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Hydrological Uncertainty and Hydropower: New Methods to Optimize the Performance of the Plant

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Abstract

Hydrological uncertainty due to daily flow variability and to the effect of climate change on water resources is a critical topic in the feasibility evaluations of hydro-power projects, especially for run-of-river power plant.
The effect produced by these factors on the annual energy output of such type of plant was investigated. Empirical methods to improve the performance of the plant are proposed, which enable the choice of the most suitable design flow (Q_d) according to the hydrological features of the river, to the frequency of dry and wet years in the basin and to the target energy production.

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Keywords: Hydropower; Capacity Factor; Design Flow; Flow Duration Curve; Hydrological Uncertainty.

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1. Introduction

In the last few years, public opinion on environmental issues due to possible climate change and international protocols to reduce emissions of climate-altering gases have led to increasing attention to renewable sources for sustainable power generation [1].

Significant data emerging at global level indicate that energy production increasingly needs water, not only for hydropower generation but also for the extraction, transport and processing of gas, coal and oil and, to an increasing extent, also for crop irrigation for the production of biomass and biofuels. In particular, the amount of water used in 2010 has been estimated at 583 10^9 m^3. 66 10^9 m^3 of this amount was not returned to river networks [2]. The above data indicate that water will become an increasingly significant parameter in the feasibility evaluations of power

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projects, especially in view of the lack of water resources and the resulting inevitable conflict between various types of use and priorities [3].

The hydropower sector is rather relevant in world energy production. Old and new hydropower plants now require more in-depth feasibility studies and economic evaluations, according to new climatic scenarios [4].

In the present study, the link has been investigated between the hydrological features of the river basins and the performance of a hydropower plant, with a view to identify the most suitable design flow. In particular, hydrological aspects have been addressed by using the Flow Duration Curve (FDC), and the annual energy output from the hydropower plant has been estimated through the Capacity Factor index (CF) [5,6].

Finally, the obtained results has been used to analyze and control for the effects of hydrological uncertainty on energy production through appropriate design choices, taking into account expected changes in climate.

2. Methods

The methodology explained in this section links the hydrological analysis to the energy evaluations relating to hydropower plants, in order to obtain a synthetic estimate of the energy production, also in hydrological scenarios characterized by variability and uncertainty. In order to do this, results from the hydrological approach has been used as input data for the energy approach.

2.1. Hydrological approach

The FDC method has been applied to a sample of 15 catchment basins belonging to the Umbria Region. Table 1 shows the main characteristics of these river basins, which are highly heterogeneous in terms of mean annual discharge (Q_m) and Base Flow Index (BFI) [7]. Concerning the FDC, this variability can be noted in the slopes (α) of the mean annual flow duration curves (AFDCs), which depends on the geology and permeability of the basins [8].

Table 1. Studied river basins with acronyms, catchment areas, BFI, Q_m and α values

River	Location	Acronym	Catchment area (km^2)	BFI (%)	Q_m (m^3/s)	α
Sovara	Pistrino	SVPS	129	39	1.4	0.037
Nestore	Marsciano	NSMA	708	36	3.7	0.036
Caina	Monticelli	CAMN	230	39	1.3	0.039
Tiber	Santa Lucia	TVSL	934	44	10.7	0.024
Tiber	Pierantonio	TVPR	1805	43	18.3	0.028
Tiber	Ponte Felcino	TVFO	2033	42	20.2	0.030
Tiber	Monte Molino	TVMM	5568	53	49.8	0.031
Chiascio	Pianello	CIPA	532	45	6.7	0.033
Chiascio	Petrignano	CIPE	556	51	5.2	0.030
Chiascio	Torgiano	CITG	1956	59	18.2	0.024
Topino	Valtopina	TPVA	176	70	2.9	0.019
Topino	Bevagna	TPBE	445	78	3.3	0.024
Menotre	Pale	MEPL	108	92	1.1	0.012
Timia	Cantalupo	TRCA	549	69	4.2	0.010
Nera	Vallo di Nera	NEVN	1110	90	4.2	0.006

In Fig. 1a, a summary of the trends of the computed AFDCs is shown, for basins characterized by low, medium and high permeability respectively. In the range of duration p from 20% to 95%, the AFDC can be well interpolated by the equation:

$$\frac{Q_i}{Q_m} \cdot 100 = c \cdot e^{-\alpha p} \tag{1}$$

where α is the slope parameter that have to be used in the energy approach, and c is a dimensionless coefficient, specific of each basin [9].

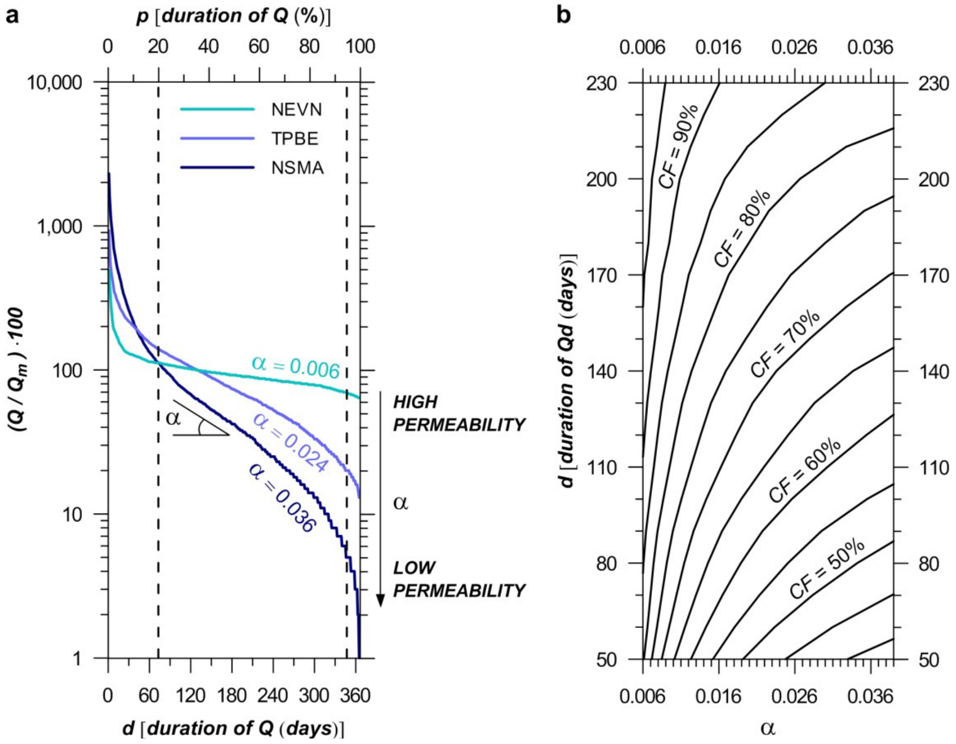

Fig. 1. (a) FDCs of three study basins having different degree of permeability. *Q*: daily flow, Q_m: mean annual flow, *α*: slope of the FDC calculated between the dotted lines; (b) Trend of *CF* as a function of *α* and *d* (duration of Q_d). The *CF* curves are drawn in steps of 5%

This type of hydrological approach, based on the standardized non-parametric computation of the FDC [10], is very performing for the goal of this study, and it could also be used in ungauged basins by resorting to regionalization procedures.

2.2. Energy approach

In the design of a power plants the Capacity Factor (CF) is used as an index of its performance. CF is a dimensionless quantity expressing the actual energy produced, with respect to the hypothetical maximum which would be delivered if the electrical power system operated full time at its rated power.

The variability affecting renewable energy sources such as solar, wind and hydro, greatly influences the power at the station and therefore the CF, which also depends on the technology employed [11,12].

In the case of hydropower plants CF varies with design flow (Q_d). In particular, in a run-of-river power plant the choice of Q_d can strongly affect its value depending on the run-off regime of the river, the latter described by the slope of the FDC.

This dependence has been evaluated for 15 catchment basins, by testing n=19 Q_d values extrapolated from the mean AFDC, within the range 50-230 days of duration, in 10-day steps, and by calculating the CF values associated to each of them. For each of the 19 Q_d tested, the CF values thus obtained result power-law linked to the slope α of the AFDC (Eq. 2).

$$CF = A \cdot \alpha^{-B} \tag{2}$$

where the values of the coefficients A and B are different for each Q_d and A increases with increasing duration, while B shows an opposite trend.

This result can be described in a graph (Fig. 1b) where, for each α, it is possible to identify the optimal duration of the design flow for a fixed CF. As we can see from the graph, the range of variability of CF and the CF values depend on α. In particular, for low values of α, CF varies within a narrow range and it always takes high values while for high values of α it varies within a wider range.

To summarize, in a river with constant flow the choice of Q_d has little influence on annual energy production, and the expected CF will always have a high value. Conversely, the size of the turbine has a great influence on the performance of a plant installed on a torrential river.

The estimate of CF from equation 2 is affected neither by the value of the hydraulic head nor by the turbine efficiency, and it has been also tested for high α values and various types of turbine [9].

3. Hydrological uncertainty and hydropower

Global warming is expected to influence the hydrological cycle and consequently available water resources on regional scales. For this reason, the effects of wet and dry years on the power generated at the station have been analyzed, and it has been emphasized that it is possible to control this effect by careful choice of the design flow, using the proposed method.

Similarly to what described in section 2.2, for each of the 15 study basins the performance of 19 hypothetical hydropower plants have been calculated by using the probabilistic AFDCs with a 20-year return period, one describing dry conditions in the basin ($AFDC_{5°}$) and the other describing wet conditions ($AFDC_{95°}$). The probabilistic AFDCs have been obtained by using the procedure of percentile estimation of Vogel and Fennessey [10].

The CF calculated, respectively called $CF_{5°}$ and $CF_{95°}$, have been compared with the CF_m obtained from the mean AFDC, in order to evaluate the decrease in energy production in dry years ($\Delta CF_{m(5°)}$) and its increase in wet years ($\Delta CF_{m(95°)}$).

Both for the dry and for the wet year, the ΔCF values obtained for each basin result linearly linked to the duration d of Q_d (Eqs. 3-4).

$$\Delta CF_{m(5°)} = \left(\Delta CF_{m(5°)}\right)_{MAX} - m_1 \cdot d \tag{3}$$

$$\Delta CF_{m(95°)} = \left(\Delta CF_{m(95°)}\right)_{MAX} - m_2 \cdot d \tag{4}$$

where $(\Delta CF_m)_{MAX}$ is a constant indicating the maximum potential decrease (Eq. 3) or increase in CF (Eq. 4) and depending on the actual availability of water in the time series in question, and m_1 and m_2 are reduction coefficients, typical of each basin, of the maximum potential decrease in the driest year and of the maximum potential increase in the wettest year, respectively [9]. These last terms allow for partially control the increase and decrease in energy production, by acting on Q_d during the planning phase of the hydropower plant.

For a detailed analysis of the effects of Q_d on $\Delta CF_{m(5°)}$ and $\Delta CF_{m(95°)}$, terms m_1d and m_2d have been isolated from Eqs. 3 and 4 and plotted versus duration d of Q_d.

Fig. 2a shows that the maximum potential decrease of CF_m in the driest year for the chosen return period can be reduced by a quantity equal to m_1d, which increases with increasing d following a straight line. Therefore, the greater d, the smaller the negative effect of dry years on energy production.

Fig. 2b shows that the maximum potential increase in CF_m in the wettest year for the chosen return period risks being reduced by a quantity equal to m_2d, which increases with increasing d, following a straight line. Therefore, the greater d, the smaller the positive effect of a wet year on energy production.

The values of m_1 and m_2 depend both on the hydrological response of the catchment area to variations in precipitation and stored water volume, and on the time series of flow data used in processing. As regard to the latter aspect, a minimum of 13 years of flow data were used for all the study basins, for periods ending in 2010. These periods clearly represent the extreme events in river run-offs, with several years of water crisis in the Umbria Region, e.g., in 2002-2003 and 2006-2007, and also exceptionally wet years which caused floods (e.g., 2005). In addition, the significant differences between the basins (in terms of geological features, permeability and run-off regime) produce very different hydrological responses.

Mean trends $(m_1d)_m$ and $(m_2d)_m$ have been calculated from the 15 series of m_1d and m_2d shown in Fig. 2a and 2b, together with the 90% confidence interval for the mean trend (Fig. 3). Because of the above explained representativeness of the data series and because of the great variety of hydrological regimes used in this study, the confidence interval must be viewed as capable of identifying, for each Q_d, the actual range of variation of m_1d and m_2d for most of the rivers in the study area.

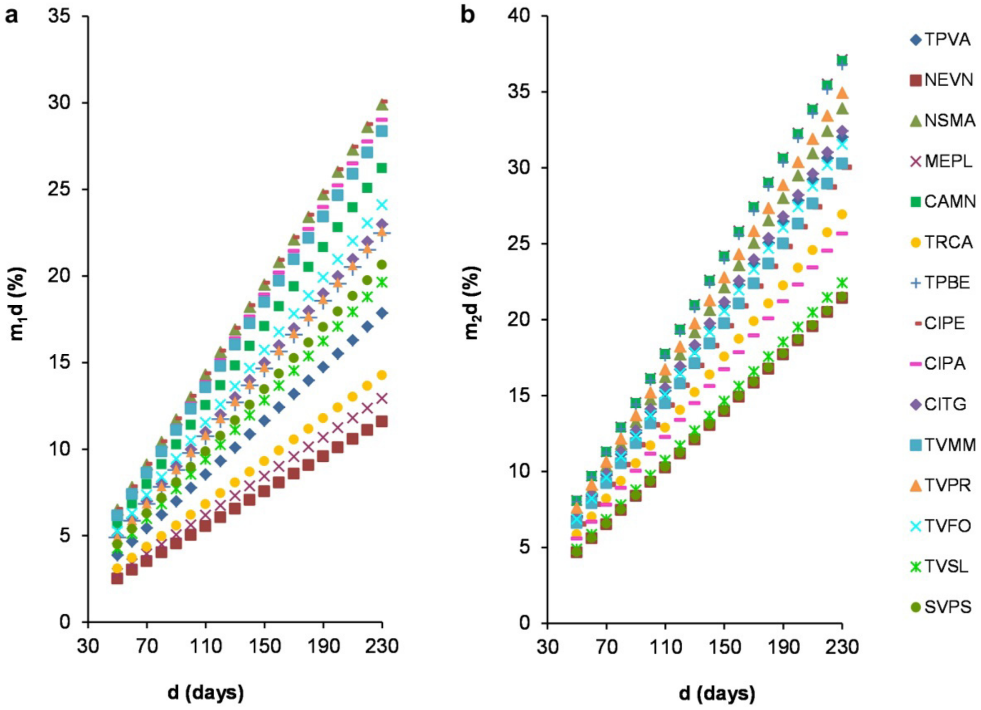

Fig. 2. *md* values from Eqs. 3 and 4, for basins listed in Table 1. a) m_1d: reduction from maximum potential decrease in CF in dry years; (b) m_2d: reduction from maximum potential increase in CF in wet years

The mean trend in the dry years (Fig. 3a) is described by:

$$(m_1d)_m = 0.0964 \cdot d \tag{5}$$

Substituting the extremes of the range of duration tested, that is d=50 and d=230, in Eq. 5, i.e., referring to the mean trend, we obtain that $(\Delta CF_{m(5^\circ)})_{MAX}$ can be reduced in the range from 4.8% to 22.2%. Moreover, the extreme values of the confidence interval $(m_1d)_{INF}$ and $(m_1d)_{SUP}$ may be expressed as:

$$(m_1 d)_{INF} = 0.57 \cdot (m_1 d)_m \tag{6}$$

$$(m_1 d)_{SUP} = 1.35 \cdot (m_1 d)_m \tag{7}$$

The mean trend in wet years (Fig. 3b) is described by:

$$(m_2 d)_m = 0.1316 \cdot d \tag{8}$$

Making the appropriate substitutions in Eq. 8, we obtain that $(\Delta CF_{m(95^\circ)})_{MAX}$ risks being reduced in the range from 6.6% to 30.3%. Moreover, the extreme values of the confidence interval $(m_2d)_{INF}$ and $(m_2d)_{SUP}$ may be expressed as:

$$(m_2 d)_{INF} = 0.71 \cdot (m_2 d)_m \tag{9}$$

$$(m_{21} d)_{SUP} = 1.22 \cdot (m_2 d)_m \tag{10}$$

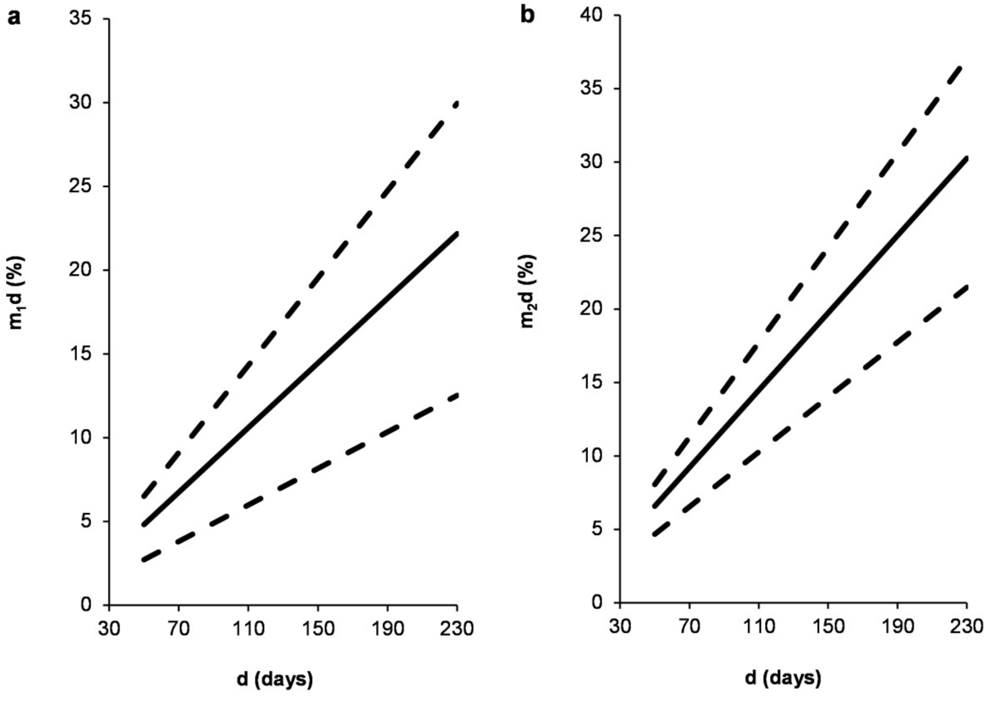

Fig. 3. *md* mean trend (solid line) and 90% confidence interval (dotted line). (a) dry years; (b) wet years

Results from this analysis show an opposite trend in dry and wet period, in particular, a choice of Q_d which is good to reduce the decrease in energy production in dry years may be inappropriate in wet years. This indicates that the study of possible climate change scenarios must be combined with a careful technical and economic analysis during the design of the hydropower plant [13,14]. The outcomes of this research can be very helpful in this direction.

4. Conclusion

The results of this study have shown that CF is analytically linked to the regime flow and it depends to a great extent on it. In particular, CF decreases from a constant run-off regime to a torrential one and the greater the design flow, the greater the rate of this decrease. A simple, equation-based procedure was developed, which allows identifying the optimal design flow only using the slope of the FDC. Since no other information is required, this approach could be also useful for evaluations in ungauged basins, through the use of regionalized FDCs. Moreover, the validation of the method used to derive the procedure, indicates that it may be used whatever the flow regime of the river and the turbine installed at the station.

Additional analyses have shown that the effect of extreme weather years on energy production is not the same for all basins and that it also depends on the design choices. Manipulation of the data obtained by the FDCs with a 20-year return period have shown that the percentage decrease in energy production in dry years, compared to the annual average, is linearly linked to the design flow, as well as its increase in wet years. In particular, if the design flow is extrapolated from the right part of the FDC the negative effect of dry years on CF can be reduced, vice versa, if it is extrapolated from the left part the increase of flows in wet years can be better exploited to enhance the value of CF. The procedure developed allows us to derive the characteristic linear function of the basin which, together with the knowledge of climate trends in the area of interest, enables more accurate design of hydropower plants.

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