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Energy generation of a small hydropower plant considering the ecological flow

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Abstract. Because of an increased care for the environment, many related EU directives were issued on this subject. The Water Framework Directive is one of that and since it was published dramatically influenced the development of new SHPPs and the operation of the existing ones. The longitudinal connectivity of rivers and the available flow downstream SHPP weirs, due to the ecological flow and changes in the way to calculate it are reasons for operational and sometime even constructive changes of the SHPPs. This paper presents some methods for assessing the energy generation of a small hydropower plant considering the ecological flow. For that purpose, 3 different scenarios were considered to determine the ecological flow, and 4 methods were used to obtain the annual energy production: the classical method, a so-called simplified method and software packages dedicated to SHPPs, CASiMiR Hydropower and SMART Mini-Idro. The obtained results indicated that the simplified method and CASiMiR Hydropower performed very well, obtaining relative errors below 1%. The assessment of losses in energy production of a SHPP due to ecological flow for Romanian legislation case is also presented for a case study.

1 Introduction

There is a huge experience in designing hydropower plants (HPPs), same related to small hydropower plants (SHPPs). In typical schemes for greenfield SHPPs, some time ago there were no preoccupations related to longitudinal connectivity of rivers, upstream fish migration, and not many designers had in mind that a certain amount of water must be continuously released downstream SHPP weir to keep the river alive, the ecological flow (EF). Both problems can be solved by providing the weir with a fish passage dimensioned for the ecological flow.

If the powerhouse of the SHPP is part of the weir and the ecological flow is significantly larger than the flow for which the fish passage is designed, one turbine can be dimensioned to have the installed capacity equal with the difference between the ecological

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flow and the designed flow of the fish passage. This is the case of most low head SHPPs. If the water goes to the powerhouse through a penstock, the SHPP can provide energy only when the available flow is larger than the ecological flow plus the minimum flow for which the turbine with the smallest installed capacity can be operated. This is the typical case for high head SHPPs.

No matter what the case is, the necessity of leaving the ecological flow and the existence of a fish passage led to a loss in hydropower generation of SHPPs.

This paper presents the classical method and a simplified method to determine the volume of water that can be used for hydropower generation in a SHPP and the related energy generation, estimating the loss of energy due to the ecological flow in the conditions of the regulations in Romania for the classical method. Results are then compared with those obtained using dedicated software.

2 Materials and method

Alternative 1

Regarding energy generation of a SHPP when no ecological flow is required, the restrictions at the operation of the plant related to the daily average flows, Q_d, are:

$$\begin{gathered} \text{if } Q_d < Q_{\min}\text{, then } Q_{SHPP} = 0 \\ \text{if } Q_{\min} <= Q_d < Q_i\text{, then } Q_{SHPP} = Q_d \\ \text{if } Q_i <= Q_d\text{, then } Q_{SHPP} = Q_i \end{gathered} \tag{1}$$

where Q are the flows, usually referred in [m^3/s], as it follows:

- $Q_{\min}$ – minimum flow for which the SHPP can be operated (due to turbines),
- Q_{SHPP} – flow used in SHPP for energy generation,
- Q_i – installed flow in SHPP turbine(s),
- Q_{ec} – ecological flow.

Alternative 2

If a certain ecological flow must be released downstream the weir of the SHPP, the available flow to be used in the SHPP for energy generation can be determined with the help of relation (2):

$$\begin{gathered} \text{if } Q_d < Q_{ec,k} + Q_{\min}\text{, then } Q_{SHPP} = 0 \\ \text{if } Q_{ec,k} + Q_{\min} <= Q_d < Q_{ec,k} + Q_i\text{, then } Q_{SHPP} = Q_d - Q_{ec,k},\ k = 1,\ldots,12\,, \\ \text{if } Q_{ec,k} + Q_i <= Q_d\text{, then } Q_{SHPP} = Q_i \end{gathered} \tag{2}$$

where $Q_{ec,k}$ – ecological flow, different values, one for each month of the year. In (2) there were supposed to be 12 values for the EF, one for each month, anticipating the related actual regulations in Romania.

The Romanian Water Law closely follows the provisions of Water Framework Directive (WFD) [1] and the technical report of the EC related to ecological flows [2]. In Romania there were 3 phases of considering the ecological flow from not considering this aspect before 1990, then defining the healthy flow as 10% from the mean flow, according to Water law [3] and ANAR methodology until 2017, since then a more complex method for calculation of the ecological flow was introduced by the Government Ordinance (GEO)

78/2017 [4] on the Methodology for determining the ecological was issued, making amendments and additions to [3], enforced by Government Decision (GD) 148/2020 [5], the result being 12 values depending on the multiannual monthly average flows.

In the last regulations it was required that the ecological flow should be dynamic and variable during a year, i.e. to have different values depending on the month of calculation, thus introducing the notion of "eco-hydrograph". A minimum analysis period of 30 years is required for the determination of the ecological flow, considering the data from the calculation section downstream of the dam and the water intakes. As a result, Article 5 specifies that the ecological flow rate will have 12 different values for each month, regardless of the year. This restriction is desired to ensure optimal conditions for achieving the environmental objectives of water bodies. With this change, the operating regulations of the hydrotechnical retention structures must also be modified to ensure these ecological flows downstream.

The case of hydrometrically monitored rivers is considered for which the multiannual monthly average flows, $Q_{mm,j}$, and the mean flow – the multiannual average flow, Q_m, are determined using the whole volume of available data and information (for a characteristic period of at least 30 years). The equation (1) represents the compute formula for the multiannual monthly average flows for month *j*:

$$Q_{mm,j} = \frac{\sum_{i=1}^{n} Q_{mm,ij}}{n}, \tag{3}$$

where *n* represents the number of years and $Q_{mm,ij}$ is the average flow for month *j*, year *i*.

Mean flow is computed with equation (2):

$$Q_m = \frac{\sum_{i=1}^{n} Q_{Qma,i}}{n}, \tag{4}$$

where $Q_{ma,i}$ represents the annual average flow for the i -th year and is obtained with the equation (3):

$$Q_{ma,i} = \frac{\sum_{j=1}^{n} Q_{mm,ij}}{12}, n = 12. \tag{5}$$

Alternative 3

Following GD 148/2020 [3] the computational calculus of the ecological flow, Q_{ec}, for each month of the year based on the $Q_{mm,j}$ of the current month in the calculation section is done as follows:

- if $Q_{mm,j} \leq Q_m \Rightarrow Q_{ec,j} = \beta_1 \cdot Q_{mm,j}$, considering $\beta_1 = 0.25 \div 0.35$, for mountain and hill typologies, and $0.2 \div 0.3$, for plain typology,
- if $Q_{mm,j} > Q_m \Rightarrow Q_{ec,j} = \beta_2 \cdot Q_{mm,j}$ considering the same interval for $\beta_2 = 0.25 \div 0.35$, for mountain and hill typologies, and $0.25 \div 0.3$, for plain typology.

Choice of β_1 and β_2 coefficients from of the above ranges shall be made according to the local conditions of the catchment corresponding to the calculation section, if the location is in a protected area and according to the habitat needs of the dominant fish species.

3 Annual energy generation of a SHPP considering the ecological flow

3.1 Classical method

The available hydropower potential of a certain sector is the hydraulic energy corresponding to the volume of water that can be used for hydropower production (VHP), so: the volume of water corresponding to that sector minus the volume required to ensure the servitude flow (VSF). The servitude flow represents the flow that must be released in the riverbed downstream an obstacle in the water for ensuring the ecological flow (VEF) and water use for existing water users downstream (VWU). Usually, the assessment of the hydropower potential is done for a timespan of one year, so the corresponding volumes of water are considered for one year, so annual values. The considered year is the mean hydrological year defined by the mean flow (the multiannual average flow), monthly flows being the multiannual monthly average flows.

Thus, the hydropower potential that can be used in a Small Hydropower Plant (SHPP) is the hydraulic energy corresponding to the VHP. The volume available for hydropower production (V_{SHPP}) can be calculated as the area under the flow duration curve of the daily average flows bounded above by the servitude flow plus the installed flow of the SHPP, and inferior by the servitude flow.

Starting from the classical formula for mechanical energy of the water:

$$E = GH \text{ [J]}, \tag{6}$$

where:
- G – weight in [N] of a volume of water, V, in [m^3],
- H – head, in [m],

it follows:

$$\begin{aligned} E &= m \cdot g \cdot H = \rho \cdot V \cdot g \cdot H = 9.81 \cdot 1000 \cdot V \cdot H \text{ [W·s]} = \\ &= 9.81 \cdot 1000 \cdot V \cdot H / 1000/3600 \text{ [kWh]} = 1/367 \cdot V \cdot H \text{ [kWh]}. \end{aligned} \tag{7}$$

where:
- $\rho = 1000$ kg/m^3 – water density,
- V – water volume, in [m^3],
- $g = 9.81$ m/s^2 – gravity acceleration,
- 1/1000 – coefficient for transforming [W] in [kW],
- 1/3600 – coefficient for transforming T from [s] in hours, [h].

The energy given by relation (7), E, represents the hydraulic energy or the theoretical linear potential. Having in mind relation (7) for the hydraulic energy, that the volume of water used for hydropower generation in the SHPP, V_{SHPP}, is the area between $Q_{ec} + Q_i$, FDC and $Q_{\min}$ on the FDC (Figure 1) and that SHPPs have usual efficiencies, η, around

70% [6], the annual energy produced in a SHPP, E_{SHPP}, can be determined with the help of the simplified practical formula:

$$E_{\text{SHPP}} = \eta \cdot E\,[\text{kWh}] = 1/367 \cdot \eta \cdot V_{\text{SHPP}} \cdot H\ [\text{kWh}] \cong 1/525 \cdot Q_{\text{SHPP}} \cdot H \cdot T_s\ [\text{kWh}], \quad (8)$$

where Q_{SHPP} represents the flow used in SHPP for energy generation and T_s – time, in [s].

The classical method is considered the method where the daily energy generation of the SHPP is calculated with relation (8) where η is the mean efficiency and Q_{SHPP} is the daily flow that can be used for hydropower generation determined with help of relations (2). Annual average energy generation is then determined as the average of the annual energies for the analysed period. The value for the energy generation determined with this method is considered the exact one and is used as reference for the other 3 methods.

3.2 Simplified method

The use of the water related to a river section where is realized the weir of a SHPP can be illustrated with the help of Figure 1, where it is represented an imaginary annual flow duration curve (FDC), and the lines corresponding to the ecological flow, Q_{ec}, to the mean flow, Q_{m}, and to the ecological flow plus the installed flow in SHPP turbine/s, $Q_{\text{ec}} + Q_i$. Notations on the figure are the same as used in equation (1).

To illustrate how to define the different forms of hydropower potential, and to highlight the different volumes of water, it is graphically represented the flow duration curve of the average daily flows in Figure 1. As the curve is flow versus time, area of the surfaces (integrals) delimitated by the different lines represents volumes of water.

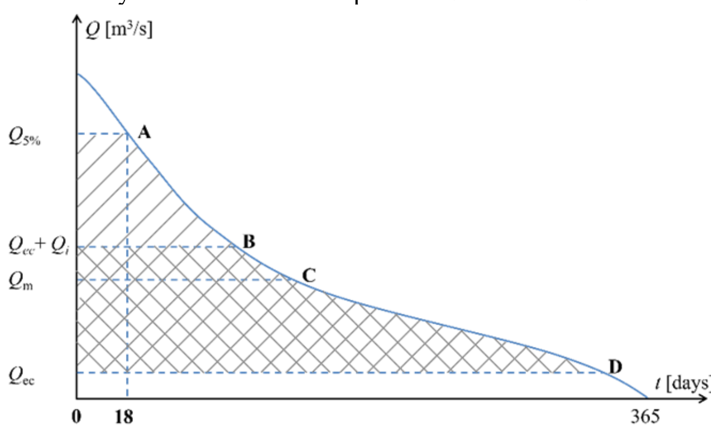

Fig. 1. Annual flow duration curve with daily inflows.

Consequently, in the mentioned river section (related to the SHPP), area of the different surfaces represents annual volumes of water as it follows:

- Under the FDC – the total volume,
- Under Q_{ec} – volume left in the riverbed downstream the weir, lost for hydropower generation (unless the powerhouse is in the weir front and one turbine is dimensioned to use the ecological flow),
- Under $Q_{\min}$ – lost for hydropower generation due to turbine limitations,
- Between $Q_{ec} + Q_i$ and $Q_{\min}$ – volume of water used for hydropower generation in the SHPP.

Annual FDC with daily inflows can be obtained in three steps: order of daily inflows for the historical period (at least 10 years, the best more than 30 years) and build the dataset for the FDC. Second step is transforming this dataset/curve for a probability of exceedance dataset/curve. Third and final step is to build the dataset/curve for the annual flow duration curve with daily inflows attributing the 365 days to 100% probability of exceedance and then determining each value on the abscissa every 5 days for example.

Evaluation of the double hatched areas on Figure 1 give the V_{SHPP} that can be used directly in relation (8). This is considered the simplified method, where the daily energy generation of the SHPP is calculated with relation (8) and V_{SHPP} as described in Figure 1.

3.3 Use of dedicated software for the assessment of SHPP

For the correct evaluation of a SHPP development various software was developed and can be used mainly for the preparation of pre-feasibility studies.

Various programs necessary for SHPP development are presented and compared by Punys et.al. [7]. Also, the main characteristics of the historic and new software tools used in the small hydro industry are described. To have an overview of this software tools, in Table 1 are presented some examples and some information like countries where it applies (Countries), if can be provided information about hydrology (H), power (P) and energy (E). As it can be seen, four of the seven programs presented have international applicability. Only RETScreen and IMP can perform a power and energy analysis for SHPP development internationally.

Table 1. Useful programs for evaluating SHPP projects [7].

Software	Countries	H	P, E	Software	Countries	H	P, E
Hydro HELP	International	-	-	Remote Small Hydro	Canada	yes	yes
RET Screen	International	yes	yes	IMP	International	yes	yes
Virtual Hydropower Prospector	USA	yes	yes	Green Kenue	International	yes	-
PEACH	France	yes	-				

In [8], a new tool for technico-economic analysis of SHPP developed in Python is described. The software tool contains seven modules (e.g. net/designed flow, net head, turbine, energy production, investment, financial and economic, and sensitivity analyse).

VAPIDRO ASTE [9] and HOMER Software [10] can represent two valuable tools for those interested in the field of SHPPs.

VAPIDRO ASTE, developed within the EU project SEE HydroPower, Clean Water, Clean Energy, is a more complex software which requires the use of ArcGis 10.0 Service Pack 4.0 with Spatial Analyst extension and VBA Macros modules [11]. It is a software that focuses on GIS analysis of a region (the area where the project is or will be implemented) to assess the remaining hydropower potential for a watercourse taking into account the analysis of hydropower abstraction, inflow and outflow scheme, as well as the application of minimum restrictions for water areas on rivers that have various uses (navigation, recreation, fishing) and that do not affect the water supply. It allows numerical calculations to be made for the assessment of potential hydropower energy and all possible alternatives in terms of future locations for hydropower plants along the river network, considering the relationship between total costs and the benefits of selling the generated energy on the national market.

Hybrid Optimization of Multiple Energy Resources (Homer) is a software developed for the implementation of microgrids and distribution systems, which can include a combination of renewable energy plants and fossil or nuclear fuel plants.

This program is considered a simulation, optimization and analysis program for hybrid systems that are or are not connected to central (large) grids. For this, optimization and analysis algorithms have been implemented, which allow economic and technical analysis to be carried out to determine technological costs, electrical load and availability of energy resources. This program is a product of the National Renewable Energy Laboratory.

3.3.1 CASiMiR Hydropower

Computer Aided Simulation Model For Instream Flow Riparia (CASiMiR) is a Microsoft Windows-based simulation model developed in the 1990s by the Institute of Hydraulic Engineering at the University of Stuttgart [12]. The initial motivation was to study the economic effects of hydropower production.

The current version of CASiMiR Hydropower, as part of CASiMiR software, allows the calculation of power and energy production for any combination of hydrographs and flow duration curves, minimum flow regulation rules, constant or flow-dependent drop and technical characteristics of the power plant, such as efficiency dependency on turbined flow and operational data [13].

In order to perform a simulation with CASiMiR certain inputs such as [14]:

- The inflow as: a constant value, duration curve for the site analysed (a dependence on an average annual non-exceedance day for certain flows), hydrograph (average daily inflows values over 1 year),
- The ecological flow as a constant value, discharge-dependent or ordered temporally (values per day over 1 year - can be a constant value even over several months, considering the season),
- The head as a constant value or discharge dependent,
- The total efficiency as a constant value or discharge dependent - total efficiency as a function of the flow through the turbine,
- The operational data as minimum and maximum flows required to operate the plant,
- The discharge during periods of high water.

The results obtained for a hydropower plant consist of calculation of annual energy production based on daily and annual parameters and calculation of financial profitability.

3.3.2 SMART Mini-Idro

On the Ricerca Sistema Energetico (RSE) website [15], in addition to VAPIDRO ASTE, also it can be found the SMART Mini Idro software, which can be downloaded free.

It is a software that doesn’t require installation, it is made in Excel in which Visual Basic functions have been implemented and commands for MACROS tools that need to be activated [16].

It is an application designed to perform a quick analysis of the main parameters of a SHPP, using the flow duration curve, the available head, the types of turbines to be or are installed, the range of flow variation.

This application allows the possibility to apply government incentives for investments such as "Green Certificates" and can evaluate the cash flow of the investment.

It provides the user with information about the investment to be made through a SHPP, as a first approach to start a preliminary project, leading to an analysis of the economic and financial parameters of a new SHPP.

The basic data used are:

• The duration curve for the site analysed,
• The available head,
• The types of turbines to be installed and their efficiency,
• The price of energy and the price of green certificates.

The results obtained for a SHPP consist of:

• The duration curve of turbine flows,
• Calculated head losses per pipeline,
• Power and energy calculations,
• Calculations of initial investment parameters,
• The "cash-flow" of the investment where green certificates have been considered.

In the work modules, an analysis can be made on the availability of flow, assessment of energy production, benefits and financial aspects of SHPP. It supports pre-feasibility studies and the requirements to run this program are minimal, requiring only the installation of Microsoft Excel.

4 Results for a case study SHPP

4.1 Data for the case study SHPP

For the application of the four methods described in section 3, a river section was chosen for which average daily flows are known. Based on these, the hydropower potential and the possible energy generation in a so-called case study SHPP was determined.

The annual FDC with daily values is presented in Figure 2.

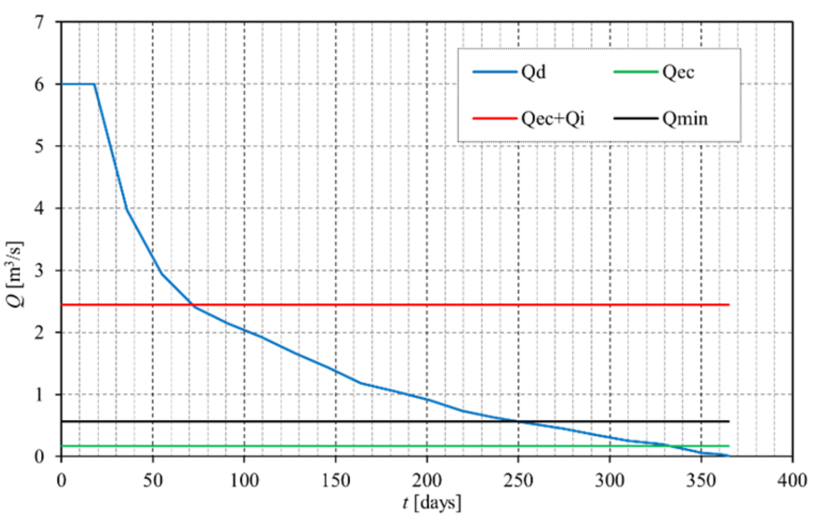

Fig. 2. Annual flow duration curve with daily inflows for the case-study SHPP.

The legend on Figure 2 is:

- Q_d – river flows in descending order,
- Q_{ec} – ecological flow,
- Q_i – installed flow in SHPP,
- $Q_{\min}$ – minimum flow that can be used by the SHPP due to turbine restrictions.

The data considered in computations for the case study SHPP are presented in Table 2.

Table 2. Data regarding the case-study SHPP.

Data	Value	Unit
Mean flow	1.76	m^3/s
Minimum flow for turbine	0.39	m^3/s
Installed flow	2.27	m^3/s
Ecological flow	0 / Table 3	m^3/s
Gross head	152.8	m
Overall efficiency	0.79	-

The two alternatives, 2 and 3, considering the ecological flow, are presented in Table 3.

Table 3. Alternatives for the ecological flow, Q_{ec} [m^3/s].

Month / Alternative	1	2	3	4	5	6	7	8	9	10	11	12
2	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17
3	0.36	0.41	0.78	0.91	0.41	0.56	0.31	0.14	0.09	0.58	0.97	0.83

There will not be detailed calculations related to the classical and the simplified methods described in sections 3.1 and 3.2. Detailed presentations on the evaluation of energy generation using two open-source software packages will be presented in the next paragraphs of this section.

The data presented in this section are the minimum data needed to calculate the hydropower potential, for example to determine the characteristic volumes of the river sector: the average volume flowing through the river cross section, the remaining available volume of the total volume and the average annual volume that can be used by the analyzed SHPP.

Table 3 shows the values of the ecological flow required to be left in the riverbed downstream the SHPP, as considered, month by month.

These values are very important because the available hydropower potential on the analyzed sector represents the hydraulic energy corresponding to the total volume of water drained on the sector and calculated as the surface area under the duration curve of the average annual flow, from which the annual volume required to ensure the ecological flow is subtracted.

4.2 CASiMiR Hydropower

One of the dedicated software is CASiMiR Hydropower that can be applied to all the three alternatives related to ecological flow. In the dedicated field for the main discharge, time series were used. In figures 3 to 5, the program interface is presented with the initial set up and with graphs for the three alternatives for the ecological flow.

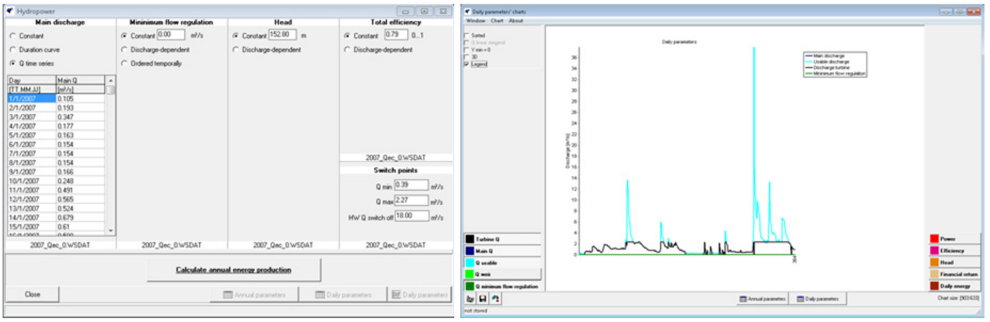

Fig. 3. Print screen from CASiMiR with the initial setup and with results, Q_{ec}=0.

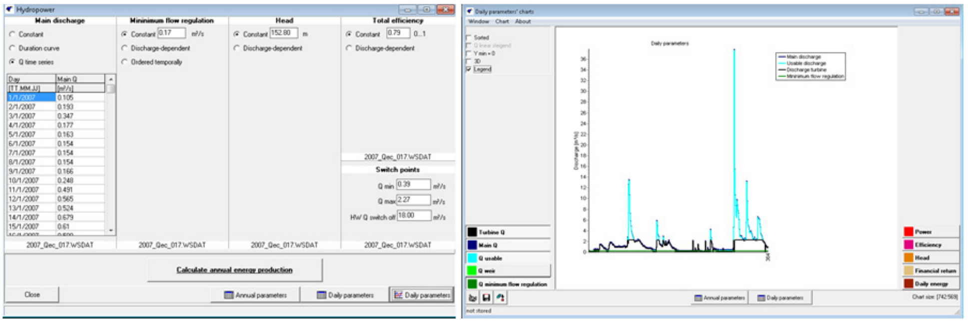

Fig. 4. Print screen from CASiMiR with the initial setup and with results, Q_{ec}=ct.

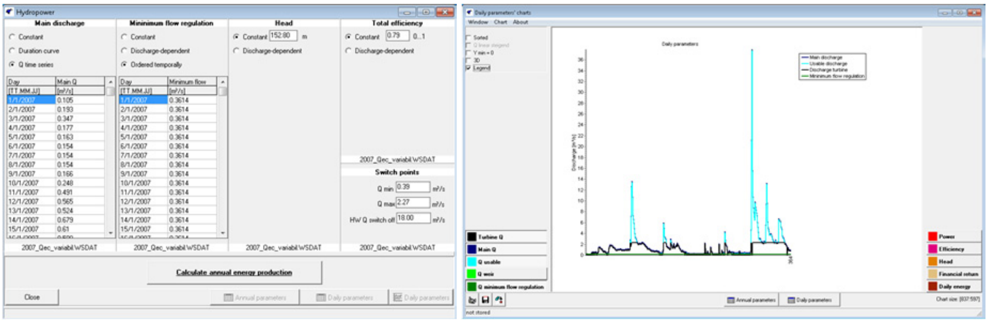

Fig. 5. Print screen from CASiMiR with the initial setup and with results, Q_{ec}=variable.

4.3 SMART Mini-Idro

The second software package applied is SMART Mini-Idro. Using the FDC, the results for no ecological flow hypothesis are presented in Figure 6.

The notations on Figure 6 are:

- MIF for the minimum instream flow, another name for the ecological flow (or environmental flow),
- Q_{diverted} for the flow used for energy generation in the SHPP.

On Figure 7 there are presented the results obtained with SMART Mini-Idro with data for the SHPP from Table 2.

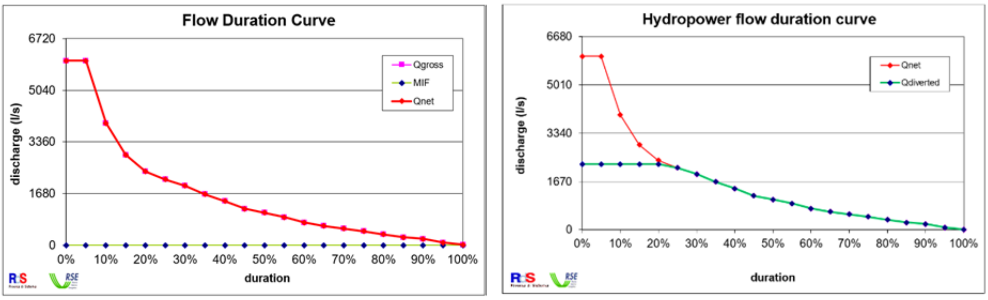

Fig. 6. FDC (left) and with flow used for SHPP = diverted (right), Q_{ec}=0.

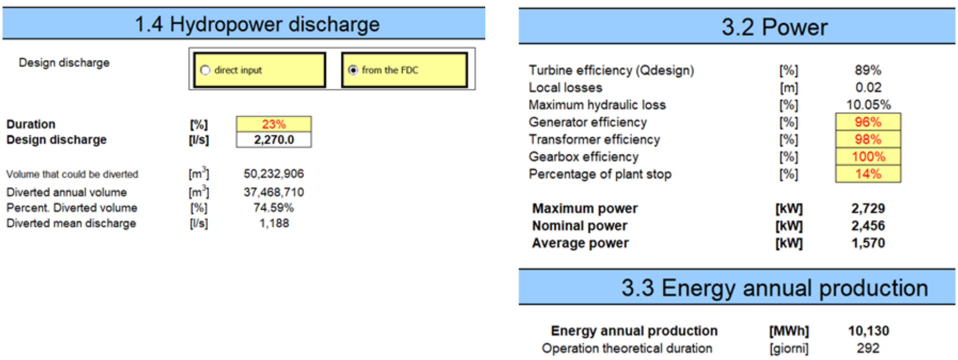

Fig. 7. Print screen from SMART Mini-Idro with results for Q_{ec}=0.

One more simulation was made with SMART Mini-Idro using as input data from FDC and as value for MIF = the ecological flow, one value determined as a percentage of the average annual inflow, Q_m , namely 10%, as a constant value, 0.17 m^3/s. The FDC and the diverted flow are presented in Figure 8.

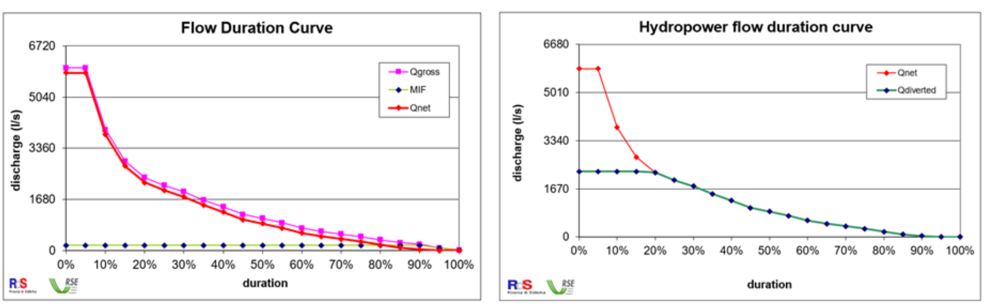

Fig. 8. FDC (left) and with flow used for SHPP = diverted (right), Q_{ec}=ct.

4.4 Results

For the case study with the characteristics presented in section 4.1, the classical and a so-called simplified method were applied for the assessment of energy generation for 3 alternatives for the ecological flow: zero, 10% from the mean flow and one value for each month corresponding to 30% of the multiannual monthly average flow. The alternatives correspond to different stages for considering the ecological flow in Romanian legislation.

The results are compared with those obtained using two traditional software packages dedicated to SHPPs, namely CASiMiR Hydropower and SMART Mini-Idro. As it is based on the FDC the simplified method doesn't allow considering different values for the ecological flow, so the computations for alternative 3. SMART Mini-Idro also doesn't have this possibility.

The annual energy generation of the case study SHPP assessed using the four methods for the three alternatives for the ecological flow are presented in Table 4. The results obtained using the 2 software packages, CASiMiR Hydropower and SMART Mini-Idro, include also the suggested installed capacity of the SHPP, 2.688 MW and 2.729 MW, respectively.

Table 4. Annual energy generation of the case study SHPP.

Alternative	**Classical method**	**Simplified method**	**CASiMiR Hydropower**		**SMART Mini-Idro**	
	Ean [MWh]	Ean [MWh]	Ean [MWh]	Pi [MW]	Ean [MWh]	Pi [MW]
Alt 1	11884	11818	11798	2.688	10130	2.729
Alt 2	10527	10489	10441	2.688	9003	2.726
Alt 3	8209	-	8123	2.688	-	-

As the classical method is the most accurate, errors related to the classical method were determined for the other three methods related to this one and presented in Table 5.

Table 5. Errors for the calculation of energy generation related to the classical method, in [%].

Alternative	**Simplified method**	**CASiMiR Hydropower**	**SMART Mini-Idro**
Alt 1	0.56	0.72	14.76
Alt 2	0.36	0.82	14.48
Alt 3	-	1.05	-

For the classical method there are determined losses in energy generation for alternatives 2 and 3 related with no ecological flow alternative 1, and the results are presented as values and percentage in Table 6.

Table 6. Classical method – losses due the ecological flow, in MWh and in [%].

Alternative	**DE [MWh]**	**DE/Ean [%]**
Alt 2 to Alt 1	1357	11
Alt 3 to Alt 1	3675	31
Alt 3 to Alt 2	2318	22

5 Conclusion

Four methods – the classical method, a simplified method based on the FDC and two dedicated software packages (CASiMiR Hydropower and SMART Mini-Idro) were used for the assessment of energy generation in a SHPP for three alternatives considered for the ecological flow: zero, a constant value and different values for each month of the year. The simplified method and SMART Mini-Idro don't allow considering different values for each month for the EF but only a constant value.

The simplified method and CASiMiR Hydropower have very good results, relative errors related to the classical method being under 1%; SMART Mini-Idro has errors under 15%.

Regarding the losses in energy generation due to the ecological flow, for the classical method, there were determined the differences in energy generation for alternatives 2 and 3 related to the alternative 1 (no ecological flow), resulting 11% and 31% respectively. This demonstrates the increase care for environmental issues related to water use for energy generation in SHPPs. The only problem is for the existing SHPPs when legislation specifies new values for the ecological flow and when constructive changes are difficult to make. From the operational point of view every increase of the ecological flow determines reduction of energy generation.

Considering the need of the ecological flow, correct planning and design of new SHPPs must consider this aspect in technical and economic calculations and in the possibility of future changes in legislation.

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