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The Application of Environmental Flow Regulations to Small Hydropower Plants in Alpine Areas

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ABSTRACT: within a framework of conflicting needs and under water scarcity scenarios, environmental issues are assuming more and more relevance in water cycle management. An important role in this context is played by the minimum discharge release downstream of diversion structures, the so-called “environmental flow”, aiming at assuring acceptable ecological conditions along natural watercourses. In this paper the regulation criteria adopted in several European alpine countries will be briefly discussed. The implementation of environmental flow regulations to small hydropower plants in the province of Brescia (Northern Italy), which is one of the most relevant Italian district in terms of number of hydropower plants, installed capacity and energy production, will be presented. In particular, the prevailing environmental flow release devices and their main technical characteristics, operating features and design criteria are briefly discussed. The introduction of environmental flow legislation entails both benefits and disadvantages which are often difficult to quantify. This paper gives a contribution to this costs-benefits analysis, by estimating the loss of energy producibility for a small alpine hydropower plant, related to the enforcement of environmental flow regulations and to the design criteria of the release devices.

Keywords: Alpine hydropower plants, Energy production, Environmental flow, Loss of producibility.

1 INTRODUCTION

According to the Water Framework Directive 2000/60/CE (European Parliament, 2000), the water cycle has to be managed with a catchment-wise approach. In this context, the Directive remarks the importance of the release of environmental flow, also identified as “minimum” or “ecological” flow, defined as “the water regime provided within a river, wetland or coastal zone to maintain ecosystems and their benefits where there are competing water uses and where flows are regulated” (Dyson et al, 2003). Accordingly, environmental flow prescriptions do not necessarily aim to bring stream ecosystems back to their original condition; rather, they aim to a re-regulation of the existing water uses in order to match with ecological goals. Adequate quantity, quality and timing of flow are the founding elements of such rules, which prove really effective only when included into a wider catchment governance background. The compliance with such criteria introduces both detriments and benefits, the latter being hardly quantifiable, since they are related to recreational opportunities, economical activities, increased water quality (e.g., pollutant dilution) or cultural aspects. On the contrary, detriments are often well measurable, because direct and opportunity costs are a consequence of needed structural adaptation and of reduced earnings from water use (e.g., Ranzi et al., 2009). In particular, in the case of hydropower, the additional environmental cost of increased request of fossil fuel due to the reduced hydroelectric production should not be disregarded. In order to find a match point between these conflicting aspects, a costs-benefits analysis may be a starting point that accounts for both stream quality objectives and water uses (Dyson et al., 2003; Richter & Thomas, 2007).

Environmental flow quantity and timing definition are related to the hydrologic, physical and biotic characteristics of the stream. Accordingly, the discharge value in itself may not be adequate to protect the ecosystem if other hydraulic parameters (e.g., wetted perimeter and velocity) are not considered (e.g.,
Kumar et al., 2007); moreover, all these variables are constrained by the biotic species to be preserved. Accordingly, there is a progression from low to high level assessment methods: hydrological, hydraulic, microhabitat and holistic (Rebillard, 2006). In general, the most efficient way to handle this issue is case by case testing based on local hydrological, morphological and ecological status (e.g., APER, 2006, Gollessi & Valerio, 2007).

Although Small Hydropower Plants (in the following, SHP) have a lower impact on the hydrologic variability of a watercourse than reservoirs (APER, 2006; Richter & Thomas, 2007), nevertheless they have to be built, or adapted, and managed in order to release downstream the suitable environmental flow discharge and to preserve the continuity of the stream (e.g., through fish passages). The operation of these devices is usually based on the respect of a minimum design depth, computed using energy balance principle, that guarantees the release of environmental flow before any water diversion. A proper design of the release devices makes possible to cope with seasonal variability and future adjustments of regulations (e.g., Ferri et al., 2004), reducing at the same time obstructions by sediments and floating debris. A relevant issue in SHP is related to the natural flow variability of the stream, that induces level fluctuations upstream of the barrage, leading in turn to an increase of the released ecological flow. Accordingly, where it is not possible to apply electronic or mechanic self-regulating devices, incremental production losses can be expected and frequent human maintenance is needed.

Moving from these considerations, in this paper environmental flow application in province of Brescia will be considered; the province of Brescia is a wide area (4,784 km$^2$) located in the northern part of Italy, that, with its 2181 MW of installed hydroelectric power (12.2% of the national total) and 2863 GWh of energy production (5.6% of the national total), ranks second in terms of national installed power and fifth in terms of production (GSE, 2009 and 2010). In particular we shall focus our contribution on existing SHP with an installed power lower than 3 MW and low head barrages (<15 m), with specific attention to the devices used for the discharge release and the related hydraulic design criteria. As a specific case, an alpine SHP has been studied in order to assess the energy production loss due to the introduction of environmental flow rules, comparing the increase of production obtainable with an ideal device that releases no more than established outflow, with respect to the production achievable with ordinary devices whose release varies as a function of water level fluctuations.

2 ENVIRONMENTAL FLOW REGULATIONS IN THE ALPINE REGION

In the following, a review of regulations of European alpine States regarding environmental flow release from barrages will be presented, in order to identify a common methodology based on simple hydrological criteria with further hydraulic and ecological assessments.

2.1 Austria

According to the Federal Austrian regulation, the *ecologically-required minimum discharge level* (NQ$_{\text{Residual flow}}$) is defined on the basis of hydrological criteria to be coupled with hydraulic and ecological elements. Three conditions may satisfy the requisites for a good hydromorphological status of a stream:

– the permanent minimum flow is greater than the *natural lowest daily minimum flow* (NQ$_{\text{t natural}}$);
– the permanent minimum flow is equal at least to one third of the *natural mean annual minimum flow* (MJNQ$_{\text{t natural}}$, which for the Austrian territory is closely correlated to the discharge exceeded 95% of time – e.g., Laaha & Blöschl, 2007) in streams where NQ$_{\text{t natural}}$ < 1/3 MJNQ$_{\text{t natural}}$;
– the permanent minimum flow is equal at least to one half of the *natural mean annual minimum flow* (MJNQ$_{\text{t natural}}$) in streams where NQ$_{\text{t natural}}$ < 1/2 MJNQ$_{\text{t natural}}$ and a mean discharge lower than 1 m$^3$/s.

The parameters involved in this procedure has to be calculated from datasets that ideally cover at least the last ten years. Beside this hydrological requirement, water depth, flow velocity, thermal condition and oxygen disposability constraints have to be fulfilled; in particular, a minimum velocity of 0.3 m/s and a minimum water depth ranging from 0.1 m to 0.3 m are suggested (Republic of Austria, 2010).

2.2 France

Minimum flow releases are regulated by the Ministre of Ecology, Sustainable Development and Energy through the Environmental Code (art. 214-18) (Gouverne de France, 2012); this duty is compulsory for each new structure and has to be fulfilled by existing barrages or dams by January 2014. The minimum
flow to be released by diversion structures in each watercourse is a function of the mean annual discharge, calculated as the average value of at least five years data. The release must be equal or greater than 10% of the mean annual flow; for rivers with an average annual discharge of 80 m³/s or greater, this contribution can be reduced to 5%. This exception can be applied also to reservoirs assigned to supply the high power request peaks. A variable distribution in time of minimum flow is possible unless the mean value obeys the general principle and the minimum value is at least 1/2 of the uniform minimum flow.

2.3 Italy

The Italian regulation of environmental flow is based on the Ministerial Decree 28 July 2004 that states general definitions and guidelines, while the specific procedures for the definition of environmental flow values have to be given by regional or local water authorities. Since several different approaches characterize the Italian territory, in the following only some of the most representative ones in the alpine area will be briefly described.

2.3.1 Po river Water Authority

The Po river Water Authority (Autorità di Bacino del Fiume Po, 2002) suggests a parametric relation to calculate the environmental flow discharge \( DMV \) [l/s]:

\[
DMV = k \cdot q_{mean_y} \cdot S \cdot M \cdot Z \cdot A \cdot T
\]

where \( k \) [-] is an experimental parameter to be defined for each hydrographic area as a function of the watershed surface, \( q_{mean_y} \) [l/s/km²] the mean annual specific discharge, \( S \) [km²] the catchment area, \( M \) [-] a morphological parameter (from 0.7 to 1.3), \( A \) [-] a coefficient between 0.5 and 1.5 that represents the interaction between surface water and groundwater, \( T \) [-] the environmental flow timing, \( Z \) [-] the maximum value assumed by the naturalistic, fruition and quality parameters, which are all dimensionless and equal or greater than 1. The product of the first three parameters gives the “hydrological factor” to be released by the end of 2008, while the “corrective” parameters have to be applied by 2016 for existing structures. The regional Authorities within the Po river basin have to define both the hydrological and the corrective parameters. In particular Regione Lombardia (2008), which enjoins a minimum release of 50 l/s for new withdrawals in mountain watersheds, suggests \( k=0.10 \) and provides two methodologies for the determination of \( q_{mean_y} \) through regionalization procedures or stream gauging measures; the corrective parameters are not defined yet. Regione Piemonte (2007) provides similar approaches for the definition of \( q_{mean_y} \) while allows different values of \( k \) factor (from 0.07 to 0.15); moreover, the assessment of \( M \) and \( A \) parameters is already available. Finally, Regione Valle d’Aosta (2006) provides \( k \) values as function of the basin area; here the definition of the corrective parameter has been completed except for the factor \( A \).

2.3.2 Autonomous Province of Bolzano

The autonomous Province of Bolzano demands a minimum specific discharge from 2 l/s/km² to 4 l/s/km², to be increased in case of specific environmental needs. An additional variable percent (from 3% to 25%) has to be applied depending on the natural flow values and the basin area, as to guarantee the natural discharge variability (Provincia Autonoma di Bolzano, 2010).

2.3.3 Autonomous Province of Trento

The autonomous Province of Trento provides, for each basin, the value of specific environmental flow to be released downstream each new diversion structure and its seasonal variability; the demanded release for existing withdrawals is 50% of the provided value, but not lower than 2 l/s/km² (Provincia Autonoma di Trento, 2005).

2.3.4 Regione Veneto

For the regional areas into the Po river catchment the mean specific discharge \( q_{mean_y} \) is 30 l/s/km², the experimental parameter \( k \) is 0.14 and no corrective coefficients have to be applied. For the Piave river basin, specific environmental flow values have been identified by the Alto Adriatico Water Authority (Autorità di Bacino dei Fiumi dell’Alto Adriatico, 2007). For all the remaining streams in the Regione Veneto (2012) a specific discharge of 4 l/s/km² or 3 l/s/km², depending on the basin area, must be applied.
2.4 Switzerland

The Swiss Confederation (1991) defined the environmental flow release criteria into the Water Protection Act (art. 30-32), where minor and major withdrawals are distinguished. With regard to the former, the maximum amount of total withdrawn discharge has to be less than 20% of $Q_{347}$ and 1000 l/s. For the major diversions the hydrological criterion described in Table 1 has to be followed. In case water quality cannot be complied with existing wastewater discharges or water depth does not allow free fish migration (e.g., lower than 20 cm), the minimum flow has to be increased. On the contrary, ecological flow can be reduced for water bodies with low ecological potential or in case of emergency situations.

Table 1. Swiss minimum flow criterion

<table>
<thead>
<tr>
<th>$Q_{347}$ classes</th>
<th>minimum flow</th>
<th>additional release to the minimum flow values</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_{347}$ up to 60 l/s</td>
<td>50 l/s</td>
<td>for each additional 10 l/s of $Q_{347}$ add 8 l/s</td>
</tr>
<tr>
<td>$Q_{347}$ up to 160 l/s</td>
<td>130 l/s</td>
<td>for each additional 10 l/s of $Q_{347}$ add 4.4 l/s</td>
</tr>
<tr>
<td>$Q_{347}$ up to 500 l/s</td>
<td>280 l/s</td>
<td>for each additional 100 l/s of $Q_{347}$ add 31 l/s</td>
</tr>
<tr>
<td>$Q_{347}$ up to 2500 l/s</td>
<td>900 l/s</td>
<td>for each additional 100 l/s of $Q_{347}$ add 21.3 l/s</td>
</tr>
<tr>
<td>$Q_{347}$ up to 10000 l/s</td>
<td>2500 l/s</td>
<td>for each additional 1000 l/s of $Q_{347}$ add 150 l/s</td>
</tr>
<tr>
<td>$Q_{347}$ greater than 60000 l/s</td>
<td>10000 l/s</td>
<td>------------------------------------------------</td>
</tr>
</tbody>
</table>

An approach similar to the Swiss one has been followed by the Friuli Venezia Giulia Regional Water Authority (Italy), where the suggested values in Table 1 are multiplied by the factor $CL$ [-] which is a function of the distance $D$ [km] along the water course between the withdrawal and the tailrace: $CL = 1 + 0.075 \cdot D$ (Autorità di Bacino Regionale della Regione Friuli Venezia Giulia, 2007).

Finally, according to several regulations, the established value of the ecological flow release from barrages has to be clearly displayed in correspondence of each diversion structure and the minimum water level in compliance with the environmental flow release should be shown on a staff gauge properly located upstream of the barrage in order to ease the control.

3 THE RELEASE OF ENVIRONMENTAL FLOW FROM LOW HEAD STRUCTURES: THE SITUATION IN PROVINCE OF BRESCIA

The province of Brescia is one of the most important Italian areas in terms of installed hydropower capacity and production. Because of the morphological complexity and economic relevance of the territory, both low and high head power plants and diversion structures are present; in the following, due to space constraints, only SHP will be considered.
In the province of Brescia 6 homogenous zones can be identified (Figure 1a): the alpine valley along the Oglio river (Valcamonica, 34% of SHP present in the whole Province), the alpine valley along the Mella river (Valtrompia, 16% of SHP), the alpine valley along the Caffaro and Chiese rivers (Valsabbia, 19% of SHP), the area directly drained by Iseo lake (4% of SHP), the area directly drained by Garda lake (13% of SHP) and the floodplain area in the southern part of the province (13% of SHP). In the whole district, about 90 low head weir SHP can be found; among them, 70 have an installed capacity between 100 kW and 3 MW while 4 are enclosed into the pico-hydro class (<5 kW) (Figure 1b). According to the gross head classification (ESHA, 2004), the distribution appears equilibrated, with low and high head SHP numerically quite equivalent and only few medium head SHP (Figure 1c). According to the morphology of the territory, Valcamonica is characterized by the maximum value of the mean geodetic head (Figure 2a). On the contrary, in the floodplain, in Valsabbia and in Valtrompia, the higher values of withdrawn discharge are registered (Figure 2b). Finally, the peak value of the percent distribution of mean annual potential energy production (37%) is concentrated in Valcamonica, because of the elevated number of high head plants, whilst the lowest percentage is located in Valtrompia and in the areas surrounding the lakes (each one contributing with 7%). An intermediate situation characterizes Valsabbia (27%), where many low head plants with considerable discharges are located, and the floodplain (15%), with few low head plants with large discharges.
The most widespread barrage typologies, among SHP in this district, are low head gates and gravity weirs with lateral intakes or drop (especially tyrolean) intake. The first category is peculiar of the floodplain areas and of the lower part of Valsabbia and Valtrompia, while gravity weirs are common devices in high head plants of Valcamonica. According to national and local regulations, each new or existing barrage needs equipments for the release of environmental flow. Generally three main outflow solutions may be identified: gates, weirs and orifices. The first type of release can occur under gates opened in the barrage and sediment flushing gates in gravel or sand desilting basins; while the first group is peculiar of SHP with large diverted discharge and related ecological flow values, the second class is indifferently widespread. Weirs, often in thin plate, are usual outflow devices especially where fish passages are present; in particular, these solutions can be coupled with gate releases in order to reduce fish ladder dimensions. In many plants, especially in alpine basins where a small ecological flow discharge is required, this is often released from orifices opened within existing gates. Figure 3 shows the percentage distribution of release devices for SHP in Brescia district.

**CONSIDERATIONS ON THE DESIGN OF ENVIRONMENTAL FLOW RELEASE DEVICES**

Due to its simplicity, the most widespread solution is the release of ecological flow under gates, because it does not require additional intervention in existing structures. This approach is often favored by the plant manager because it guarantees high flexibility with respect to the annual release trend and to possible adjustments by the Authorities, also contributing to a gradual self cleaning effect of the area upstream of the barrage where sediment clogging could be a problem. On the other hand and for the same reason, these structures are extremely prone to obstructions, especially if the transport of coarse sediment is relevant. For this reasons, release under gate is in our opinion seldom acceptable because it is difficult to guarantee a total cleaning of the gate opening. Moreover, in many situations the theoretical clearance under the gate would be only few centimeters high or even less: in these cases it is doubtful whether ordinary gates mechanics allow this level of precision, especially if no electronic controls are installed. In any case the installation of mechanical blocking systems to guarantee the minimum required opening and an appropriate maintenance program to ensure the respect of ecological flow release are needed. Free
surface outlets (e.g., weirs, sector gates, etc.) can be considered very effective devices to be designed on the basis of weirs efflux law or free surface flow theory; the risk of obstruction is usually limited to floating debris and it can be reduced through an appropriate upkeep program. The main criticalities of traditional weirs with fixed height are linked to their low flexibility and to the high variability of flow due to water level fluctuations. When such facilities are communicating with fish passages, the knowledge of the ichthyologic aspects of the stream and specific fish species requirements are basic information needed for their rational design (Grishin, 1982). Then, when an existing fish ladder is used for the adaptation to ecological flow release, attention must be paid because the modification of the flow parameters from design conditions may reduce its effectiveness. Finally, as far as obstruction risk is concerned, the best release solution is possibly provided by orifices opened within sluice gates, when their axis is located at a sufficient distance from the bottom and from the water surface; in such a case only partly floating advected debris may reduce the opening so that an appropriate upkeep program would be anyway advisable. The drawbacks of this solution are its poor flexibility if no partialization is possible and the possible weakening if the gate structure; for this reason, orifices require a case-by-case evaluation.

All of the presented solutions are designed using the energy balance equation, usually under the assumption of still water behind the barrage so that the whole specific energy available is equal to the water depth. Accordingly, a drought condition depth must be selected as reference for their design and it must be guaranteed by some geometrical constraint (e.g., desilting basin or diversion channel threshold height) or by a hydraulic machinery set point. Whilst in the first case (Figure 4) an incoming discharge less than the ecological flow cannot enter into the diversion channel, in the second one the constancy of an upstream water level (e.g., in the forebay) is controlled by pre-set hydraulic machinery regulations. Both these design conditions imply that if in operational conditions the discharge in the stream is greater than the environmental one, the water level behind the barrage may rise and a greater discharge than the design one will flow out from the release devices to the detriment of the production. For this reason, in order to minimize the loss of production, practitioners often design release devices with respect to a mean water depth upstream of the barrage, identified through recorded time series or experience. Clearly, this is not an acceptable criterion because, in case of low flows, the release prescribed by law is not guaranteed.

The best solution to cope with this problem would be the installation of self-regulating mechanisms adapting the device geometry on the base of the upstream water level. In the considered district, both oleodynamic small plane gates and buoyant systems, that partialize orifices on the base of the upstream water level, are installed. Anyway these approaches are hardly applicable in absence of power supply or in case of severe freezing problems. In such cases orifices are preferable to free surface weirs because their stage-discharge relation is a function of the water level at the power 0.5 and so less sensitive to depth variations. Other approaches to reduce outflow variability are weirs with narrow vertical slot (e.g., Regione Piemonte, 2006), which however appears to be obstruction-prone, or proportional weirs, that assure more self-cleaning capacity. For these reasons, in case of refurbishment of SHP with already present fish passage, a combination of free surface and low pressure devices might be preferable.

5 EVALUATION ON THE LOSS OF HYDROPOWER PRODUCIBILITY FOR AN ALPINE SHP DUE TO THE ENFORCEMENT OF ENVIRONMENTAL FLOW REGULATIONS

The run-of-river SHP case study is located into an alpine sub-basin of the Po river watershed. It has a drained catchment of 11.6 km², mean altitude of 2250 m a.s.l. and an average slope gradient of 0.50 m/m. The basin is characterized by a mean annual precipitation of about 1000 mm; taking into account a snow
equivalent of 280 mm of rainfall, through regionalization procedures (Regione Lombardia, 2008), a mean annual discharge of 0.38 m³/s can be estimated. An aerial image of the watershed is shown in Figure 5a while Figures 5b and 5c respectively present geological units and land use from Corine 2000.

Since no gauged data are available for this basin, the flow duration and the characteristic hydrological curves (Figure 6) have been estimated moving from the dataset of 34 years daily measured discharge data from the Sarca of Nambrone stream watershed (Northern Italy) (Bacchi et al., 2000; Bavera & Ranzi, 2006; Bavera et al., 2007) because of the geological and hydrological similarity between the two basins.

![Aerial Image](image1)

**Figure 5.** Case study catchment aerial image (a), geological units (b), Corine 2000 land use (c).

![Flow Duration and Hydrological Curves](image2)

**Figure 6.** Flow duration curve (a) and characteristic hydrological curve (b) without ecological flow abstraction.

The case study barrage (Figure 7) is a 2 m high gravity broad crested weir with a lateral intake which is followed by a chamber containing the desilting basin and the forebay, separated by a sill; the steel penstock is 3800 m long and with a diameter of 0.6 m. Two Pelton turbines are present for greater flexibility, operating with a discharge ranging from 0.030 m³/s to 0.750 m³/s and a gross head of 564 m; the operational scheme of the hydraulic machinery, in terms of sequence and number of running turbines, is set to keep its efficiency from 0.78 to 0.93, depending on the flowing discharge. At the barrage, the flow repartition is controlled by a frontal broad crested weir for high flows and a lateral Belanger intake weir; the environmental flow is released through a thin plate triangular weir for fish passage and a low pressure circular orifice into the flushing gate at 0.3 m from the bottom. From the operational viewpoint, considerations related to minimum submergence on the inlet of the penstock suggest to keep constant the water depth at the forebay. This is done by controlling the depth with an ultrasonic water level gauge and regulating the discharge in the penstock through the conical needle inside each nozzle ahead of the runner. Accordingly, the design of the release devices is based on the set point water depth.
In order to assess the loss of production for this SHP due to the enforcement of ecological flow, the incoming discharge $Q$ at the barrage must be partitioned between the elements that characterize the intake (i.e., broad crested weir of the barrage, triangular weir, circular orifice and drowned broad crested weir at the intake). The unknown discharges flowing through the listed devices are functions of the unknown water depth $h$ at the barrage; on the other hand $Q$, from the flow duration curve, and the fixed water level of the forebay are known values. To this purpose, a simple numerical code has been written to solve the continuity equation (2) providing, for each $Q$, the upstream water depth and the related discharge sharing:

$$Q = \sum_{i=1}^{4} f_i(h)$$

(2)

where $f_i(h)$ is the stage-discharge relation of the i-th device. Initially, an ideal device that releases constantly the ecological flow discharge that could be provided by each national regulation (Table 2) has been supposed, so that these discharges substituted the $f_i(h)$ functions related to the triangular weir and to the orifice in Equation (2). Afterward, the real release devices have been considered and the additional production loss due to the increased flowing environmental discharge has been computed.

Table 2. Environmental flow values

<table>
<thead>
<tr>
<th>Country</th>
<th>Environmental flow discharge [m$^3$/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Austria</td>
<td>0.042</td>
</tr>
<tr>
<td>France</td>
<td>0.038</td>
</tr>
<tr>
<td>Italy – Regione Lombardia</td>
<td>0.038</td>
</tr>
<tr>
<td>Switzerland</td>
<td>0.050</td>
</tr>
</tbody>
</table>

Finally, the net head has been estimated through an energy balance along the penstock and the annual energy producibility in the two scenarios has been computed; the results are shown in Table 3, where reductions are calculated with respect to the potential production, in absence of any ecological release, of 10691 MWh.
Table 3. Results

<table>
<thead>
<tr>
<th>Country</th>
<th>Energy production [MWh]</th>
<th>Reduction [%]</th>
<th>Variation ideal/real [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ideal</td>
<td>Real</td>
<td>Ideal</td>
</tr>
<tr>
<td>Austria</td>
<td>9940</td>
<td>9842</td>
<td>-7.0</td>
</tr>
<tr>
<td>France</td>
<td>10020</td>
<td>9938</td>
<td>-6.3</td>
</tr>
<tr>
<td>Italy – Regione Lombardia</td>
<td>10020</td>
<td>9938</td>
<td>-6.3</td>
</tr>
<tr>
<td>Switzerland</td>
<td>9786</td>
<td>9696</td>
<td>-8.5</td>
</tr>
</tbody>
</table>

As one can see, the application of ecological regulations under ideal conditions implies a producibility reduction ranging from 6.3% to 8.5%. Since the actual release varies with the water depth at the barrage, that increases with the discharge $Q$ in the stream, in real operating conditions a further energy reduction of about 1% is expected so that the overall loss of producibility ranges from 7.0% to 9.3%.

6 CONCLUSIONS

The assessment of environmental flow discharge implies hydrological and ecological aspects; all the European alpine states considered in this paper deal with this topic on the basis of an hydrologic approach, often supported by hydraulic and ecological evaluations. Moving from the analysis of the application of such regulation in province of Brescia, pros and cons of different devices used for environmental flow release are briefly discussed. Although bottom opened flushing gate are the most widely used solutions, they are inevitably prone to obstructions with consequent potential reduction of released discharge; in particular this solution may be considered acceptable only if accompanied by an appropriate management program and if the self-cleaning effect under the gate is guaranteed. Weirs are suitable approaches especially if fish ladders are required. In case of streams with small ecological flow release and relevant sediment transport, the most suitable solution might be low-pressure orifices, opened sufficiently far from the bottom in order to prevent obstructions. A key point for the verification of the correct operation of such devices is the identification of a reference level, chosen on the basis of geometrical or hydraulic constraints, that guarantees the absence of water diversion before the complete release of the environmental flow. Moving from these considerations, the influence of different ecological flow rules and structure design criteria on the potential loss of producibility for an alpine high head SHP has been assessed. To this purpose, the annual producibility obtainable with an ideal adaptive device, that releases constantly the design environmental discharge, and with a real outflow configuration, characterized by a circular orifice and a triangular weir for fish passage, have been compared. Accordingly, in the real situation the actual released discharge may increase, with respect to the design one, as a function of the water depth behind the barrage. Then, an ideal loss of production ranging from 6.3% to 8.5% has been estimated while a further 1% reduction is caused by water level variability. Although this additional loss is small in relative terms, from an economic point of view it might justify technical improvements aiming at keeping environmental flow release as constant as possible.

ACKNOWLEDGEMENTS

We gratefully acknowledge the support of Provincia di Brescia, Ufficio Usi Acque, that prompted the research on the issue of ecological flow and supported the monitoring activities which provided the basis for this publication. We also acknowledge Prof. Roberto Ranzi for his support in hydrological analysis.

NOTATION

$A$ parameter of interaction between surface water and groundwater in Eq. 1 [-]
$CL$ amplification factor [-]
$D$ distance between the intake and the tailrace [km]
$DMV$ environmental flow discharge in Eq.1 [l/s]
$h$ water depth at the barrage [m]
$k$ experimental parameter in Eq. 1 [-]
$M$ morphological parameter in Eq. 1 [-]
$MJNQ_{natural}$ natural mean annual minimum flow according to Austrian regulation
$NQ_{\text{Residual flow}}$ ecologically required minimum discharge according to Austrian regulation

$NQ_{t, \text{natural}}$ natural lowest daily minimum flow according to Austrian regulation

$Q$ discharge [m$^3$/s]

$Q_{347}$ discharge equaled or exceeded for 347 days each year [m$^3$/s]

$Q_{\text{max}}$ design discharge for the SHP in Figure 6 [m$^3$/s]

$Q_{\text{mean}}$ mean discharge usable in the SHP in Figure 6 [m$^3$/s]

$q_{\text{mean} \_y}$ mean annual specific discharge in Eq. 1 [l/s/km$^2$]

$S$ catchment surface in Eq. 1 [km$^2$]

$T$ parameter of environmental flow timing in Eq. 1 [-]

$Z$ parameter accounting naturalistic, fruition and water quality aspects in Eq. 1 [-]

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