National Technical University of Athens – School of Civil Engineering – Department of Water Resources & Environmental Engineering

Course title: Renewable Energy and Hydropower Works

Exam period: June 2022

Exercise 1

We seek for the construction of a hydroelectric system producing peak energy, in a river site with mean annual discharge 12.0 m^3/s. This will comprise a dam, a reservoir of useful capacity 500 hm^3, and a power station close to the dam foot. The reservoir level will range from +260 to +280 m, while the tailrace will be put at an elevation of +120 m.

a) Based on reasonable assumptions, estimate the net head, the mean annual water volume, which is expected to pass from the turbines, and the mean annual energy production.

The mean annual runoff produced upstream of the dam is:

$$V_a = 12.0 \times 86400 \times 365 \times 10^{-6} = 441.5\ hm^3$$

Assuming that 10% of this amount are the hydrological losses due to seepage, evaporation and spill, the mean annual water volume that passes through the turbines is:

$$V_T = 0.90 \times 441.5 = 397.4\ hm^3$$

Considering the mean reservoir level, the gross head is:

$$h = \frac{260+280}{2} - 120 = 135.0\ m$$

Under the premise that the hydraulic losses across the conveyance system are 3% of the gross head, the net head is estimated to be:

$$h_n = 0.97 \ \times 135 = 131\ m$$

Finally, by setting the typical efficiency value of large hydropower works, i.e., 90% the mean annual energy production is:

$$E = \frac{9.81 \times 0.90 \times 397.4 \times 131}{3600} = 127.6\ GWh$$

b) Estimate the design flow of the penstock and the power capacity of the turbines.

Since the system will produce peak energy, it is expected to operate up to 5 hours per day, or approximately 1800 hours per year. Thus, the design flow of the penstock is estimated by dividing the annual volume passing through the turbines by their operation time, i.e.:

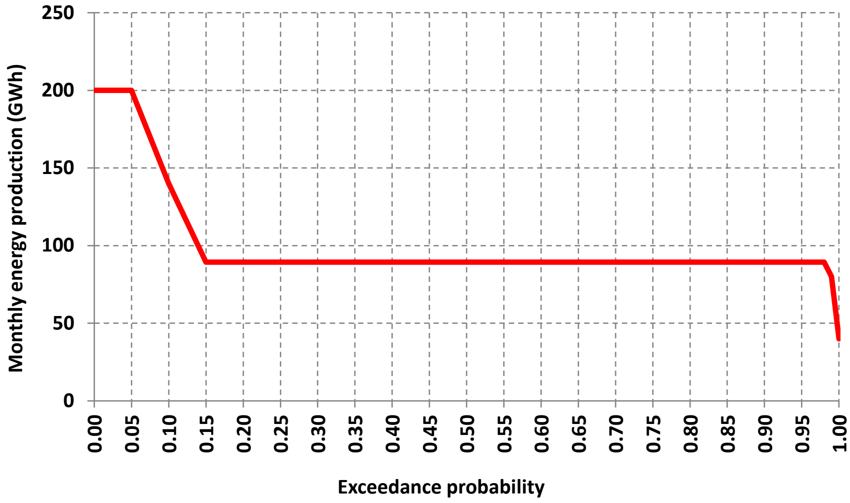
$$Q_d = \frac{397.4 \times 10^6}{1800 \times 3600} = 61.3\ m^3/s$$

Similarly, the turbine capacity is:

$$P = \frac{127.6 \times 10^3}{1800 \times 3600} = 70.9\ MW$$

γ) After running a simulation model to represent the reservoir operation on monthly basis, where we assigned a firm energy target equal to 70% of the mean annual production, the frequency of spilling, secondary energy production and energy deficits was equal to 5, 15 and 2%, respectively. In this respect, provide a sketch of the probability curve of monthly energy production.

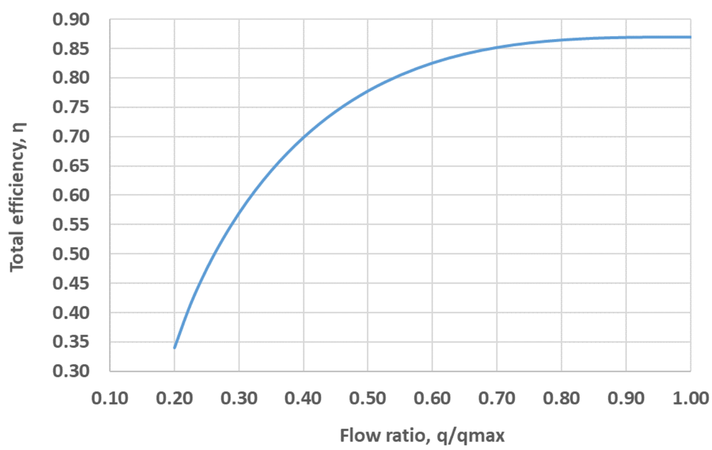
Herein we illustrate the aforementioned percentages, which represent exceedance probability values, as well as the firm energy target value (89.3 GWh, flat line), which is produced 98% of time. 15% of time, the energy production exceeds this target, thus the turbines are forced to produce surplus energy in order to avoid spills, *by taking advantage of their remaining capacity. Finally, 5% of time the system operates in its full capacity (here we set an arbitrary value of 200 GWh/month), while the overflow passes through the spillway.*



Exercise 2

Run-off-river plan that exploits a net head of 120 m comprises two turbines of 4.0 and 0.8 MW. The mean monthly streamflow values are the inlet site are given in the table, while the nomograph depicts the variation of total efficiency with respect to flow ratio.

Month	Streamflow (m^3/s)
Oct.	0.47
Noe.	1.36
Dec.	1.45
Jan.	0.98
Feb.	1.39
Mar.	1.51
Apr.	1.64
May	1.02
June	0.42
July	0.23
Aug.	0.15
Sep.	0.12



a) Estimate the environmental flow constraint, according to the Greek legislation.

Following the legislation standards, the environmental flow is defined as the maximum value between 50% of summer flow (mean value of June to August), 30% of mean flow of September or 30 L/s. This results to 0.08 m^3/s, to be released downstream of the inlet, through the fish ladder.

b) Estimate the minimum and maximum discharge of each turbine, as well as the corresponding minimum and maximum of the system.

The maximum discharge is estimated by considering the associated power capacity and the maximum efficiency, which is 87% (see nomograph). In particular:

$$Q_{max,1} = \frac{4.0\times10^3}{9.81\times0.87\times120} = 3.91\ m^3/s$$

$$Q_{max,2} = \frac{0.8\times10^3}{9.81\times0.87\times120} = 0.78\ m^3/s$$

According to the nomograph, the minimum discharge for hydropower production is 20% of the maximum one, thus $Q_{min,1} = 0.78$ *m^3/s and* $Q_{min,2} = 0.16$ *m^3/s. Therefore, the system operates in a range from 0.16 m^3/s (minimum discharge of the small turbine) to 4.69 m^3/s (sum of two turbines).*

c) Estimate the distribution of flows across the two turbines and the associated energy production within a time interval of three hours, during which the streamflow upstream of the inlet is 4.20 m^3/s.

Initially, we subtract the environmental flow (0.80 m^3/s), thus the flow entering the diversion channel is 4.12 m^3/s. This value exceeds the maximum discharge of the large turbine yet it is smaller than the maximum discharge of the system. In this respect, 3.91 m^3/s will be conveyed to the large turbine, while the rest amount, (0.21 m^3/s), to the small one. Under this premise, the large turbine is expected to operate in its full capacity, thus producing 3.2 MW for three hours. On the other hand, in order to estimate the power produced by the small turbine, we need to estimate its efficiency. The flow ration is 0.21/0.78 = 0.275, corresponding to a total efficiency up to about 50%. In this respect, the power production is:

$$P_2 = 9.81 \times 0.50 \times 0.21 \times 120 \times 10^{-3} = 0.13\ MW$$

Therefore, the total power provided by the turbine system will be 4.13 MW, corresponding to an 3-hour energy production value of 12.38 MWh.

d) Estimate the capacity factor of the system and the mean annual energy production, if the individual factors of the large and small turbine are 35% and 15%, respectively. Based on these outcomes, evaluate the economic viability of the system.

For given power capacity and capacity factor, the energy production by the two turbines are:

$$E_1 = 0.35 \times 8760 \times 4.0 \times 10^{-3} = 12.26\ GWh$$

$$E_2 = 0.15 \times 8760 \times 0.8 \times 10^{-3} = 1.05\ GWh$$

Thus, the total production is 13.32 GWh, which corresponds to a capacity factor equal to:

$$CF = \frac{13.32 \times 10^3}{8760 \times 4.8} = 0.32$$

This value exceeds the empirical threshold of 30%, indicating an efficient small hydropower plant.

Exercise 3

The energy mix of a small non-connected island comprises wind turbines of 1.5 MW and photovoltaic panels with dimensions 1950×850 mm and nominal power 300 W.

(a) Estimate the efficiency of PV panels.

According to the global standards for PV panels, their nominal power is achieved at 1000 W/m^2. For the given dimensions (1.76 m^2), this corresponds to an incoming power of 1760 W, thus their efficiency is the ratio 300/1760 = 0.181.

(b) Configure a suitable mix of the two renewables in order to fulfill an hourly demand of 5.0 MWh, for a solar radiation intensity of 700 W/m^2 and a wind velocity, assigned to the blade elevation, equal to 17.0 m/s.

An electricity demand of 5.0 MWh for a time interval of one hour corresponds to a power demand of 5.0 MW. To fulfill this, we consider three turbines producing 4.5 MW, since the wind velocity is large enough to allow operating at their nominal power. The remaining power of 0.5 MW will be provided by P/V panels, producing:

$$P = 0.181 \times 700 \times 1.76 = 210\ W$$

This results to a number of $500\ 000\ /\ 210 = 2381$ *panels.*