Hydrologic-economic risk analysis in small hydropower schemes based on synthetic series of daily flows

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Abstract: This study aims to perform a risk analysis concerning the energy production in run of river small hydropower schemes (SHS) by evaluating the effect of the natural variability of the flow regime in their expected incomes.

To accomplish this objective a procedure to generate annual and daily synthetic streamflow series was applied to a data set of 14 Portuguese river daily streamflow samples.

This procedure encompasses a probabilistic model, namely the log-Pearson III distribution, for generating values at the annual level and a disaggregation model, namely the method of fragments, to disaggregate these values into the daily level. Based on the historical samples of mean daily flows, the previous procedure was used to generate $M = 5000$ synthetic daily flow series with lengths (N) equal to the ones of the historical samples.

For different design discharges and for the global period, a methodology to simulate the daily exploitation of run of river SHSs and obtain the daily and annual energy productions and its respective incomes was applied to both the synthetic (M) and historical (1) series. By applying economic criteria to the $(M + 1)$ annual revenues, its cumulative present value is determined. The resulting collection of revenues were statistically analyzed using the Pearson-III distribution in order to estimate the SHS revenues as non-exceedance probabilities.

As a result, it was concluded that the usual design of SHS based on average conditions, this is, based on a reference revenue corresponds to a suitable design as the referred revenue represents a good estimate of the expected income in SHS.

Keywords: hydrological risk; flow regime temporal variability, small hydropower scheme; synthetic series; disaggregation model

Resumo: O presente estudo visa a análise do risco associado à produção de energia em pequenas centrais hidroelétricas (PCHs) com exploração a fio de água, avaliando o efeito da variabilidade natural do regime hidrológico nas suas receitas esperadas.

Para tanto, recorreu-se à geração de séries sintéticas de escoamentos anuais e diários em 14 secções da rede hidrométrica nacional.

Este procedimento engloba um modelo probabilístico (lei log-Pearson III) para gerar valores a nível anual e um modelo de desagregação (método dos fragmentos) desses escoamentos em escoamentos diários. Em cada um dos locais geraram-se $M = 5000$ séries sintéticas, cada uma com dimensão N, igual à da correspondente série histórica.

No pressuposto de exploração a fio de água puro, de diferentes valores do caudal de dimensionamento e de período de licenciamento coincidente com o período global de registos, procedeu-se à simulação da exploração diária de cada hipotética PCH tendo por base as séries sintéticas (M) e histórica (1) de caudais médios diários, com estimativa das correspondentes produções diárias de energia e receitas anuais. Através da aplicação de critérios económicos às $(M + 1)$ receitas anuais, obteve-se o seu valor acumulado atualizado. Tais receitas foram, seguidamente, adimensionalizadas por consideração de uma receita de referência e analisadas estatisticamente, utilizando a distribuição Pearson III, a fim de as associar a probabilidades de não-excedência.

Como resultado, conclui-se que o dimensionamento de PCHs com base no critério de projeto mais frequentemente utilizado, ou seja, com base na receita de referência, constitui um bom estimador das receitas esperadas.

Palavras chave: risco hidrológico; variabilidade temporal hidrológica, pequeno aproveitamento hidroelétrico; série sintética; modelo de desagregação

1. Introduction

1.1. General framework

The emission of greenhouse gases (GHG), especially carbon dioxide (CO_2), is the main responsible for global warming. These gases are mainly produced by transports and electricity production[1].

Faced with an accelerated increase of these gases, European Union (EU) countries have made a commitment to reduce their emission to values 20% below 1990 levels by 2020 and 40% below by 2030. Additionally, they would have to guarantee that, at least, 20% of their energy comes from renewable sources by 2020[2], a value that increases to 27% ten years later[3]. To accomplish this reduction, EU countries will have to promote energy efficiency and increase the investment on renewable energy sources, like hydropower[4].

Due to their small construction time and exploration costs, but especially due to their easier integration in the local ecosystems, run-of-river small hydropower schemes (SHSs) represent a good alternative to schemes based on large dams and reservoirs aiming at regulating the river flows[4,5].

As a run-of-river small hydropower scheme does not have storage capacity, it only produces energy when the natural river discharges allow the turbine to operate[4,6]. Its design is usually made assuming a constant annual turbinated volume, equal to the average of the annual turbinated volumes provided by the available historical series of river flow discharges[7,8].

However, the temporal variability that characterizes such series is not compatible with the assumption of a constant annual turbinated volume but instead with yearly variable volumes, and consequently with yearly variable energy productions and incomes[7].

For this reason, one of the major issues when designing SHSs is the uncertainty that results for not considering the natural temporal variability of the river discharges and its impact on the expected revenues[7,8].

To understand the relevance and the effect of the natural temporal variability of the river regime in the profitability of small hydropower schemes there were performed some studies[9–13], based on different approaches that aimed at extracting as much information as possible from the available samples of river discharges.

Due to the enormous potential for the construction of new SHSs, it was considered relevant to continue the previous studies by applying a recently developed approach that utilizes information that goes beyond the available samples to address the effect of the temporal variability of the flow regime, namely based on synthetic daily flow series.

Under the assumption of hydrological stationarity, synthetic daily flow series can be seen as alternative flow series with the same probability of occurrence and, expectably, with statistical characteristics similar to the observed/historical ones[14].

The generation of synthetic series can be made concurrently at different time levels by using a disaggregation technique. This technique assumes a combination of two models: a first model for generating values at a given time level, for example year, and a second one for disaggregating these values into a lower time level, for example month or day, preserving the main statistics of the samples, such as the mean, standard deviation and skewness coefficient at both time levels[14,15].

1.2. Aims of study

Taking into account the previous studies that proved the good results yielded by the method of the fragments to generate synthetic flow series, the present study aimed at using such series to perform a risk analysis in small hydropower schemes by assessing the effect of the natural flow regime variability in the expected incomes.

In order to accomplish the previous objective, a methodology to simulate the daily exploitation of run-of-river small hydropower schemes was applied to the synthetic streamflow data. Therefore, the energy productions and consequently the revenues for different design discharges were obtained.

The procedure implemented to generate the synthetic flow data combined a probabilistic generation model at the annual level, namely the log-Pearson III distribution, and a disaggregation model directly from that level to the daily level, namely the method of fragments, as mentioned before. By considering different design discharges in each case study, a large number of synthetic daily flow series were generated and utilized to compute the cumulative present values of the expected revenues based on the assumption of a licensing period equal to the length of the historical sample to which the case study refers.

By applying a statistical model, namely, the Pearson III distribution, non-exceedance probabilities were assigned to those revenues aiming at expressing their plausibility. Furthermore, the aforementioned simulation was also applied for two other periods smaller than the global period of records, specifically ten and twenty-five years, to evaluate the susceptibility of SHSs to the temporal variability of the flow regime for different periods.

2. Streamflow data

To analyze the risk related to the temporal variability of the river flow regime in small hydropower schemes based on synthetic series of daily flows by disaggregation models it is necessary to have sufficiently long historical samples of mean daily flows that characterize well enough the natural regime. For that, there were selected 14 gauging stations spread mainly over the north of Portugal, as shown in Figure 1. These river gauging stations were selected due to their long continuous period of records, but mainly because they represent natural flow regimes with different temporal patterns. As some studies suggest[15], in Portugal, the temporal variability of the flow regime is related to the mean annual flow depth, H, this is, the greater the flow depth, the more regular the regime is.

Table 1 summarizes some of the streamflow samples main characteristics, namely, the name and code of each gauging station, the period with records and the main catchment/river where they are located, as well as the area and mean annual flow depth of each catchment.

The 14 stations were ranked according to the mean annual flow depth, which range from 300 mm to around 1000 mm, covering a wide variety of flow regimes, from more irregular to more regular, respectively.

It is important to refer that the mean daily flow series were provided by the *Agência Portuguesa do Ambiente* (APA), via the public database *Sistema Nacional de Informação de Recursos Hídricos* (SNIRH)[16], which is the main source of Portuguese hydrological and hydro meteorological data and has very high quality standards. It is important to notice that the statistics presented are referred to the period of records without the 29th of February of every leap year. As a matter of fact, all leap days were removed before any studies in order to standardize the samples and to make the procedure easier to apply.

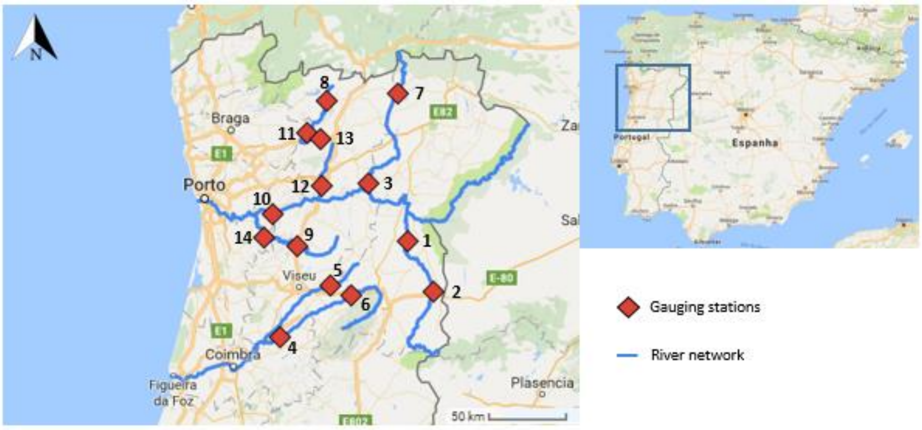

Figure 1: Schematic location of the stream gauging stations used in the study.

*Table 1: S*treamflow samples and some of their characteristics.

Gauging station				Catchment area (km²)	Period of records (number of years)	Mean annual flow depth (mm)
Sample nº	**Code**	**Name**	**Main catchment/ /river**			
1	08O/02H	Cidadelhe	Douro/Côa	1685	1955/56 - 2003/04 (49)	300
2	10P/01H	Castelo Bom	Douro/Côa	897	1957/58 - 2003/04 (47)	347
3	06M/01H	Castanheiro	Douro/Tua	3718	1958/59 - 2005/06 (48)	366
4	11I/06H	Ponte Tábua	Mondego/ Mondego	1552	1937/38 - 1978/79 (42)	421
5	10K/01H	Pte. Santa Clara Dão	Mondego/Dão	177	1921/22 - 1972/73 (52)	454
6	10L/01H	Pte. Juncais	Mondego/ Mondego	604	1918/19 - 1984/85 (67)	481
7	03N/01H	Rebordelo	Douro/Rabaçal	857	1955/56 - 2002/03 (48)	597
8	03K/01H	Vale Giestoso	Douro/Beça	77	1957/58 - 2005/06 (49)	703
9	08J/01H	Castro Daire	Douro/Pavia	291	1945/46 - 2003/04 (59)	736
10	07I/04H	Cabriz	Douro/Ribª S. Paio	17	1966/67 - 1997/98 (31)	773
11	04J/04H	Cunhas	Douro/Beça	338	1949/50 - 2005/06 (57)	823
12	06K/01H	Ermida-Corgo	Douro/Corgo	291	1956/57 - 2005/06 (50)	887
13	05K/01H	Sta. Marta do Alvão	Douro/Louredo	52	1955/56 - 2005/06 (51)	922
14	08H/02H	Fragas da Torre	Douro/Pavia	660	1956/57 - 2005/06 (50)	1016

3. Methodology

3.1. Generation of synthetic series

3.1.1. General considerations

The methodology used in this work consists on a two-level approach containing a generation model for the annual synthetic streamflow series and a disaggregation model to create the corresponding daily streamflow series.

The hydrological year was adopted as the annual time-step to ensure the statistical independence of the annual flows. In fact, the annual streamflows, when referred to a hydrological year, is an independent time series, thus, the modelling of the annual flow series may use a non-deterministic probabilistic model[17].

Probabilistic models often generate negative flows, due to the hydrological temporal variability, representing a physically impossible situation. For this reason, the generation model is based on the probability density function of the log-Pearson III law, which applies the Pearson III law to the logarithms of the random variable. As this distribution only allows positive numbers, the generation of negative flows is avoided. Moreover, this law has a flexible distribution ensuring the treatment of skewed data, by assuming different shapes depending on its three parameters, namely, mean, standard deviation and skewness of the sample.

The disaggregation model used to obtain the corresponding daily flows was the method of fragments proposed by Svanidze in 1961. De forma resumida, tal método baseia-se no pressuposto de que a distribuição de escoamentos diários é similar em anos com escoamentos anuais próximos[18].

The quality of the synthetic daily flow series depends upon their capability of preserving the main statistical characteristics of the historical series to which they refer.

To solve this problem a large number, M=5000, of synthetic time series, each one with length equal to the one of the historical sample is generated for each case sudy. A given historical statistical characteristic is preserved if it is contained in the confidence interval defined for that characteristic based on the M synthetic series.

3.1.2. Synthetic annual streamflows generation

As referred before, the annual flows were generated through a random sampling of the log-Pearson III distribution. Therefore, the first step is to compute the series of natural logarithms of each annual streamflow series [1]:

$$Y_k = \ln(X_k + c) \qquad [1]$$

where Y_k represents the series of the natural logarithm of the annual streamflows, X_k (k=1, ..., N, where N represents the number of years with data of a given sample), and c is a constant to avoid null flows. This constant should be very small to minimize its effect on the characteristics of the sample. The application carried out consider c=0.0001.

The generation of synthetic series of N logarithms of annual flows, Y_k^{ss}, is based on the following equation:

$$Y_k^{ss} = \bar{Y} + K_k \times s_y \qquad [2]$$

where $\bar{Y}$ e s_y represent, respectively the mean and standard deviation of the logarithms of the annual flows and K_K represents the probability factor of the Pearson III distribution obtained by the application of the Wilson-Hilferty transformaion[19].

The synthetic series of annual flows, X_k^{ss}, are obtained by inverting the logarithm transformation, and subtraction the constant c [3].

$$X_k^{ss} = e^{Y_k^{ss}} - c \qquad [3]$$

The described model is applied M times for each sample of length N, thus generating 5000 synthetic annual streamflow series, each with length N.

3.1.3. Daily disaggregation of annual streamflows

As referred before, the model adopted to disaggregate the synthetic annual flows is the method of fragments. The main assumption of this method is that the temporal distribution of a given hydrologic parameter over a defined time interval Based on a historical sample of annual and daily flows, the daily flows in each year, k, $X_{k,i}$, with i=1,...,365 are divided by the respective annual streamflow, X_k, resulting in a fragment, f_k, composed by 365 dimensionless values. A generic fragment, f_k, for a given year, is described by equation [4]:

$$f_k = \frac{X_{k,i}}{X_k} = \left[\frac{X_{k,1}}{X_k} \;\; \frac{X_{k,2}}{X_k} \;\; \ldots \;\; \frac{X_{k,364}}{X_k} \;\; \frac{X_{k,365}}{X_k}\right] \qquad [4]$$

where $X_{k,i}$ represents the daily flows for the year k (k=1,...,N) and the day i (i=1,...365).

Naturally, for a sample with N years of records, an array of N fragments, f_k,(k=1,...,N), is obtained as expressed by equation [5]:

$$[f] = \begin{bmatrix} f_1 \\ \ldots \\ f_N \end{bmatrix} = \begin{bmatrix} \frac{X_{1,1}}{X_1} & \cdots & \frac{X_{1,365}}{X_1} \\ \vdots & \ddots & \vdots \\ \frac{X_{N,1}}{X_N} & \cdots & \frac{X_{N,365}}{X_N} \end{bmatrix} \qquad [5]$$

In Figure 2, three typical fragments of consecutive years for Cidadelhe gauging station can be seen, as an example of the variation of the daily flows within-the-year and among years.

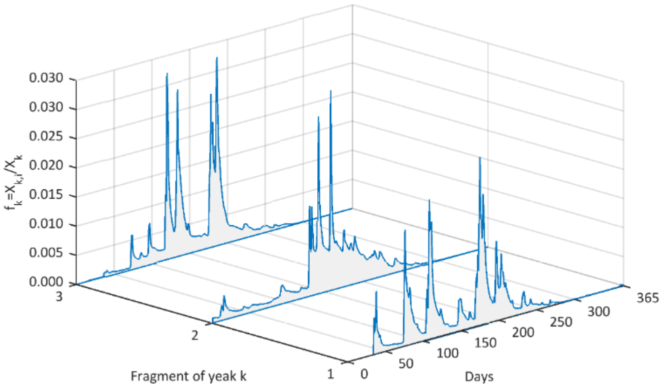

Figure 2: Daily fragments for three consecutive years (from 1955/56 to 1957/58) at Cidadelhe gauging station.

The application of the method of the fragments implies that the fragments are constituted and assembled into classes beforehand. For that purpose, prior to computation of equation [5], the N annual flows are ranked from smallest to highest. After performing an analysis involving different criteria to create and define the fragment classes when using the method to disaggregate annual flows into monthly flows, Arsénio[20] suggested that the definition of classes should be done based on a trial and error procedure, aiming at finding the assembly of fragments that best preserves the statistical characteristics of the samples.

To avoid this procedure, Silva[15] and Portela & Silva[21–23] suggested the definition of the fragments classes as probability intervals for the disaggregation of annual flows into monthly flows. In this way, the authors considered classes of fragments, each one delimited by two annual flows in a way that the difference between the non-exceedance probabilities of each one was constant and equal to 100%/C, being C the number of classes. For example, for 10 classes of fragments, the amplitude of the intervals would be 10%. If the precedent procedure results in one or more empty classes, i.e., one or more classes without fragments, half of the probability amplitude that defines the empty class is attributed to the two adjacent classes. This step is valid only for the internal classes. If the empty class is the first or the last one, then that class is included in the next or in the previous class, respectively, by changing its upper or lower limit. The authors also concluded that this method leads to good results in what concerns the preservation of the statistical parameters of the samples at the monthly level.

Motivated by the good results at this time level, Pinto[9] applied the precedent method to the disaggregation of annual flows directly into daily flows, attesting the preservation of the statistics at the daily level in most of the cases. Although the preceding procedure starts with classes of fragments equally-spaced in terms of non-exceedance probability limits, the possible existence of empty classes and their consequent re-allocation will end up by changing the limits of some classes. Thus, when applying this method to a large number of samples, it is difficult to categorize the different class definitions and, consequently, to observe its consequences in the performance of the model. In this way, the study conducted by Portela & Silva[14,24] introduced a new way to define the number and amplitude of the fragments classes related to the previous one - classes always equally-spaced in terms of the non-exceedance probabilities of their limits.

For that purpose and starting again with a fixed number of classes, C, with fixed amplitude of $100\%/C$, in the allocation of fragments into classes results in one or more empty classes of fragments, the number of classes is progressively reduced by one until there are no empty classes or, equivalently, until it is identified the maximum number of classes, C^* that corresponds to all the classes have at least one fragments. In this way, all the classes have the same constant amplitude, equal to $100\%/C^*$.

This procedure was the one applied in this study for two scenarios of the number of initial classes of fragments – 10 and 20 classes.

Once defined the classes of fragments, the methodology proceeds by selecting a synthetic annual flow and identifying the class of fragments to which it belongs. After that, one of the fragments belonging to that class is selected and used to disaggregate that synthetic annual flow to the daily level, obtaining 365 synthetic daily flows.

The random selection of fragments from a given class is done without replacement until the class runs out of fragments. When this happens, all the fragments that composed the class are restored with the same exact order as they were in the beginning. The aforementioned process is realized as many times as the number of years, N, of the sample.

This procedure is repeated until M N-year synthetic daily streamflow series are obtained. As said before, for each sample M=5000 synthetic daily streamflow series were generated.

3.1.4. Evaluation of the generated synthetic series

The quality of the generated synthetic series are assessed by evaluating the preservation of the historical statistical parameters at the different time levels.

In this way, the statistical parameters of an historical series, θ, like the mean, standard deviation and skewness coefficient, are preserved by a given synthetic series when they are included in the confidence interval below:

$$\left]\overline{\theta_{ss}} - z_{\left(1-\frac{\alpha}{2}\right)} s_{\theta_{ss}}; \overline{\theta_{ss}} + z_{\left(1-\frac{\alpha}{2}\right)} s_{\theta_{ss}}\right[\qquad [6]$$

where $\overline{\theta_{ss}}$ e $s_{\theta_{ss}}$ represent the mean and the standard deviation of θ in the M synthetic series and $z_{\left(1-\frac{\alpha}{2}\right)}$ represent the $\left(1-\frac{\alpha}{2}\right)$ quantile of the normal distribution, being α the significance level.

At all temporal levels, it was adopted a confidence level of $100\%\times(1-\alpha)$=95% for the confidence intervals. Therefore, expression [6] can be represented by equation [7]:

$$\overline{\theta_{ss}} - 1.96 s_{\theta_{ss}} \leq \quad \theta \leq \overline{\theta_{ss}} + 1.96 s_{\theta_{ss}} \qquad [7]$$

3.2. Analysis of the hydrological variability for the global period of records

3.2.1. General considerations

In this study, the daily simulation of a SHS considers the most common scenario, which is a run-of-river exploitation regime. For this reason, no regularization volumes are considered. In order to make the procedure even more generic, some SHS's characteristics are considered identical and equal to a reference value. More precisely, the net head, the global efficiency of the powerhouse and the unitary selling price of the energy are considered equal to one. One of the main objectives of this study is to analyze the effect of the maximum flow that can be turbinated or design discharge, Q_{max}, in the production of energy and, consequently, in the SHS revenue. For that purpose, there were adopted values for $Q_{max}=Q/Q_{mod}$ between 1.0 and 3.0, with increments of 0.2, $(1.0 \leq Q/Q_{mod} \leq 3.0)$. This interval of flows includes the most utilized criteria when designing a SHS, which is commonly around 2.0 Q_{mod}. In any case, no minimum or ecological flows are considered.

Due to the lack of appropriate legislation regulating the licensing period of small hydropower schemes, in a first approach, the period of analysis considered in each case study was coincident with the length of the corresponding flow sample.

In economic terms, the present values of the annual revenues resulting from the sale of the energy produced in these hypothetical SHS are determined based in a constant market price system referred to the first year of the exploitation of the schemes (year 0). The discount rate, t, is set in 7%, being a common value in this type of projects.

The economic analysis in each case study utilized sequences of dimensionless annual revenues, obtained by dividing the revenue provided by the models for each year by a reference revenue obtained from the historical series, thus allowing comparing results among the different case studies. The following sections present the methodology applied to determine both the reference and the synthetic series revenues.

3.2.2. Determination of the reference revenue

As referred before, the design of a run-of-river SHS is usually made assuming a constant annual volume that can be used for energy production, equal to the average of the annual turbinated volumes, $V_{med}[m]$, based on the historical series of daily flows.

The annual energy production, E_{med} $[GWh]$, is determined according to:

$$E_{med} = \frac{\frac{V_{med} \times H}{3600}}{9.81 \times \eta} \qquad [8]$$

where H $[m]$ represents the head and η the global efficiency of the powerhouse.

The annual average revenue, R_{med} represents the incomes with the sale of the produced energy, this is, the energy production multiplied by its unitary sale price.

Having in mind that R_{med} represents an annuity, it is very easy to calculate its cumulative present value (CPV) on a period equal to the dimension of the sample, also called reference revenue, R_{ref}, as represented by equation [9]:

$$R_{ref} = R_{med} \times \frac{(1+t)^N - 1}{(1+t)^N \times t} \qquad [9]$$

As referred before, this model is applied for a range of values of Q/Q_{mod}, comprehended between 1.0 and 3.0 with increments of 0.2, resulting in 11 reference revenues for each case study, each one for a given value of Q/Q_{mod}.

3.2.3. Determination of the synthetic series revenues

The procedure implemented to obtain the revenues from the sale of energy in each one of the $M = 5000$ generated daily flow synthetic series has to take into account the temporal variability of the turbinated volumes. In this way, it was implemented a daily simulation computational algorithm to determine the annual turbinated volumes and, consequently, the annual revenues obtained from the selling of that energy.
It is important to refer that this process can be applied not only to the M=5000 daily flow synthetic series but also to the historical one, as both represent events equally likely to happen.
In this way, for each daily flow series and each design flow, Q_{max}, the daily production of energy was estimated, based on equation [8]. By accumulating the daily energy productions, the respective annual production, $E_s^{(k)}$, was determined, where s represents the order of the series of daily flows and k the year to which that production refers. The annual income, $R_s^{(k)}$, is obtained by multiplying the annual energy production by its energy selling price. As this price was considered equal to one, the annual incomes are given by:

$$R_s^{(k)} = E_s^{(k)} \qquad [10]$$

Accordingly, the cumulative present value of the incomes resulting from each one of the 5001, for a period of time coincident with the dimension of the sample, is given by:

$$R_s = \sum_{k=1}^{N} \frac{1}{(1+t)^k} \times R_s^{(k)} \qquad [11]$$

Where R_s represents the cumulative present value of the incomes.
This procedure results in $(M+1)$ cumulative present values of the incomes for each desing flow and case study, exressing, not only the effects of the hydrological temporal variability, but also, the economic analysis criteria.
As referred before, those incomes are made dimensionless by dividing by the respective reference revenue, allowing a straightforward comparison between the different case studies.
To better characterize the energy production conditions, the aforementioned dimensionless incomes were statistically analyzed, based on the application of the Pearson III distribution.

3.3. Analysis of the hydrological variability for subperiods

The analysis described in the previous section considered that the licensing period of each SHS was equal to the length of the sample of daily flows in the stream gauging station to which the case study refers. As it can be seen in Table 1, each case study has around 50 years of records. This period normally exceeds the usual expected licensing period of a SHS. In fact, and despite the current lack of legislation, until a few years ago, 35 years was a common licensing period. This period was subsequently reduced to 15 years eventually plus 10 years[25], and more recently, to 20 years eventually plus 5 years[26]. The decree-laws that supported the previous periods are no longer in force and the replacing legislation was not yet produced[27].
Therefore, for a more realistic perception of the economic risk on SHSs, the procedure described in the previous chapter was performed for smaller periods, in order to identify the extremes incomes CPV, this is, the maximum and minimum CPV of the incomes that could occur in a more realistic exploitation period, this is 25 years.
However, the smallest the period is, the more susceptible the SHS becomes to the temporal variability of the flow regime, meaning that the expected revenue can be considerably apart from the reference one. In this way, periods of 10 years were also considered in order to analyze the susceptibility of the investments to adverse hydrological conditions during the first years of exploitation.
Similarly to the analysis for the global period of records, the cumulative present value of the incomes for both subperiods were also made dimensionless by dividing by the reference revenue in those subperiods, determined based on the global period of records.

4. Results and discussion

4.1. Synthetic series generation

For each case study identified on Table 1, there were generated, by applying the log-pearson III distribution, $M = 5000$ synthetic series of annual flows, each one with N years of records, equal to the sample to which each case study refers. These annual synthetic series were next disaggregated to synthetic series of daily flows by the method of fragments. In the application of this method there were considered two maximum number of initial classes of fragments, namely, 10 and 20 classes, each one with constant amplitudes of non-exceedance probabilities, equal to 10% and 5%, respectively. Furthermore, there were obtained 5000 synthetic series of monthly flows of N years, taking advantage of the additivity property of the method of the fragments that allows the determination of the series of monthly flows, by the simple accumulation of the daily flows.
The evaluation of the performance of the models is made by comparing the statistics (mean, standard deviation and skewness coefficient) of the synthetic series with those derived from the samples. As referred before, this comparison utilized confidence intervals, expressed by equations [6] and [7] for a confidence level of $100\% \times (1-\alpha) = 95\%$.

Hence, Table 2 summarizes, for each case study and for both numbers of initial classes of fragments considered, the number of days and months in which a given statistical characteristic of the historical series was not preserved. The table shows also the number of classes effectively adopted, resulting from the reallocation of empty classes.

It is important to notice that the results at the annual level were not included in the aforementioned table due to the good results obtained by the model based on the log-Pearson III distribution at this time level, having preserved all the statistical characteristics in all case studies.

The table shows clearly the good performance of the applied model at the monthly and daily levels. For both initial classes of fragments, the model was able to preserve almost all the statistical characteristics of the historical series, especially for 20 initial classes of fragments. Ponte Santa Clara Dão river gauging station is the exception, with only 9 equally-spaced classes of fragments, regardless the initial number of classes. However, in some gauging stations, an increase in the number of initial classes of fragments results in a worse preservation of the statistics these cases. One justification for that is that, increasing the initial number of classes, may result in some unused classes, thus reducing the variability of the synthetic streamflow series, affecting the standard deviation and the skewness coefficient of the synthetic streamflow series. This issue requires further investigation, especially regarding the correct identification of an optimal number of classes.

Table 2: Performance of the model at the daily and monthly level for ten and twenty initial classes of fragments.

Estação hidrométrica		Numero máximo de classes de fragmentos: 10							Numero máximo de classes de fragmentos: 20						
		Nº efetivo de classes	Nível diário			Nível mensal			Nº efetivo de classes	Nível diário			Nível mensal		
Nº	Nome		Média	Desvio-padrão	Coeficiente de assimetria	Média	Desvio-padrão	Coeficiente de assimetria		Média	Desvio-padrão	Coeficiente de assimetria	Média	Desvio-padrão	Coeficiente de assimetria
1	Cidadelhe	10	0	**6**	**6**	0	0	0	18	0	0	**1**	0	0	0
2	Castelo Bom	10	0	0	**2**	0	0	**1**	13	0	0	0	0	0	0
3	Castanheiro	10	0	**21**	**26**	0	**1**	**1**	12	0	**6**	**24**	0	0	**1**
4	Ponte Tábua	10	0	0	0	0	0	0	20	0	0	**1**	0	0	0
5	Ponte Santa Clara Dão	9	**12**	**24**	**16**	0	**2**	**2**	9	**12**	**24**	**16**	0	**2**	**2**
6	Ponte Juncais	10	0	0	**4**	0	0	**1**	20	0	0	0	0	0	0
7	Rebordelo	10	0	0	0	0	0	0	19	0	0	**2**	0	0	0
8	Vale Giestoso	10	0	0	0	0	0	0	19	**2**	0	0	0	0	0
9	Castro Daire	10	0	0	**1**	0	0	0	19	0	0	**4**	0	0	0
10	Cabriz	10	0	0	0	0	0	0	16	0	0	0	0	0	0
11	Cunhas	10	0	0	**2**	0	0	0	20	0	**1**	**2**	0	0	0
12	Ermida Corgo	10	0	0	**2**	0	0	0	18	0	0	0	0	0	0
13	Santa Marta do Alvão	10	0	0	0	0	0	0	19	0	0	0	0	0	0
14	Fragas da Torre	10	0	**15**	**10**	0	**1**	**1**	18	0	0	0	0	0	0

4.2. Analysis of the hydrological variability for the global period of records

Due to the better results achieved by the generation models, the analysis of the temporal hydrologic variability on the expected incomes of a SHS will only be performed for the scenario that considers 20 initial classes of fragments on the generation of synthetic series of daily flows.

Thus, for each case study, the dimensionless cumulative present values of the incomes were obtained. These incomes result of the 5001 series of daily flows of N years, this is, of the 5000 synthetic series and the historical series.

Additionally, the Pearson III distribution was applied to these dimensionless incomes, in order to associate them to non-exceedance probabilities.

Figure 3, represents graphically, for 3 values of Q/Q_{mod}, the maximum, minimum and average value of the series of 5001 incomes CPV, for all case studies. In Figure 3 it can also be seen the cumulative present value of the revenues for different probabilities of non-exceedance, namely for 99.9%, 99.0%, 95.0%, 50.0%, 5.0%, 1.0%, 0 ,1%. The available case studies are numbered according to Table 1 and ordered by increasing mean annual flow depths.

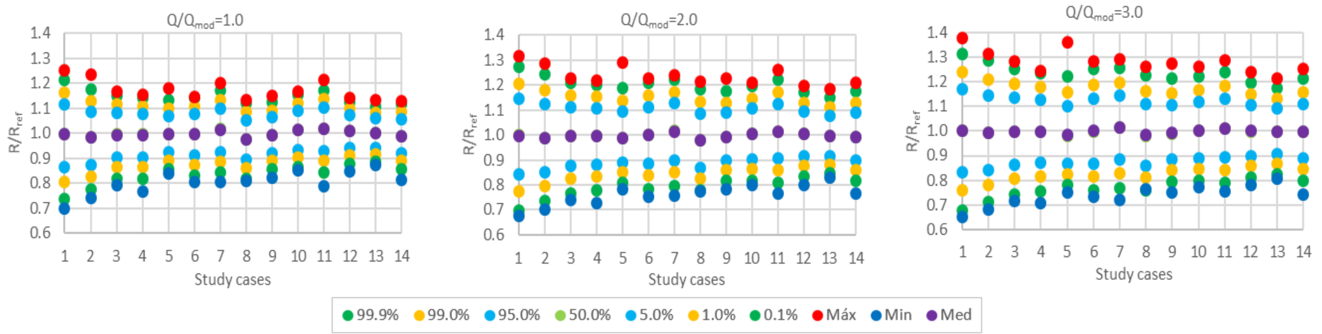

Figure 3: Maximum, minimum, mean and non-exceedance probabilities of the dimensionless revenue CPV series obtained from the historical and the generated synthetic daily flow series for each sample and for *a)* $Q/Q_{mod}=1.0$, *b)* $Q/Q_{mod}=2.0$ and *c)* $Q/Q_{mod}=3.0$.

Figure 3 clearly shows that, for all case studies, the average of the incomes CPV over a period of N years is practically coincident with the reference revenue, regardless of the design flow considered. Additionally, the incomes associated to 95% and 5% non-exceedance probabilities are around $1.1R_{ref}$ and $0.9R_{ref}$, respectively, indicating that the probability of yielding revenues 10% bigger or smaller than the reference revenue in a period of N years is only around 5%. It is also noticeable that, the greater the design discharge, the greater the probability of obtaining revenues further away from the reference ones. It is also noteworthy that for a fixed value of the ratio Q/Q_{mod}, the previous amplitude decreases as the region is more humid, i.e., as the mean annual flow depth increases.

Once again, Ponte Santa Clara Dão (sample nº 5) is clearly an exception, with maximum incomes definitely higher than the ones for river gauging stations with similar flow depths. However, this was the sample with the lowest performance of the generation model, that is, with the highest percentage of non-preserved 52 days in what concerns the statistical characteristics (see section 5.1), which may indicate that the sample may have any problem that requires a more detail analysis of its behavior.

4.3. Analysis of the hydrological variability for the global period of records

As referred, the analysis of the results from the exploitation of a SHS based on the assumption of a period larger than the expectable duration of the licensing one may lead to an unrealistic perception of the economic benefits of the scheme.

In this way, it was decided to compute the income series for two scenarios of the length of the licensing period, N_*, and to compare the results thus achieved taking into account the temporal variability of the flow regime with the reference revenue for the same period: N_*=25 and N_*=10 years.

In this way Figure 4 represents graphically, for 3 samples and for every value of Q/Q_{mod}, the average of the maximum and minimum dimensionless revenue CPV series for sequences of N_*=10 and N_*=25 years, that result from each one of the 5001 daily flow series.

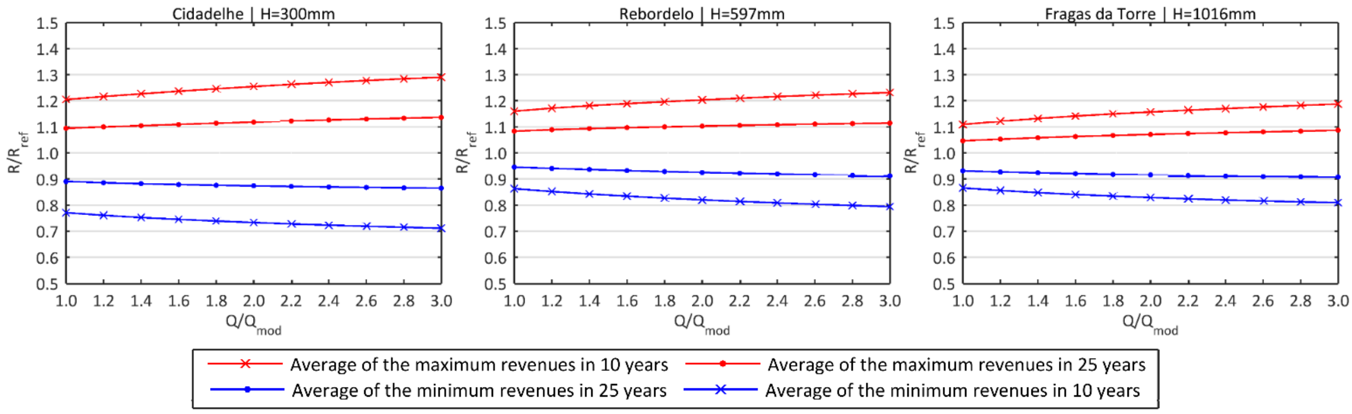

Figure 4: Average of the maximum and minimum dimensionless revenue CPV series for $N_*=10$ and $N_*=25$ years, for each Q/Q_{mod} *for the samples of Cidadelhe, Rebordelo and Fragas da Torre. (H stands for mean annual flow depth).*

Figure 4 confirms that, the smaller the exploitation period is, the more susceptible the SHS becomes to the temporal variability of the flow regime, as the expected incomes deviate more from the reference revenues. It is also possible to conclude that, similarly to Figure 3, as the temporal variability of the regime decreases (higher H), the variability of the dimensionless incomes decreases. Likewise, the greater the design discharge, Q/Q_{mod}, the greater the variability of the incomes.

Another important aspect is that the effect of the temporal variability in the expected incomes comparatively to the incomes based on the reference income is more pronounced as the length of the economic analysis period, N_*, decreases comparatively to the length of the recording period, N, utilized to compute the constant mean annual production that defines the reference income. This is the case, for instance, of Castro Daire river gauging station (sample nº 9, with 59 years of records), and Cabriz river gauging station (sample nº 10, with 31 years of records). In the first sample, comparatively to the second one, the differences between the reference income and the average of the best and worst income series for both N_* of 10 and 25 years is greater. The difference between the mean annual flow depths in those two stations is almost negligible (ΔH =37mm), and, accordingly, it cannot be the reason for the difference between the incomes.

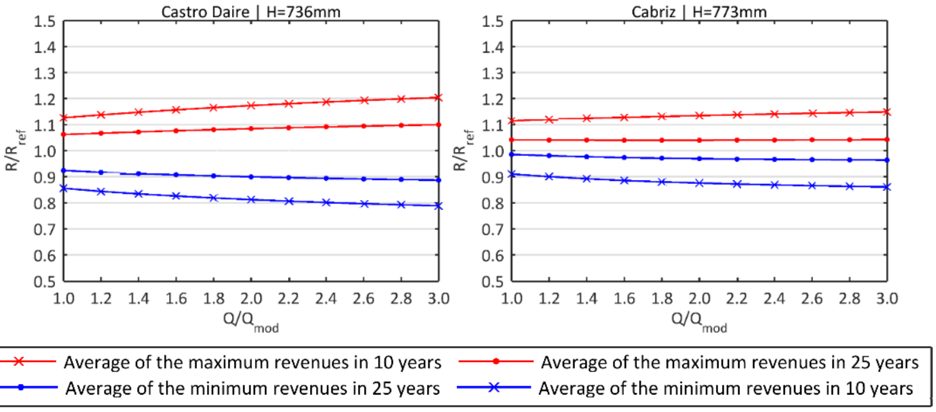

Figure 5: Average of the maximum and minimum dimensionless revenue CPV series for $N_*=10$ and $N_*=25$ years, for each Q/Q_{mod} *for the samples of Castro Daire and Cabriz. (H stands for mean annual flow depth).*

5. Conclusions

In this dissertation, it was assessed the effect of the natural streamflow variability in the expected incomes of run-of-river small hydropower schemes. Given the stochastic nature of the problem and due to previous studies that proved the good results of the method, the study utilized synthetic series.

It was developed and tested a procedure for generating annual and daily synthetic streamflow series, which encompasses a probabilistic model, namely the log-Pearson III distribution at the annual level (which prevents the generation of negative flows) and a disaggregation model, specifically, the method of fragments, at the daily level. The procedure was applied to the samples of daily streamflows at 14 Portuguese river gauging stations with different recording periods, resulting in the analysis of around 255 thousand daily flows, which were utilized to generate more than 1 billion of synthetic daily flows.

Similarly to previous studies, the probabilistic model used for generating the annual flows proved to be effective, since its application to the different samples always resulted in the preservation of all the main historical statistics.

The disaggregation model used to disaggregate the annual flows into daily flows – the method of fragments – also proved its efficiency by preserving most of the historical statistical characteristics at this time level, especially for the larger initial number of classes of fragments. The synthetic monthly flow series, obtained by the accumulation of the synthetic daily flows also ensured the preservation of most of the historical statistics, proving the additivity between daily and monthly flows without requiring any additional model.

Based on the good results provided by the model, an algorithm to simulate the daily exploitation of run-of-river small hydropower schemes was applied to both the historical and the generated synthetic daily series for different design discharges, obtaining the daily incomes that results from the selling of the energy produced in each one of those series. By accumulating, for the global period, the daily incomes, the annual incomes were obtained as well as their cumulative present values (CPV), by means of economic analysis criteria.

In each case study, the series of the CPV of the incomes has as many values as the number of synthetic flow series, plus one – the CPV that results from the sample. These series were analyzed based on the Pearson III distribution, aiming at assigning non-exceedance probabilities to the cumulative present value of the revenues.

In order to evaluate the susceptibility of the SHSs to different exploitation periods and, especially, to adverse hydrological conditions in the first years of exploitation, the aforementioned simulation was applied to two periods shorter than the global one, namely 10 and 25 years.

Due to the enormous number of synthetic series generated, the study carried out became much more general than the previous ones and allowed some new conclusions.

In what concerns the natural variability of the flow regime, it was possible to conclude that as it increases (due to the decrease in the mean annual flow depth), the variability of the expected revenues also increases, which is particularly visible as the design discharge also increases.

Nevertheless, the average of the CPV of the revenues for the different design discharges considered are of the same order of magnitude of the reference revenues for almost all case studies. Furthermore, the probability of obtaining revenues 10% bigger/smaller than the reference revenue is only 5%, which indicates a small risk when designing a SHS based on the reference revenue.

In what concerns the effect of the exploitation period on the susceptibility of SHS, it is possible to conclude that, the smaller the period of exploitation, the higher the variability of the CPV of the incomes. Even for the case studies with higher mean annual flow depths and, consequently, with more regular river regime, the revenues when considering an exploitation period of 10 years could be 20% higher/lower than the reference ones.

In a general way, it is possible to conclude that, if the period of exploitation is long enough and close to the historical one, the synthetic series do not add much information to the historical series, yielding to revenues almost equal to the reference ones. This is a direct consequence of the preservation by the models of the mean of the daily streamflows and of all the derived entities, such as the reference revenues, which only account for that mean.

Nevertheless, the analysis based on the synthetic series allows a much more detailed characterization of the temporal variability of the revenues.

So, as a general conclusion, it may be stated that the reference revenue is a good estimation for the design a small hydropower scheme with run-of-river exploitation provided that the recoding period to which the daily flows refer is long enough and close to the licensing period. However, a study based on synthetic flows series should be performed to better characterize the temporal variability of the expected incomes. This issue becomes crucial for small exploitation periods, because the consequences of the temporal variability of the river flows are no longer negligible. As the mean annual flow depth decreases, denoting a more irregular flow regime, the run-of-river scheme becomes even more susceptible.

It should be stressed that the results briefly presented for exploitation periods smaller than the recording ones only took into account average conditions. However, a statistical analysis could also be applied to the cumulative present value of the revenue series under those conditions in order to better evaluate the susceptibility of a SHS to the length of the exploitation period. This can be part of future developments of the research initiated with this thesis.

Although the present study was focused on Portuguese river gauging stations, it is believed that in other European regions, especially in the south of Europe, where the hydrological regime is similar to the Portuguese, analogous procedures may be developed in order to obtain similar type of results. Furthermore, these procedures could also be tested in countries with hydrological characteristics different from those prevailing in Portugal. It would be very interesting to apply this procedure to a real case study in order to properly compare the cumulative present value of the revenues obtained on that SHS with the ones that result from the design considering daily synthetic streamflow series. Some of the assumptions made in the current research are not realistic, as is the case of the assumption related to the selling price of the energy produced. Therefore, it would be also convenient to accomplish an analysis considering a more realistic structure for that price. For the time being this is not possible due to the lack of applicable legislation.

As a last possible, yet challenging future development, it would be interesting to explore the capability of the applied methodology to take into account some of the expected consequences of climate change. Theoretically, that could be done at the annual level, namely by applying a model capable of expressing the increase/decrease of the annual flows and/or the change in their inter annual variability. For the disaggregation model, this is, for the daily flows and their temporal variability, the subject would require extensive additional analysis.

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