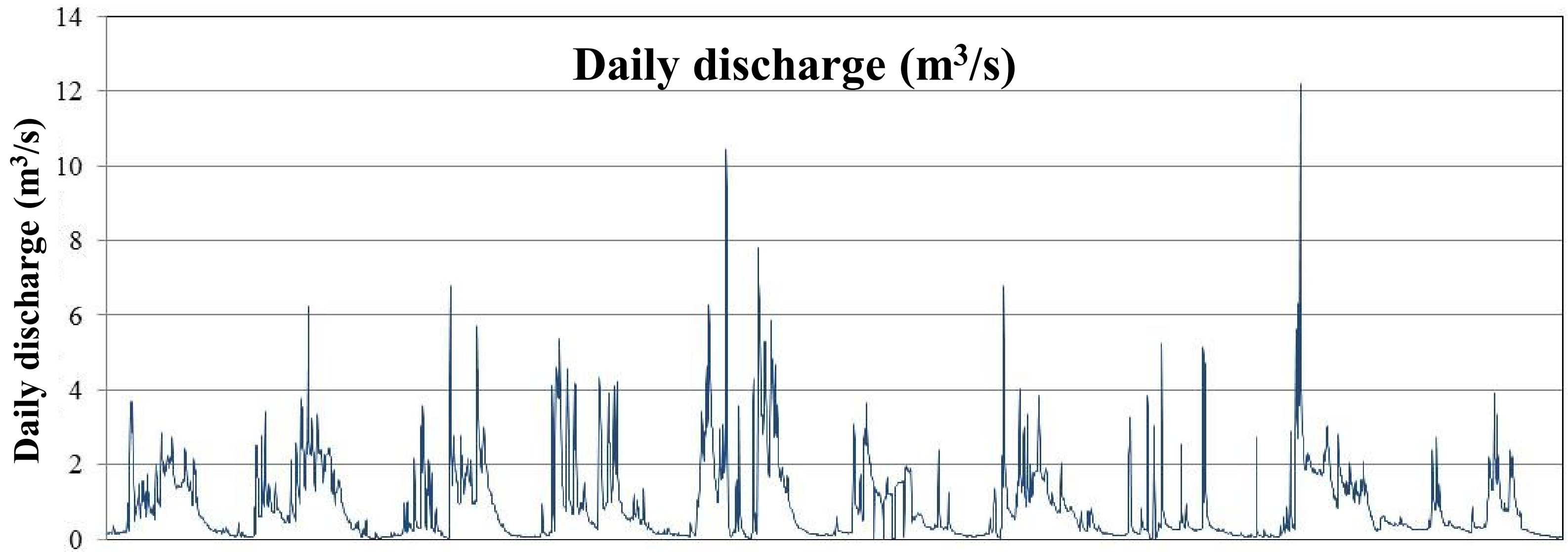


Volume-time percentage relationship



3. Daily flow duration curve





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

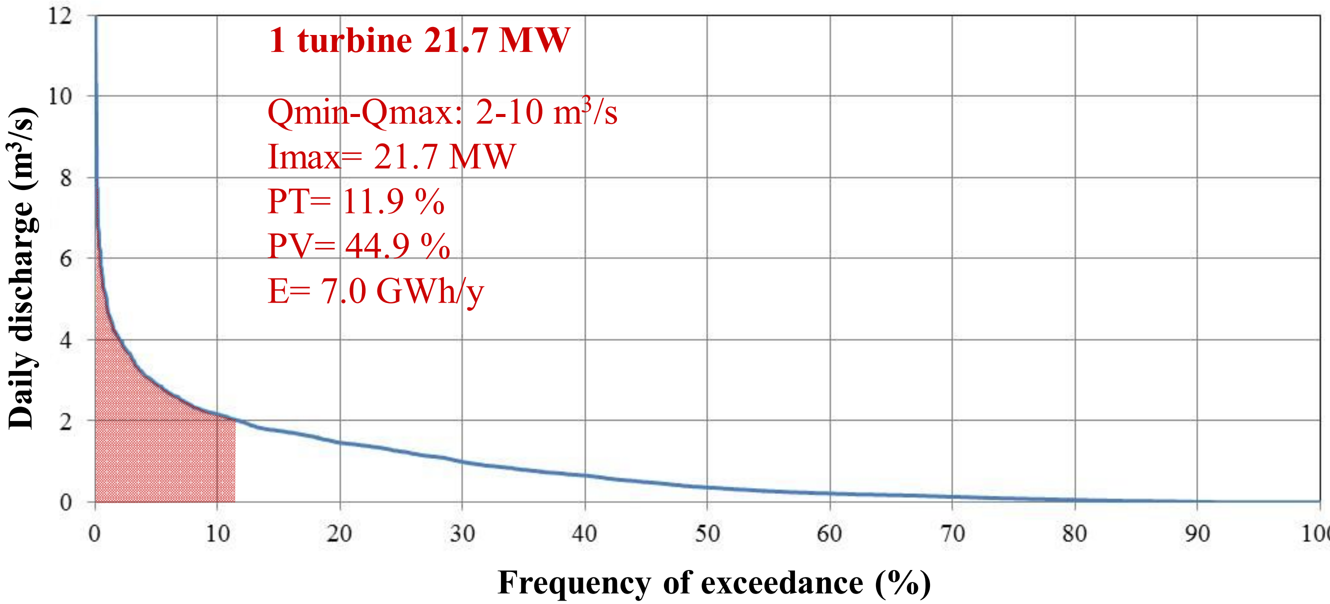
Warning: In exercise Qmin=0.1*Qmax

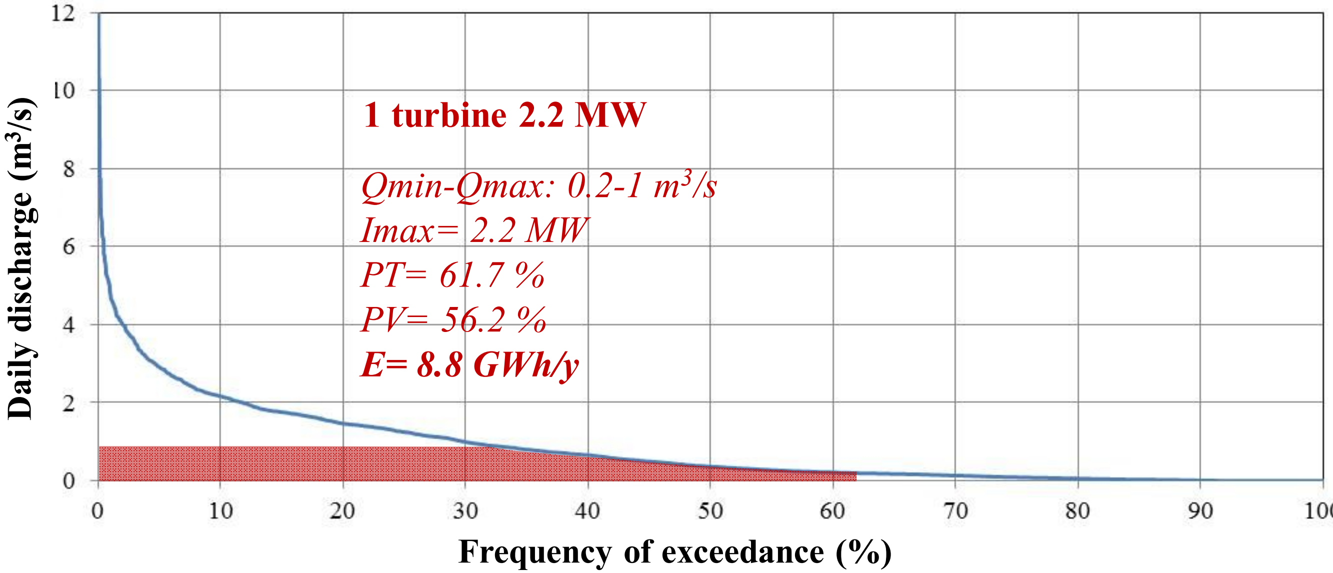
Data

H=260 m
ρ=1000 kg/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)

4. Calculations for 1 turbine

Data-Constants

Data-daily discharge timeseries

	A	B	C	D	E	F	G	H	I
1									
2				**Daily timeseries statistics (a) discharge, (b) water volume, (c) potential energy and (d) required power**					
3									
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

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(m^3)/3600=g*n*H(m)*Q(m^3/s)*86400/3600= **g*n*H(m)*Q(m^3/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
1									
2									
3									
4	H	260							
5	ρ	1000							
6	g	9.81							
7	n	0.85							
8									
9									
10									
11									
12									
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
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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: $V(m^3)=Q\ (m^3/s)*t\ (hr)*3600=E(kWh)/[g*n*H(m)]$=> **$V(m^3)=E(kWh)/[g*n*H(m)*3600]$**
- 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
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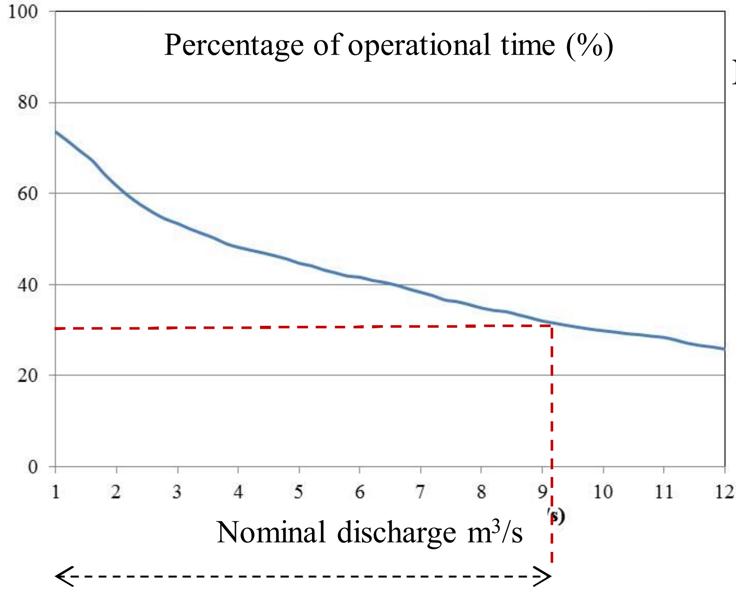
23						ΣΔ	0.06	0.15	0.33
24		m3/s	m3/day	kWh	kW		kWh/d	kWh/d	kWh/d
25	1/10/1971	0.094	8153.6	4910.3	204.6		0	0	0
26	2/10/1971	0.094	8153.6	4910.3	204.6		0	0	0
27	3/10/1971	0.094	8153.6	4910.3	204.6		0	0	0
28	4/10/1971	0.069	5941.2	3577.9	149.1		0	0	0

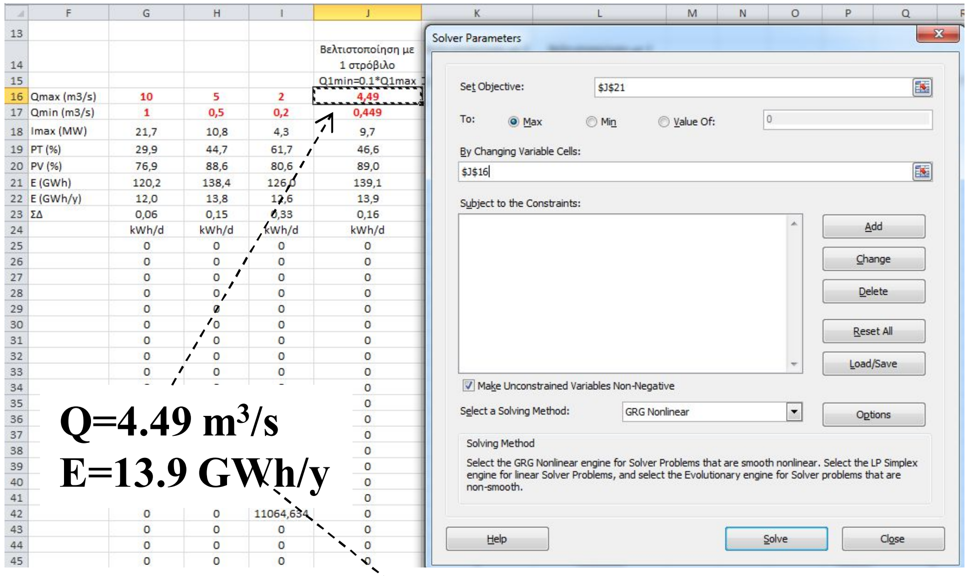
4. Examples with 1 turbine (n=0.85, Qmin=0.1*Qmax)

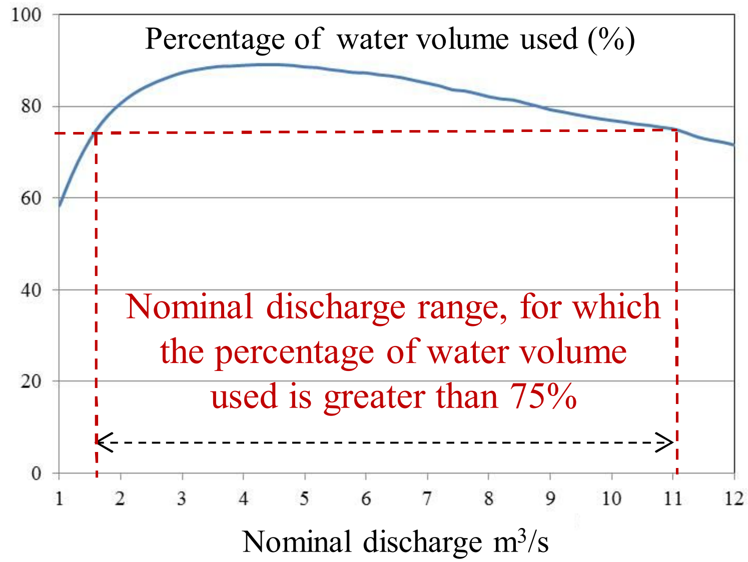


Nominal discharge range, for which the percentage of operational time is greater than 30%

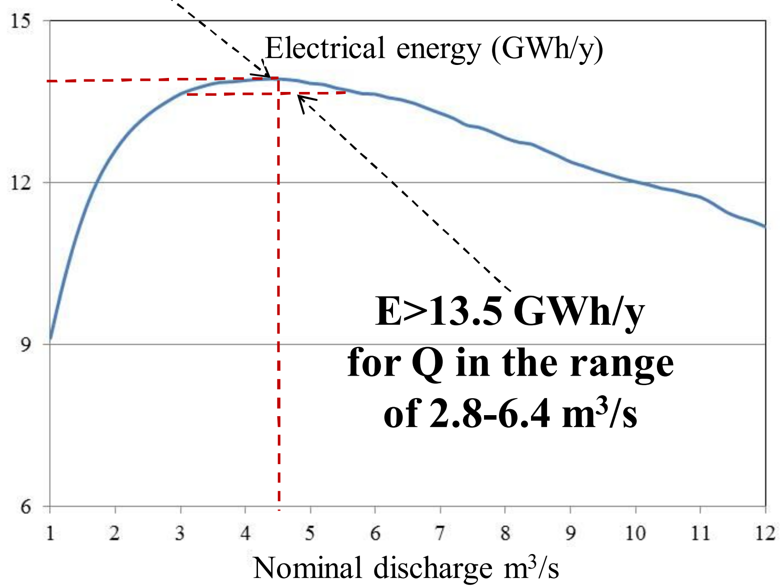
Nominal operational discharge for maximization of the produced energy

(use of solver)





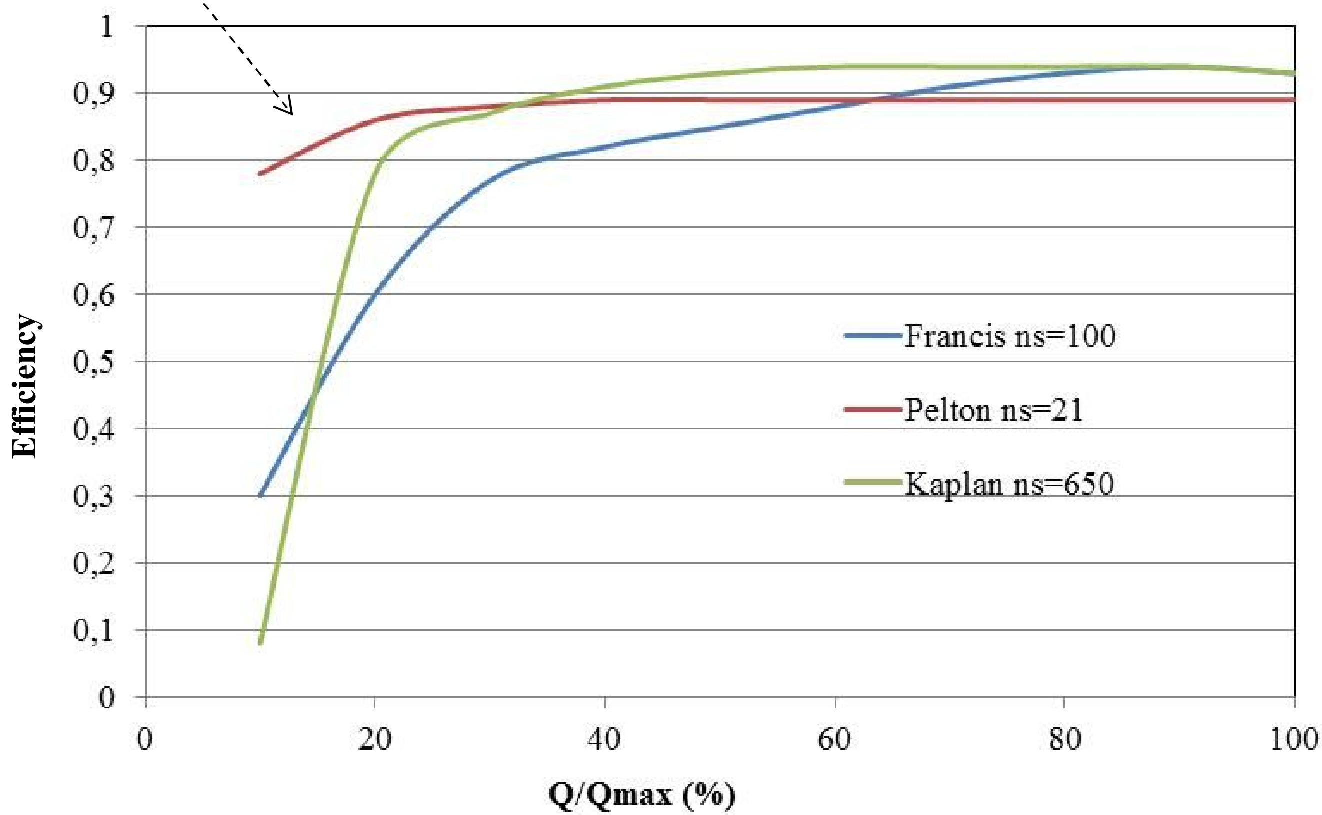
Energy production curve for nominal discharge in the range 1-12 m³/s



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 (m³/s) * H (m) * n					**Turbine efficiency curve**	
2	p	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 (m³/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/Qmx	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

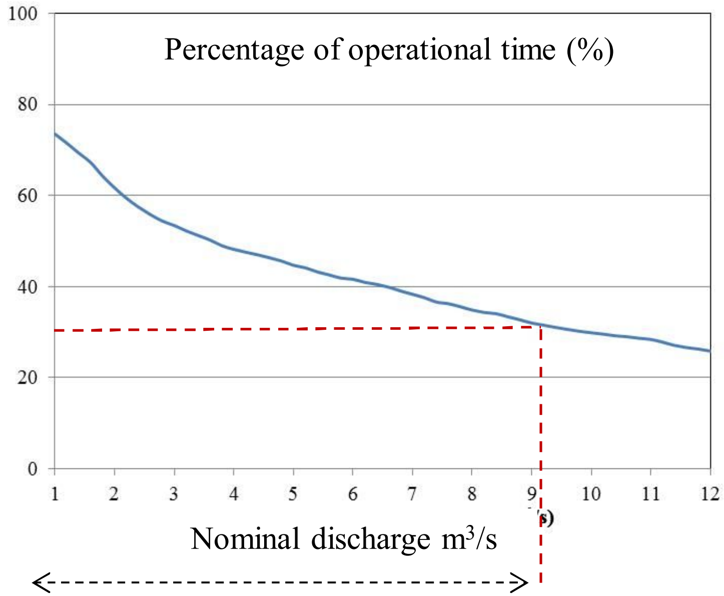
WARNING: The calculation of the percentage of the used water volume changes. Initially, the efficiency of the turbines is calculated as the quotient of the final energy to the initial energy that was calculated by taking into account the efficiency of the electromechanical equipment.

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

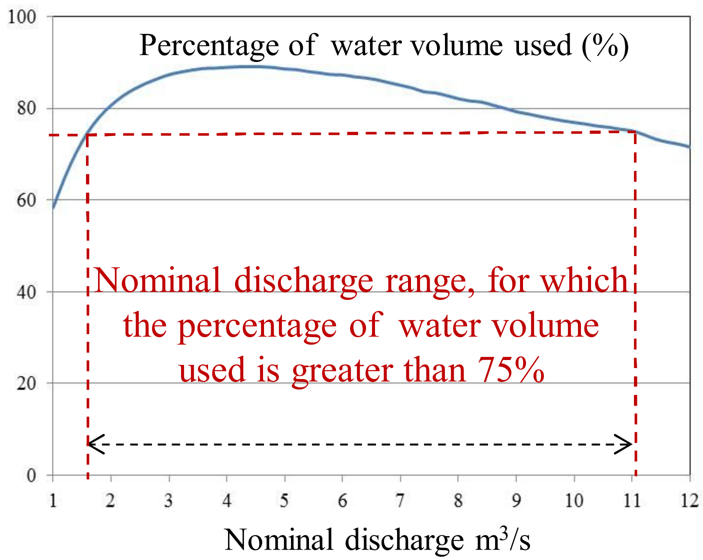
The new formula incorporates the efficiency of the turbines

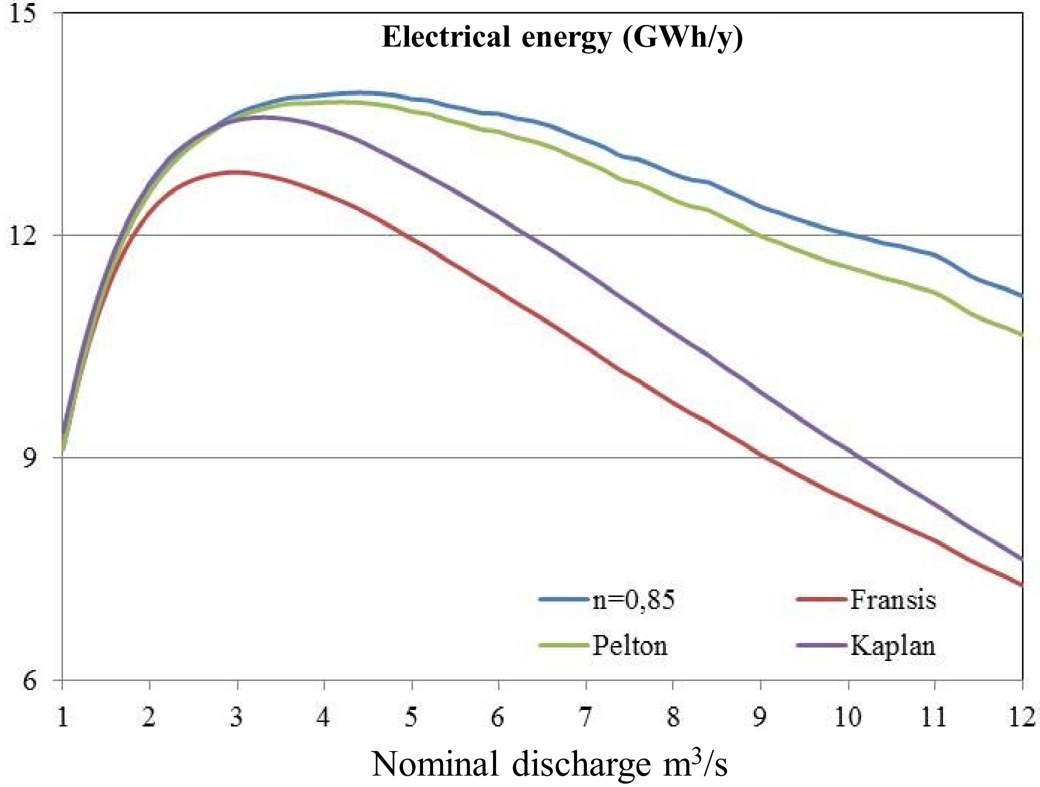
=(SUM(H27:H3679)*3600/($B$1*$B$3*$B$4***SUM(H27:H3679)/SUM(E27:E3679)**)/($C$12*1000000)*100)

5. Example with 1 turbine (with efficiency



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





Constant efficiency n=0.85	Q=4.4 m^3/s	E=13.9 GWh/y
Pelton	Q=4.2 m^3/s	E=13.8 GWh/y
Kaplan	Q=3.4 m^3/s	E=13.6 GWh/y
Francis	Q=3.0 m^3/s	E=12.8 GWh/y

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

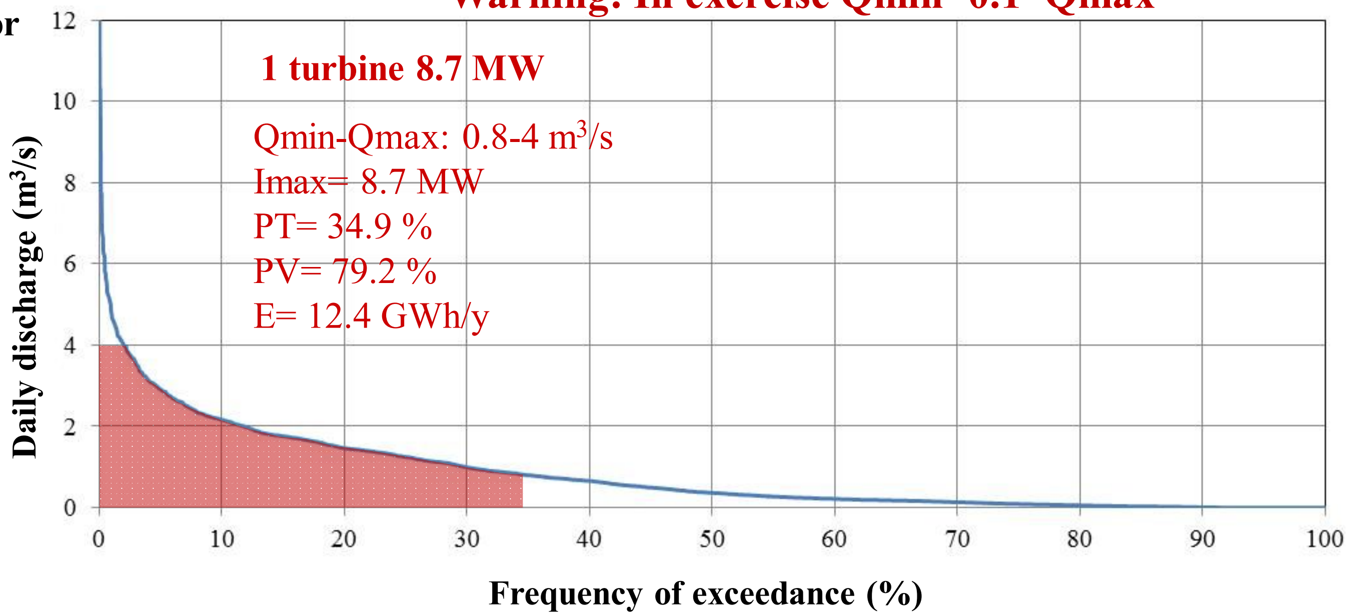
Warning: In exercise Qmin=0.1*Qmax

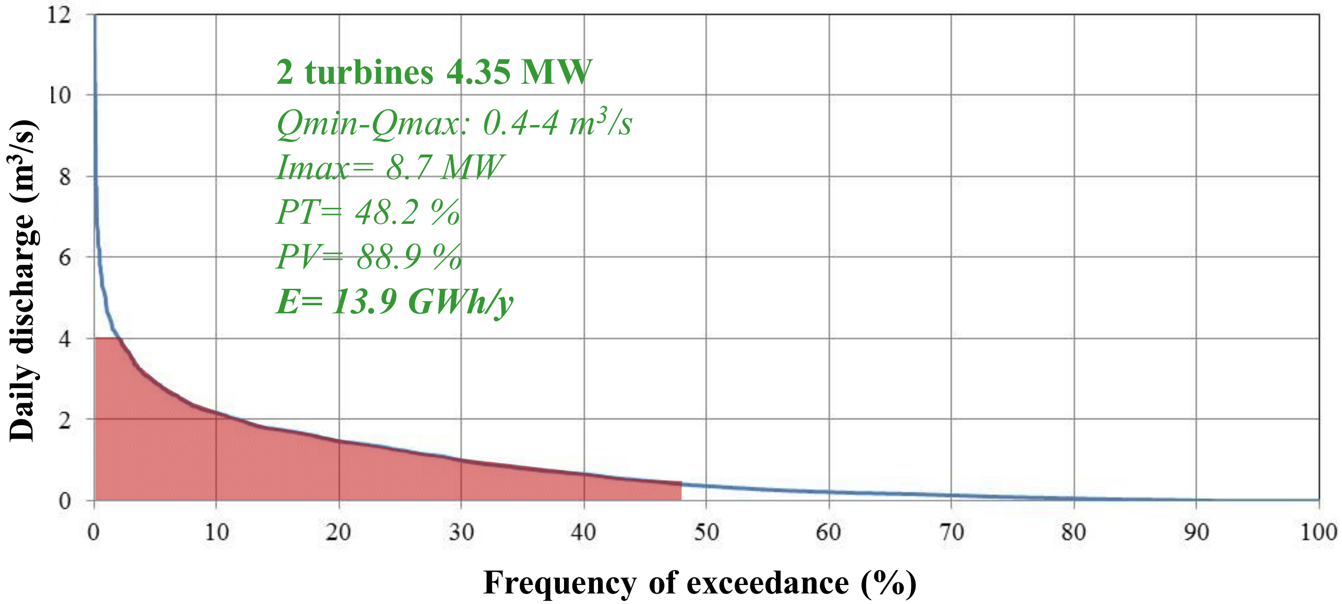
Data

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)

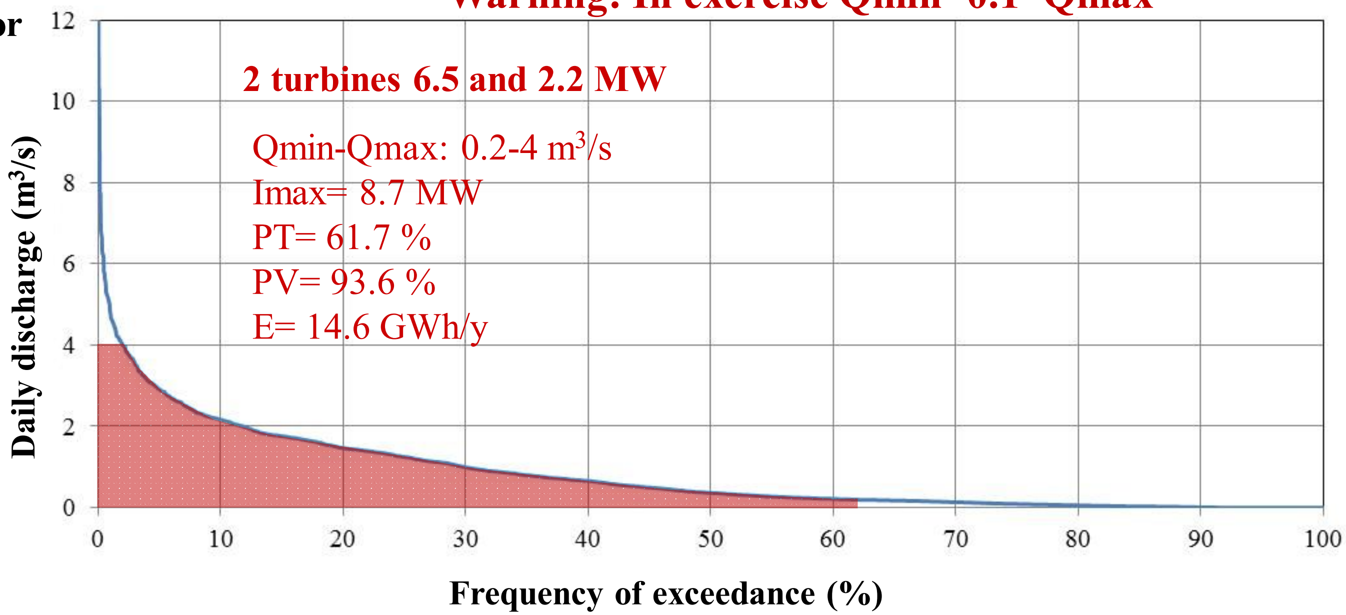
Warning: In exercise Qmin=0.1*Qmax

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

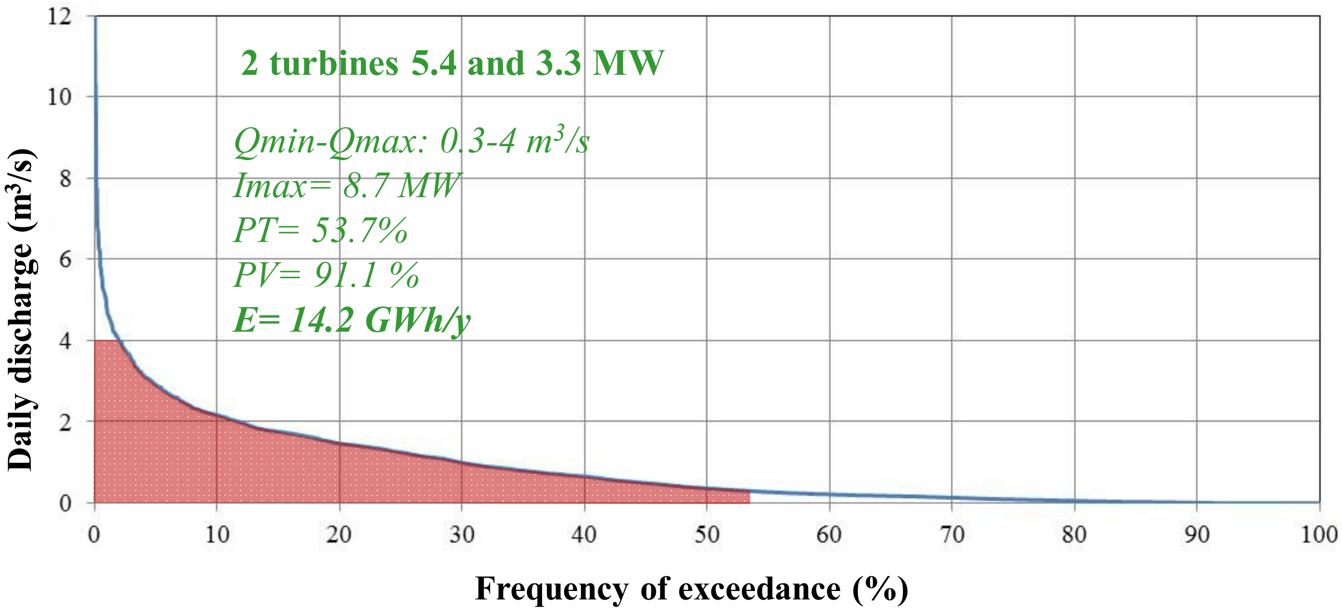
Qmin, Qmax: Minimum, maximum exploitation discharge (m^3/s)

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	p	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