Ecological flow determination on a site-specific experimental basis – an Italian case study

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Introduction

The determination of the value of the reserved (ecological) flow to be released downstream of weirs at small (and big as well) hydro power plants has been generally made using hydrological parameters (some percentage of the mean annual flow, or of some other flow rate of given duration, etc.) possibly applying correction factors in order to take into account environmental specificity. For small ungauged sites this approach leads to well known problems connected to the lack of environmental data.

At the beginning of this century all the plants located along the Borlezza river were subject to the obligation of releasing reserved flow. The values imposed seemed to be extraordinarily high if compared with the natural mean annual flow estimated from the energy production of the plants located along the river. The operator of the majority of the plants started a long negotiation with the relevant agencies in order to modify the general rule stated for the whole Northern Italy and to try to adjust the said rule to the specific situation.

Thanks to the spirit of collaboration arisen between the parties, an experimental protocol for collecting the necessary data was signed and a four years field campaign, started in 2010.

We decided to implement continuous hydrological models for evaluating the mean annual discharge that flows in every cross-section interested by an hydro power plant and, consequently, for assessing the reserved flow amount. The main idea is to calibrate the rainfall-runoff model on the gauged catchment making use of the streamflow discharge data available at Cerete, the gauged river section, and then to transfer the model parameters to the ungauged ones with a regionalization technique; it is then possible to obtain a simulated streamflow discharge series for each ungauged section. Two conceptual hydrological models, very well known in the literature, that differ for the degree of complexity were chosen: the HBV and the HYMOD model.

The paper shows in detail the scientific and operational approach to the campaign, the difficulty in interpreting the data from the field and in applying state-of-the-art rainfall-runoff models to very peculiar hydrological situations like the one at hand. The main outcomes of the campaign are reported as well as the lesson learnt, proposing improvement actions for similar situations.

1. Background

Borlezza stream, a tributary of Iseo lake (northern Italy), was almost entirely exploited for hydropower production since the very beginning of the XX century. This paper will consider in particular five hydropower plants located along the main river reach named as shown in Fig. 1.

Borlezza catchment is characterized by a particularly complex morphology resulted from the modelling action of many morphological agents as the processes of hillslope erosion by surface runoff , glaciations and karstification among all. A clear proof of karstification can be seen in the Tinazzo gorge, located downstream Tinazzo hydroelectric power plant; moreover there are evident signs of a high degree of subsurface flow witnessed by great and not linear variations of surface flow in different river sections. Furthermore, for the purposes of this paper, it is important to remind that in the upper part of this basin there are various wells and springs that supply water to an important aqueduct.

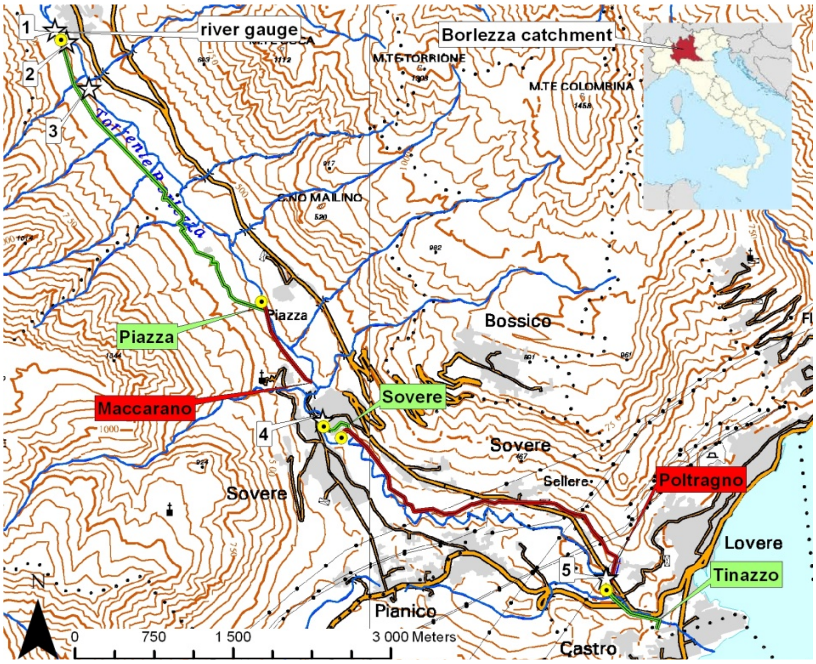

Fig. 1. Part of Borlezza stream interested by the five hydropower plants. The yellow dots symbolize the intakes position, the green and red lines show the entire plant and the white stars point out the sections identified for monitoring the river ecological status (numbered from one, the most upstream, to five, the most downstream).

In March 2003 the Po River Basin Authority issued a regulation with the basic criteria for guaranteeing the presence of the minimum ecological flow in every riverbed belonging to the Po river basin. According to this regulation the reserved flow to be released downstream of every weir is calculated as it follows:

$$\mathrm{RF} = (\mathrm{k} \cdot \mathrm{q_m} \cdot \mathrm{S}) \cdot \mathrm{M} \cdot \mathrm{A} \cdot \mathrm{Z} \cdot \mathrm{T}\ [\mathrm{l/s}]$$

where the correction parameters M, A, Z and T are possibly applied to the factor $(\mathrm{k} \cdot \mathrm{q_m} \cdot \mathrm{S})$, named “hydrologic component” (being k a parameter, $\mathrm{q_m}$ the specific mean annual discharge and S the catchment area). The correction parameters are evaluated for the specific case one is dealing with in order to account for the morphology (M), the natural value and the quality of the water flowing in the riverbed (Z), the interaction between surface and underground water (A) and the need of releasing a modulated reserved flow (T) due to particular needs during the time of the year (fish spawning, tourism, ...).

For definition the hydrologic component is the 10% of the natural mean annual discharge that flows in the considered river section while a minimum threshold of 50 l/s has always to be left to the river regardless of the size of the catchment area. The dilution parameter Q as well as all the other correction parameters are, for the moment, set equal to one as Borlezza stream is not one of the so called critical streams.

The evaluation of the natural mean annual flow rate is crucial in every ungauged river section. Borlezza stream until the beginning of 2010 did not have any measure of flow so, in order to assess the minimum flow to be released downstream of the five hydropower plant intakes considered, it was necessary to apply a regional procedure. The one suggested by a regional legislation says that, starting from the mean annual precipitation falling on the river catchment (P), it is possible to assess the mean annual discharge per unit of catchment area as $m(q) = 0{,}026 \cdot P$ [l/s/km^2] and, consequently, the flow to be released downstream of every intake ($q_{m\ regional}$). This simple approach, as well as many other regionalisation procedures, often results in imposed values of reserved flows absolutely inappropriate. A previous study, dated back to 2006 and commissioned by Bergamo Province Authority, highlighted that the regionalisation procedures applied to the Borlezza case led to values of natural mean annual flows always highly higher then what was actually flowing in the riverbed assessed starting from the energy productions (referred to the period 1990-1999) of the hydropower plants located along the river.

If one takes the ratio between the reserved flow and the mean annual flow granted by the water concession acts (q_{wc}) evaluated at every hydropower plant it is obvious that an index, for instance, of 64% (at Piazza) reflects an incorrect assessment of the natural mean annual discharge. Tab. 1 shows the same index calculated for the other hydropower plants.

The high mismatch between the imposed values of minimum flow to be released and the natural discharge assessed from the energy productions of each plant induced the plants owner to ask to the relevant agencies for a change in the general rule in order to consider the sites specificities and to define appropriate values of minimum flow both from the ecological and the hydroelectric energy producer point of view.

Hydropower plant intake	Catchment area [km^2]	m(q) [$l/s/km^2$]	q_m regional [l/s]	mean annual flow granted by the water concession q_{wc} [l/s]	$q_{m\ regional}$ / q_{wc}	$RF_{E.P.\ 1990-1999}$ [l/s]
Piazza	90,46	37,70	341,03	530	64%	68,90
Maccarano	107,33	37,70	404,63	680	60%	111,30
Poltragno/Sovere	119,54	37,70	450,67	1000	45%	155,40
Tinazzo	140,15	37,70	528,37	2900	18%	279,40

Tab. 1:Characteristics of the hydropower plants: catchment area [km^2], specific mean annual discharge m(q) [$l/s/km^2$] and the imposed reserved flow $q_{m\ regional}$ [l/s] evaluated according to the regionalisation technique described, mean annual flow granted by the water concession q_{wc} [l/s], the ratio between the imposed reserved flow and q_{wc} and the reserved flow assessed from the energy productions of the periods 1990-1999 $RF_{E.P.}$.

The operator of five hydropower plants started a long negotiation with the local agencies that led in 2010 to the beginning of an experimental protocol. An agreement between the parties was reached: the reserved flow to be released downstream of each intake for the entire duration of this experimental protocol (4 years) would have been equal to the hydrologic component estimated from the energy productions referred to the period 1990-1999 (see last column of Tab. 1). This experimentation period will have essentially a twofold aim: on the one hand the assessment of the real amount of discharge flowing in this stream is crucial while, on the other hand, it will be important to understand if the assumed released flows suffice to assure a good quality to the riparian ecosystem.

This paper will mainly focus on the first task, the assessment of the discharge flowing into the river; for this reason an ultrasonic river gauge was installed at Cerete, few meters upstream of the Piazza intake (the most upstream hydroelectric power plant), to monitor and continuously measure the stream flow rate in that cross section.

In order to pursue the second aim twice a year chemical and physical surveys as well as morphological inspections and spot measurements of discharge are carried out in four different sections of the river. In this paper we will not show many details regarding the ecological issue but we will use the inspection results to give support to the proposals we will make for each intake.

2. Materials and methods

The database available for this study consists of flow measurements, meteorological data and values of energy production for every hydroelectric power plant.

In detail daily stream flow values measured by the river gauge installed at Cerete (Piazza intake) are available starting from February the 11th 2010 ongoing, when the instrument was replaced and tested. The meteorological data consist of daily rainfall and mean temperature records collected from four weather stations in the Borlezza catchment and in its close proximities managed by ARPA Lombardia, the regional agency for environmental protection, that cover the period 1990-2013. Hourly data of energy production are available for all the power plants starting from 2008, while only for two power plants (Poltragno and Tinazzo) there exist daily data referred to previous periods.

In this paper we will make use of two different approaches in order to assess the natural streamflow at every intake: rainfall-runoff simulations and the analysis of both the measured values of discharge at Cerete and the energy production data available.

2.1. Hydrological modelling

We will use hydrologic models that, starting from rainfall and temperature records, describe the progression in time of the hydrologic variable discharge in a cross river section. The stream flow measurements at Cerete refer only to the four years period of the experimental protocol, while meteorological data span a longer interval.

We split the discharge time series in two different time series: data spanning the period 2010-2011 will be adopted for calibration purposes, while those of 2012 will be useful for validation purposes. After a previous calibration (essential for tuning the parameters to adapt the hydrologic models to this catchment and its main characteristics as morphology, geology and its response to meteorological events) and validation (useful for testing the model forecast skills) of the chosen rainfall-runoff model with the discharge data available at Cerete, we will apply the models to the period 1990-2009. In few words we will run the models to make forecasts in the past (where meteorological variables are known) in order to obtain a longer time series of flow rate useful for a more reliable estimate of the natural mean annual flow rate of Borlezza stream at Cerete.

We choose the HBV (originally developed by Bergström, 1976 and Lindström et al., 1997) and HYMOD (introduced by Boyle, 2000 and extensively used thereafter) models, two very well known rainfall-runoff models widely applied for research and practical purposes. HBV and HYMOD are both conceptual models very parsimonious as they need few input data (usually meteorological input data) and they have a limited number of parameters to be calibrated. The main difference between the models stays in the structure used for describing the hydrological processes that lead to the runoff generation on a catchment.

HBV, the more complex one, has fifteen parameters and it consists of many subroutines that account for snow accumulation and melt, interception and evaporation of part of the liquid precipitation, surface runoff and deep infiltration as well as flow propagation along the river network. There are many versions of this model as everyone can adapt it to his need; we decided to adopt the version by Parajka et al. (2007).

HYMOD model, on the other hand, is an extremely parsimonious model, provided with a low number of parameters (only five), consisting in a rainfall excess model connected to two series of linear reservoirs to simulate both the quick (surface runoff) and the slow (deep infiltration) response.

The goodness of fit of the hydrological models is measured with the Nash efficiency (Nash and Sutcliffe, 1970), an index that ranges from $-\infty$ to 1 often used to assess the hydrological simulations quality. The closer this index is to one, the better the simulation is; as this efficiency gives high importance to the high flows, in order to account for the low flows as well, we decided to evaluate the Nash efficiency of the log transformed values of flow.

We think it will be unlikely that, in this particular case, the same model will be suitable to properly reproduce the runoff generation in different parts of the same catchment. Indeed, due to the basin peculiarity, for instance the great number of wells in the upstream part of the catchment or the large amount of subsurface infiltration in some parts of it and subsequently the considerable surfacing of deep water in other parts, the hydrological processes responsible for the runoff generation interplay in a unique way in every part of the catchment. Therefore we think it will not be the case to apply the rainfall-runoff models calibrated with discharge values measured in the most upstream cross section of the Borlezza stream to downstream cross sections of the same river.

2.2. Data analysis

The other important source of information is the dataset of energy productions available for every hydroelectric power plant. There exists a quite long series of daily energy data that covers a period of at least 12 years for Poltragno and Tinazzo plants, while Sovere and Maccarano plants have only yearly data for the same period, in addition to the hourly energy data since 2008 for every plant. The natural mean annual discharge will be then derived, for the Poltragno and Tinazzo plants, from the energy productions, while other considerations will be useful for Sovere and Maccarano cases.

Knowing the main characteristics of every plant like the gross head, the minimum and maximum technical flow of turbines, the mean annual flow granted by the water concession, the total efficiency of the power plant one can easily convert the daily (or hourly) time series of energy production in mean daily (or hourly) time series of plant discharge. Considering the values of both plant discharge and reserved flow (that occasionally changed during the life of the plants) it is possible to evaluate the natural discharge flowing in the riverbed in periods of medium and low flows. On the contrary, when the turbines reach their maximum flow, it is not possible to carefully assess the amount of discharge flowing in the stream.

The natural flow duration curve can be approximated with a three parameters Weibull distribution, as suggested by Paoletti et al. (1999), as it follows:

$$q = \varepsilon + (\lambda - \varepsilon) \cdot \left[-ln\left(\frac{\theta}{365}\right)\right]^{\frac{1}{\beta}}$$

where q is the specific flow rate [l/s/km^2], ε and λ are parameters [l/s/km^2] while β is a dimensionless parameter. Paoletti et al. (1999) in their study provided different sets of value for the three ε, λ and β parameters estimated in various cross river sections of the Lombardia region water courses directly using the time series of measured natural flow. As Borlezza stream was not considered in that study the evaluation of the three parameters is performed by adapting the Weibull distribution to the "natural" values of flow derived from the energy productions, making use of the Genoud optimisation algorithm (Mebane and Sekhon, 1998).

Additional reflections are needed for the evaluation of the natural mean annual flow available at the intakes of Sovere and Maccarano plants and will be discussed in the following sections.

3. Results and discussion

3.1 Hydrological simulations

HBV simulations quality is quite poor both in calibration and in validation. This means that the model can't properly mimic the processes that drive to the discharge generation on this catchment. As HBV is not able to well reproduce the observed flows at Cerete we can't rely on it for simulating the hydrology of Borlezza stream before 2010.

HYMOD model, despite its simpler structure, is able to better reproduce what happens on the basin; in calibration, particularly, we can see a good agreement between the simulated and the observed low flows both at a visual inspection and from the value of Nash efficiency calculated on log transformed flows equal to 0,75. For high and peak flows HYMOD simulations give satisfactory results as well; the Nash efficiency evaluated with flow values not transformed reaches a value of 0,68 which is still quite good.

On the contrary HYMOD forecasting abilities are not so good. As one can see from *Fig.* 2 (upper panel) the simulated values of discharge almost always underestimate the flow time series observed in Borlezza stream at Cerete. HYMOD unreliability in validation is measured with low values of the Nash efficiency (a negative value of this index calculated with log transformed discharges and a close to zero value for the not transformed ones).

It often happens that a rainfall-runoff model is not able to mimic the dynamics of a basin and this is as much true as the model structure is complex. So there is absolutely nothing surprising about HBV inability to simulate the flows of Borlezza stream both in calibration and in validation.

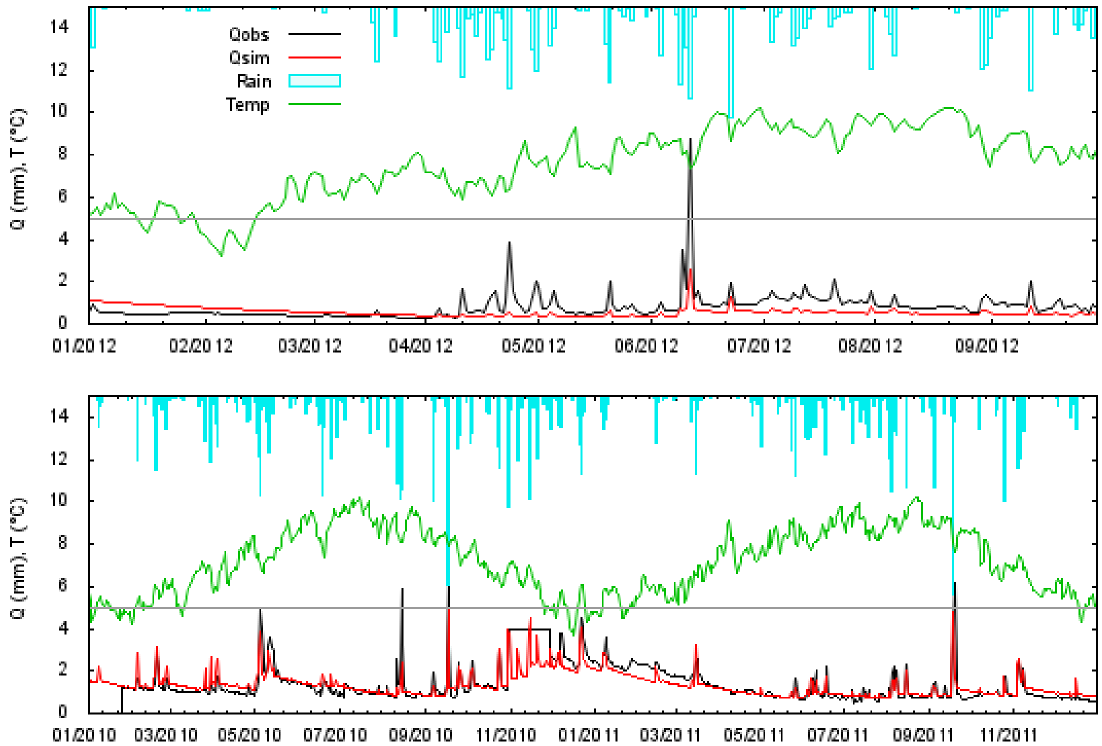

Fig. 2. HYMOD hydrological simulations applied to the Borlezza stream at Cerete in calibration (at the bottom) and validation (at the top): measured values of discharge (in black), simulated discharges (in red), mean daily temperature (in green) and cumulative daily values of rainfall (in light blue) mediated across the catchment.

HYMOD model structure simplicity gives it the ability of well simulating Borlezza catchment hydrological processes instead, but only in calibration. In this phase the best model parameters values are chosen in order to transform, with mathematical equation systems, the meteorological input data in flow simulations that have to be as close as possible (in every single moment) to the observed values of discharge actually measured in the Borlezza riverbed at Cerete. The model equations parameters choice takes place continuously comparing the simulated time series of flow with the ones measured by the stream gauge using automatic optimization algorithms. HYMOD, with the optimal parameters set chosen, is therefore suitable for fairly describing the local precipitations transformation into river flows during the period 2010-2011. In some way the simple model structure adjusts itself to the highly intricate catchment morphology and its particular way of responding to the meteorology of that time period, somehow mediating the effects of groundwater withdrawal.

Once the parameters have been fixed, the hydrological model has been definitively chosen; in validation one feeds the model with meteorological input data completely new in order to test the prediction skills of the model still having the possibility of comparing the simulated discharge time series with the observed ones not previously used for tuning the model. In this case the validation period was the year 2012 but HYMOD doesn't give a correct representation of the hydrologic processes.

There can be many reasons contributing to this failure. For instance at the very beginning of the validation period there is a long time with low precipitations (three months) that did not appear in calibration and for which the model did not learn how to react; furthermore we presume that a three years time series of measured runoff, that has to be divided in two for calibration and validation purposes, doesn't suffice for preparing an hydrologic model that reliably accounts for all the complex hydrological, morphological and human made processes that interplay in this basin. Obviously, the longer the period for calibration purposes is, the better the model suits to the hydrological processes, as with a longer time of tuning the rainfall runoff model can experience a high variety of hydrologic conditions.

It is therefore obvious that, at this stage, with the data we have at hand, we can't count on these rainfall runoff models for deriving information about Borlezza stream flows from the meteorological data of the past years.

3.2 Data analysis

In the following sections we will present few considerations in support of the ecological flow value we propose for each power plant.

<u>Piazza:</u>

A preliminary inspection of the meteorological data highlighted that the precipitation values measured by the four weather stations considered for this study in the period 2010-2012 substantially match the historical mean annual precipitations evaluated in the same catchment. We assume that, if the rainfall values reflects the mean meteorological conditions, therefore the measured runoff values in the same time lag are representative of the mean historical discharge conditions as well. As a mean annual discharge of 1200 l/s can be estimated from the measured values the hydrological component is equal to 120 l/s and therefore an ecological flow of at least 120 l/s should be released from the intake according to the general rule previously discussed (considering the correction factors equal to one).

At this stage, after three years of field campaign, the results of the biological and ecological analysis give us support to propose for the future to keep the same value of the ecological flow that is released from Piazza intake nowadays (68,90 l/s). Indeed the degree of water pollution estimated in every monitoring station along the Borlezza stream is substantially good; this is judged, according to the European directive 2000/60/CE, considering the N-NH4, N-NO3, P concentration as well as the amount of oxygen dissolved in water. From the biological point of view, according to the EBI index (Extended Biotic Index) evaluated only in the monitoring stations number one and three, the water quality is fairly good. In addition with a fish monitoring program a well developed community of brown trout is observed in the station number three; it consists of a good number of individuals spanning all the age classes, meaning that the ecological flow that is now released from Piazza intake supports healthy river ecosystems conditions.

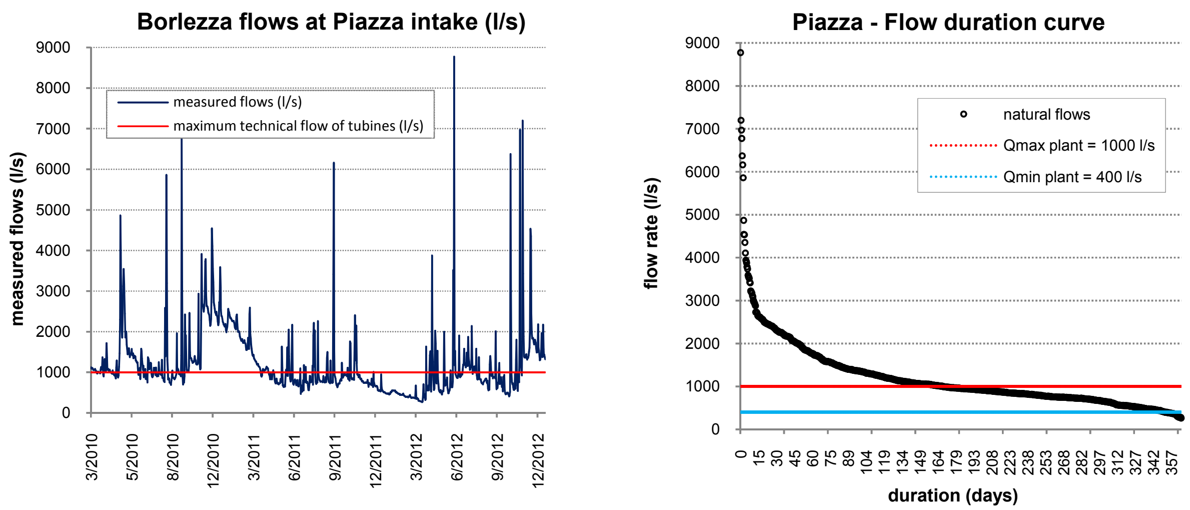

Fig. 3. On the left, the measured values of discharge at Cerete and the maximum flow turbine (in red) of Piazza power plant. On the right, the flow duration curve of Borlezza stream at Cerete and the maximum (in red) and minimum (in blue) flow turbine of Piazza power plant.

Furthermore, on average, for more than 150 days a year a natural discharge greater than the rated flow of the turbine flows into the stream immediately upstream Piazza intake, as one can see from the Fig. 3. This means that the discharge that exceeds the rated flow of the turbine remains in the riverbed and, downstream of this intake, there is a total flow which is greater than the ecological flow except for the low flow periods. It is worth underlining that the natural variability of river flows is still guaranteed as the water excesses span the whole hydrograph (see Fig. 3).

Poltragno and Tinazzo:

The amount of reserved flows released from the intakes of Poltragno and Tinazzo hydropower plants changed in the past years. Poltragno intake from 1990 to 2005 did not release any ecological flow while, starting from 2010, the reserved flow is equal to 155 l/s. On the other hand Tinazzo reserved flow history was a little bit more complicated: till 1999 it was null, then in the years 2006-2007 it was 63 l/s, in 2008-2009 it was increased to 528 l/s while from 2010 is equal to 279 l/s.

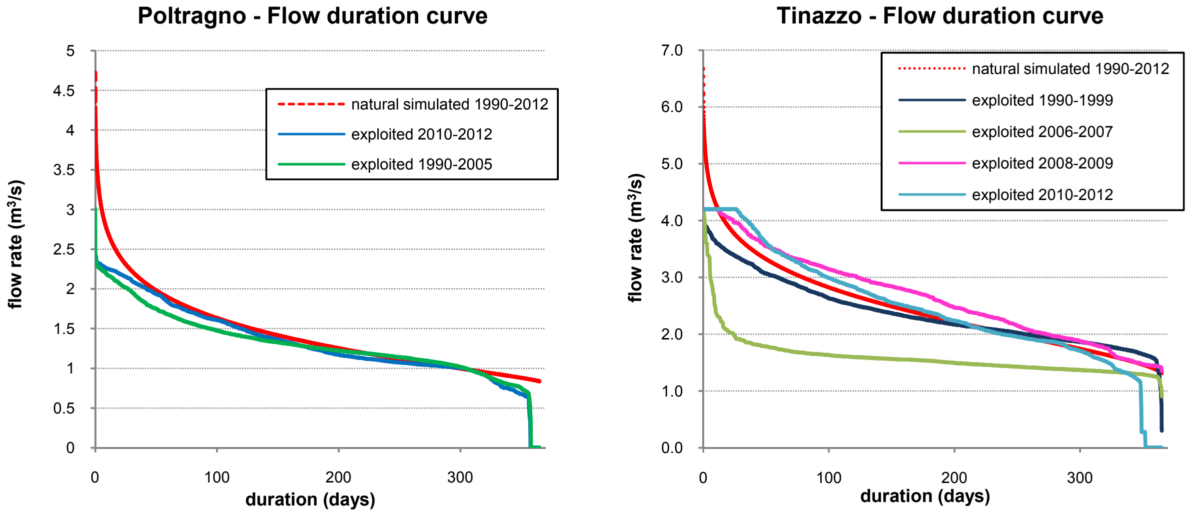

Fig. 4. Natural (in red) and exploited (various colours) flow duration curves evaluated from the energy productions of Poltragno and Tinazzo power plants.

For every period of constant ecological flow we evaluated a simulated flow duration curve of the plant (as shown in Fig. 4). Then for assessing the simulated natural flow duration curve, the different plant flow values were all referred to the same conditions, taking into account the reserved flow amount variability during the years.

A natural mean annual flow rate of 1441 l/s and 2460 l/s was therefore assessed for Poltragno and Tinazzo intakes respectively starting from the simulated natural flow duration curve. Consequently we suggest to quantify the ecological flow to be released from these intakes as the 10% of the assessed mean annual natural flow which gives, for Poltragno a value of 144 l/s and Tinazzo a value of 246 l/s.

Sovere:

Sovere plant tailrace channel discharges directly into the canal following Poltragno intake; moreover Poltragno intake is less than 400 m. downstream Sovere intake and none tributary flows in between, meaning that the river flows at Sovere and Poltragno intakes can be considered equal.

Therefore we propose to release from Sovere intake the same amount of discharge evaluated for Poltragno intake, equal to 144 l/s.

Maccarano:

We do not have any time series of measured natural flow for Borlezza stream at Maccarano intake; moreover apart from the hourly time series of energy productions available for the period 2008-2012 we only have yearly values of energy productions for the past years that can’t be of any help for our analysis.

Having so few data we can’t recur to the methodologies of analysis previously described, so we can simply make few considerations: as a result of the first three years field campaign it is possible to conclude that the stretch of stream downstream Maccarano intake can be considered of good quality. This is the main support to the suggestion of considering as ecological flow the same that is released nowadays (111 l/s).

4. Conclusions

As the rainfall-runoff models we choose were not able to properly describe the runoff generation at Piazza intake we decided to make use of the measured values of flow rate (at Piazza) and to study the dataset of the energy productions available. Thanks to the flow rate data measured at Piazza intake it was possible to evaluate the hydrologic component of the ecological flow to provide downstream the same intake. Supported by the ecological and biological monitoring results, we can then justify the idea of maintaining the same reserved flow that is released nowadays. With the energy production data we assessed the natural mean annual flow value of Borlezza at Poltragno and Tinazzo intakes, while additional observations were useful for Sovere and Maccarano plants.

The experimentation main aim is that of defining reasonable values of minimum flow from the hydroelectric energy and the ecological point of view. The presence of a well organized fish population and the good ecological status of the river water along the stretch monitored prompted us to propose continuing to maintain substantially the same ecological flows released nowadays.

According to the Po River Basin Authority the ecological flow is defined as the flow, to be found in a watercourse downstream of a water diversion, that guarantees basic quality and basic conditions of functionality to the interested ecosystems; therefore we can conclude that at Piazza intake, the only cross section for which measured flow data are available, the evaluation of the ecological flow as a value greater or equal to the 10% of the natural mean annual flow overestimates the minimum flow rate that fulfils the criteria stated by the Po River Basin Authority itself. The ecological and biological monitoring inspections give rise to the fact that, in this particular case, a flow rate of 68,9 l/s (which is less than 6% of the natural mean annual flow) to be released downstream the intake supports healthy river ecosystems conditions. This is an example of how the formulas mainly based on hydrologic considerations that don't consider the site specificities or that use correction factors always only greater than one can sometimes lead to unsuitable values of reserved flow.

The choice of placing a single river gauging station on the Borlezza stream stretch interested by the experimental campaign was probably improper. The complex morphology of this catchment, and hence the highly non linear variations of surface flow in different river sections, would probably have required a greater number of gauging stations in order to properly describe the hydrology of this stream. The high costs to be born for such a detailed campaign imposed a tradeoff between accuracy and feasibility.

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