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1 *A methodology to estimate average flow rates in Water Supply*  
2 *Systems (WSSs) for energy recovery purposes through*  
3 *hydropower solutions*

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13

14 **ABSTRACT**

15 Energy efficiency interventions in Water Supply Systems (WSSs) need a precise evaluation of the  
16 available water flow rates for energy recovery interventions; however, flow meters are generally too  
17 costly for being installed in all the gravity adduction pipelines of a WSS. This paper presents a  
18 methodology for predicting flow rates in gravity adduction pipelines based on the electricity bill  
19 consumption. In this study, the predicted average flow rate is  $0.0300 \text{ m}^3 \cdot \text{s}^{-1}$ , being 1.64% lower than  
20 the real one. A Pelton turbine has been chosen as energy recovery unit for supplying electricity to a  
21 pumping station of a preloading tank where the water is treated to make it drinkable. An energy saving  
22 of  $475.26 \text{ (MW} \cdot \text{h)} \cdot \text{year}^{-1}$  is achieved, which can be also expressed as 88.87 saved Tonnes of Oil  
23 Equivalent (TOE) and  $204.36 \text{ ktCO}_2$  not released into the atmosphere. The gross economic saving  
24 due to the installation of the Pelton turbine is equal to  $94.29 \text{ k€} \cdot \text{year}^{-1}$  and it can be further increased

25 up to 116.51 k€\*year<sup>-1</sup> if the energy efficiency certificates issued by the Italian Authorities are  
26 considered. The Payback Period (PBP) of the intervention corresponds to 3 years, and a Net Present  
27 Value (NPV) after twenty years is approximately 1.4 M€.

28

## 29 **KEYWORDS**

30 Economic saving; Energy efficiency; Flow rate estimation; Pelton turbine; Small-scale hydropower;  
31 Water Supply System.

32

## 33 **NOMENCLATURE**

34  $A_{ind}$  = Area occupied by industrial users [m<sup>2</sup>]

35  $A_{res}$  = Area occupied by residential users [m<sup>2</sup>]

36  $EC_{eec}$  = Economic saving due to the energy efficiency certificates [€\*year<sup>-1</sup>]

37  $EC_{saving\_gross}$  = Gross economic saving [€\*year<sup>-1</sup>]

38  $EC_{saving\_gross\_final}$  = Gross economic saving considering the energy efficiency certificates [€\*year<sup>-1</sup>]

39  $\overline{E}n_{after\_turbine}$  = Electric energy consumed by the pumping station after the installation of the  
40 hydraulic turbine [MW\*h]

41  $\overline{E}n_{before\_turbine}$  = Electric energy consumed by the pumping station before the installation of the  
42 hydraulic turbine [MW\*h]

43  $\overline{E}n_{electric\_bill}$  = Average electricity bill consumption of the pumping station [MW\*h]

44  $\overline{E}n_{electric\_pump}$  = Average electricity consumption of the pumping station [MW\*h]

45  $\overline{E}n_{electric\_pump,i}$  = Average electricity consumption of a hydraulic pump [MW\*h]

- 46  $\overline{E}_{\text{electric\_turbine avg\_monthly}}$  = Monthly average electric energy produced by the hydraulic turbine
- 47 [MW\*h]
- 48  $\overline{E}_{\text{saving\_after\_turbine}}$  = Electric energy saving after the installation of the hydraulic turbine [MW\*h]
- 49  $F_{\text{tCO}_2}$  = Conversion factor from kW\*h to tCO<sub>2</sub> [tCO<sub>2</sub>\*(kW\*h)<sup>-1</sup>]
- 50  $F_{\text{TOE}}$  = Conversion factor from kW\*h to TOE [TOE\*(kW\*h)<sup>-1</sup>]
- 51  $F_{\text{ec}}$  = Conversion factor from kW\*h to € [€\*(kW\*h)<sup>-1</sup>]
- 52  $F_{\text{eec}}$  = Conversion factor from TOE to € [€\*TOE<sup>-1</sup>]
- 53  $g$  = Gravity acceleration [m\*s<sup>-2</sup>]
- 54  $H$  = Head [m]
- 55  $H_{\text{available}}$  = Available head [m]
- 56  $H_{\text{loss}}$  = Head losses [m]
- 57  $H_{\text{useful}}$  = Useful head [m]
- 58  $n_{\text{ind}}$  = Population density in industrial areas [person\*m<sup>-2</sup>]
- 59  $n_{\text{res}}$  = Population density in residential areas [person\*m<sup>-2</sup>]
- 60  $\overline{P}_{\text{hydraulic avg\_yearly}}$  = Average available hydraulic power [kW]
- 61  $\overline{P}_{\text{turbine avg\_monthly}}$  = Average power produced by the hydraulic turbine [kW]
- 62  $\overline{Q}$  = Flow rate [m<sup>3</sup>\*s<sup>-1</sup>]
- 63  $\overline{Q}_{\text{avg\_yearly}}$  = Yearly average flow rate in a gravity adduction pipeline [m<sup>3</sup>\*s<sup>-1</sup>]
- 64  $\overline{Q}_{\text{pump avg\_monthly}}$  = Monthly average flow rate elaborated by the pumping station [m<sup>3</sup>\*s<sup>-1</sup>]

- 65  $\bar{Q}_{\text{pump},i \text{ avg\_monthly}}$  = Monthly average flow rate elaborated by a hydraulic pump [ $\text{m}^3 \cdot \text{s}^{-1}$ ]
- 66  $\bar{Q}_{\text{turbine avg\_monthly}}$  = Measured monthly average flow rate elaborated by the hydraulic turbine  
67 [ $\text{m}^3 \cdot \text{s}^{-1}$ ]
- 68  $\bar{Q}_{\text{turbine avg\_monthly\_meas}}$  = Measured yearly average flow rate elaborated by the hydraulic turbine  
69 [ $\text{m}^3 \cdot \text{s}^{-1}$ ]
- 70  $\bar{Q}_{\text{turbine avg\_monthly\_model}}$  = Estimated monthly average flow rate potentially elaborated by the  
71 hydraulic turbine [ $\text{m}^3 \cdot \text{s}^{-1}$ ]
- 72  $\bar{Q}_{\text{turbine avg\_yearly}}$  = Measured average flow rate elaborated by the hydraulic turbine [ $\text{m}^3 \cdot \text{s}^{-1}$ ]
- 73  $\bar{Q}_{\text{turbine avg\_yearly\_model}}$  = Estimated yearly average flow rate potentially elaborated by the  
74 hydraulic turbine [ $\text{m}^3 \cdot \text{s}^{-1}$ ]
- 75  $\bar{Q}_{\text{wells avg\_monthly}}$  = Monthly average flow rate coming from the wells [ $\text{m}^3 \cdot \text{s}^{-1}$ ]
- 76  $V_{\text{monthly, end user},i}$  = Monthly water volume consumption of a generic end user [ $\text{m}^3$ ]
- 77  $V_{\text{monthly\_ind}}$  = Monthly water volume consumption per each residential user [ $\text{m}^3$ ]
- 78  $V_{\text{monthly\_res}}$  = Monthly water volume consumption per each industrial user [ $\text{m}^3$ ]
- 79 **tCO<sub>2</sub>\_saving** = Tonnes of CO<sub>2</sub> [tCO<sub>2</sub>] saving
- 80 **TOE<sub>saving</sub>** = Tonnes of Oil Equivalent [TOE] saving
- 81  $\Delta\bar{Q}$  = Relative percentage error related to the flow rate estimation [%]
- 82  $\eta_{\text{pump}}$  = Total efficiency of a hydraulic pump [-]
- 83  $\eta_{\text{turbine}}$  = Total efficiency of the hydraulic turbine [-]

84  $\rho$  = Water density at normal conditions [ $\text{kg}\cdot\text{m}^{-3}$ ]

85  $\omega$  = Angular rotational speed [ $\text{rad}\cdot\text{s}^{-1}$ ]

86  $\omega_s$  = Specific rotational speed [-]

87

## 88 **ACRONYMS**

89 BEP = Best Efficiency Point

90 NPV = Net Present Value

91 O&M = Operation & Management

92 PBP = Payback Period

93 PID = Proportional-Integral-Derivative

94 PRV = Pressure Reducing Valve

95 PSO = Particle Swarm Optimization

96 TOE = Tonnes of Oil Equivalent

97 WDN = Water Distribution Network

98 WSS = Water Supply System

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## 104 **1. INTRODUCTION**

105 The water-energy nexus concept is becoming of great interest in the energy sector with the aim of  
106 ensuring a sustainable exploitation of the water source on both environmental and energy points of  
107 view [1, 2]. Within the water-energy nexus framework, one of the most important topics concerns the  
108 use of water for power production. Hydropower plants generate clean energy by exploiting the energy  
109 potential of a water reservoir and transforming it to electricity by a generator. Conversely, a  
110 considerable amount of energy is required by several processes to pump and treat water in civil and  
111 industrial contexts. The two perspectives can be combined in several applications, like in Water  
112 Supply Systems (WSSs), Water Distribution Networks (WDNs) [3, 4] and in wastewater treatment  
113 plants [5, 6] where a share of the energy required to run such plants can be potentially recovered. All  
114 the previous mentioned applications present facilities, such as the pumping stations, that are highly  
115 energy consuming, but also with considerable hydraulic head potentials. For this reason, the  
116 recovered energy can lead to an increase of the system efficiency, thus to a reduction of both  
117 consumed Tonnes of Oil Equivalent (TOE) and CO<sub>2</sub> emissions released into the atmosphere [7, 8].  
118 WSSs are typically constituted by a water source connected to loading/head compensation tanks  
119 downstream located at high geodetic altitudes, being in turn connected to other tanks [9] or directly  
120 to the end users via distribution network. The extension of WSSs depends on the number of  
121 inhabitants of a city/town, as well as on its dimensions. The water source can be a reservoir filled by  
122 water pumped from a low-level reservoir. About 2-3% of the electric energy consumption worldwide  
123 derives from pumping stations of WSSs [10, 11] and 80-90% of this consumption is addressed to  
124 pump motors [12, 13]. In this regard, some works in literature stated that the specific energy  
125 consumptions measured in WSSs are below 0.30 (kW\*h)\*m<sup>-3</sup> in developing countries and reach  
126 values higher than 3 (kW\*h)\*m<sup>-3</sup> in developed ones [14, 15]; in this last case, energy recovery  
127 interventions are strongly recommended to improve the efficiency of WSSs.

128 The proper choice of the energy recovery intervention in WSSs depends on their design  
129 characteristics [16, 17] and several authors investigated on the energy recovery potential through  
130 hydropower solutions. Kucukali [18] estimated that this kind of recovery potential, which has been  
131 applied in 45 WSSs located in Turkey, led to 173 GW\*h saved per year. McNabola et al. [19] analysed  
132 ten cases related to water industries in Ireland, where the hydraulic power is recovered through small-  
133 scale hydropower plants ranging between 2 and 115 kW. The installation of hydraulic turbines in  
134 WSSs provides, beside the electricity production, the water pressure regulation inside the network,  
135 which is usually performed by Pressure Reducing Valves (PRVs). Indeed, a reduction of the water  
136 pressure leads to a decrease of the water losses throughout the pipelines [20, 21] that reached  
137 nowadays a remarkable average value of 26% worldwide [22]. PRVs are installed not only in WDNs,  
138 but also in WSSs where high values of pressure are present. For instance, this situation occurs when  
139 an upstream water source is placed at a very high altitude and connected to a preloading or a  
140 loading/head compensation tank downstream that is at atmospheric pressure. The preloading tank has  
141 the aim to mix the water coming from the water source with the one coming from wells, whose  
142 chemical properties are not still acceptable. After the mixing process, the water becomes drinkable  
143 and it is pumped to loading/head compensation tanks; subsequently, it is distributed to the end users  
144 via distribution network. However, pumping stations withdraw water from the preloading tank and  
145 provide it with the proper pressure in order to reach loading/head compensation tanks. Doing this, the  
146 potential energy content of the water due to the geodetic altitude difference between the water source  
147 and the preloading tank is lost, since it is dissipated through a PRV for being lowered down to the  
148 atmospheric pressure. It is worth noting that the mixing process can be also performed inside the  
149 pipelines, unless the water pressure is enough to provide the water to loading/head compensation  
150 tanks.

151 In order to improve the efficiency of WSSs, hydraulic turbines can be installed upstream the  
152 preloading tank, thus replacing PRVs in order to recover part of this water energy content and produce



153 the electric energy required by the pumping station. The installation of small-scale hydropower plants  
154 in WSSs presents low implementation costs [23, 24]. The produced electric energy can be consumed  
155 by facilities and auxiliary systems of WSSs, thus lowering the amount of electricity withdrawn by the  
156 national grid [18]. Energy recovery interventions through hydropower solutions in WSSs have also  
157 three main advantages [25]: i) reduction of the greenhouse gas emissions due to the self-consumption  
158 of the produced electric energy, as well as its production by means of a renewable source, ii) limitation  
159 of civil works since they are adapted to the existing infrastructure, thus not requiring new spaces, and  
160 iii) to lower environmental impacts throughout the life cycle of WSSs.

161 Nevertheless, the correct average flow rate in gravity adduction pipelines has to be assessed in order  
162 to perform the energy recovery interventions properly, mostly when flow meters are not installed. In  
163 literature there are several works, based on the evaluation of the water demand of the end users, that  
164 analysed different deterministic, probabilistic and demand time-series approaches for predicting the  
165 peak demand in WSSs. In this regard, Wong et al. [26] carried out a literature review on the previous  
166 mentioned approaches and proposed the Bayesian one, which bridges the gap between model-based  
167 and field-measurement values, being more flexible and more reliable on the design point of view.  
168 Letting et al. [27] presented a simulation model for the water demand using a Particle Swarm  
169 Optimization (PSO) algorithm and compared the numerical results with the real ones obtained by  
170 sensors. Results showed that both nodal demands and pipe flows can be accurately determined.  
171 Balacco et al. [28] analysed the water demand in several towns in Puglia (Italy), leading to the  
172 definition of a relationship between the peak factor and the number of inhabitants. They found out  
173 that the design of WSSs can be done without considering the use of monthly and weekly peak factors.  
174 Moreover, the magnitude of the peak factor obtained through measured data is considerably lower  
175 compared to the literature values. However, detailed information related to WSSs and WDNs are  
176 usually required, which are not always affordable and make difficult, as well as time demanding, the  
177 calculation of the water demand, also considering the creation of optimization algorithms. Moreover,

178 to the authors' knowledge, a methodology to estimate the yearly average flow rate in gravity  
179 adduction pipelines has not been discussed and presented so far.

180 In this work, a methodology based on the knowledge of the electricity bill consumption related to the  
181 pumping station of a preloading tank to predict the yearly average flow rate that can be potentially  
182 exploited for energy recovery purposes is presented. In particular, this methodology is thought to be  
183 applied in branches where flow meters are not installed. First of all, gravity adduction pipelines where  
184 the hydraulic turbine can be installed have to be identified, taking into account the connections  
185 between a water source and the preloading tank. The developed methodology was then validated  
186 through measured data obtained by a flow meter installed upstream the preloading tank, after the  
187 hydraulic turbine installation. Finally, energy, environmental and economic analyses have been  
188 performed to assess the advantages of this energy efficiency intervention.

189 The present paper is structured as follows: Section 2 describes the methodology developed for  
190 estimating the yearly average flow rate when flow meters are not installed; then, the head that can be  
191 exploited by the hydraulic turbine has been also calculated using a formula reported in literature. In  
192 addition, the procedure to select the proper machine is also presented. Section 3 deals with the case  
193 study of a WSS related to a mid-town located in the Center of Italy. After the analysis of the flow  
194 duration curve of the site of interest, the flow rates obtained through the methodology described in  
195 Section 2 have been confirmed and validated with measured data from a flow meter installed after  
196 the hydraulic turbine installation, whose selection process has led to the choice of a Pelton machine.  
197 Section 4 presents energy, environmental and economic analyses due to the energy efficiency  
198 intervention. Finally, Section 5 reports the conclusions of the work.

199

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201

202

## 203 **2. METHODOLOGY**

204 This Section aims at describing a methodology capable of identifying the hydropower potential in  
205 WSSs through the estimation of the flow rates in gravity adduction pipelines that connect the water  
206 source to the preloading tanks downstream. The presented methodology is based on the knowledge  
207 of the electricity bill consumption of the pumping station installed in the preloading tank. After the  
208 estimation of the yearly average flow rate, the head is evaluated by knowing the geodetic heights of  
209 each element previously mentioned in the site of interest and the relative head losses. The  
210 methodology is divided in three phases:

- 211 i) analysis of the WSS structure of the site of interest, taking into account the WSS layout composed  
212 by a water source, a preloading tank with a pumping station, loading/head compensation tanks  
213 and interconnections;
- 214 ii) estimation of the hydropower potential from sites identified in the previous phase, focusing the  
215 attention to the one having the connection between the water source and the preloading tank.  
216 Then, after the analysis of the flow duration curve, the yearly average flow rate, together with  
217 the useful head, are calculated. Finally, the calculation of the power produced by the hydropower  
218 system is also provided;
- 219 iii) assessment of energy, environmental and economic benefits due to the hydraulic turbine  
220 installation; specifically, the evaluation of the energy saving, also in terms of saved TOE and  
221 tCO<sub>2</sub> emissions not released into the atmosphere, and the economic saving due to the energy  
222 efficiency intervention are discussed.

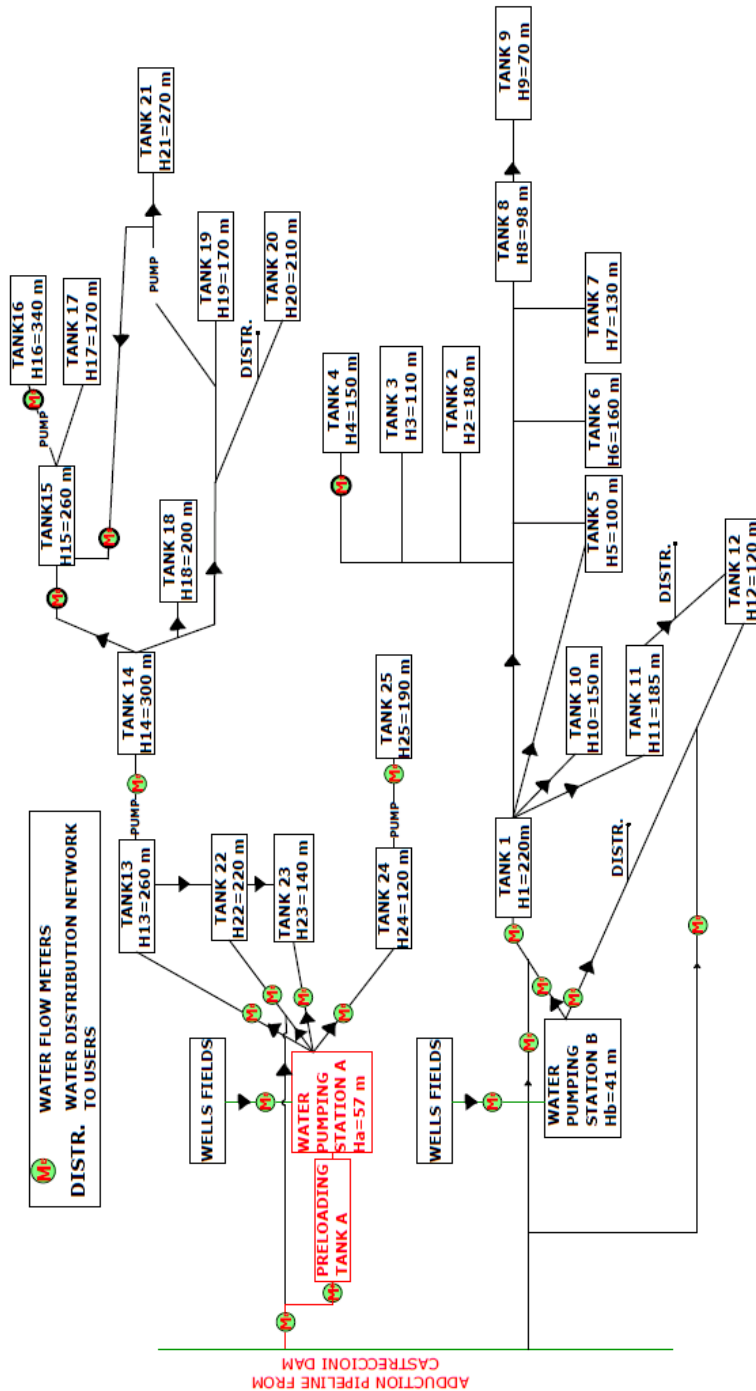
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225

226 **2.1 Water Supply System (WSS) infrastructure and an overview of the site of interest**

227 The water reservoir of the analysed WSS is located at 346 m a.s.l. with a height of 69.4 m (55 m of  
 228 depth) and a capacity of 37.3 Mm<sup>3</sup>. The water coming from this reservoir feeds one preloading tank  
 229 and then seven loading tanks placed in different zones, as reported in Figure 1 and Table 1.



230

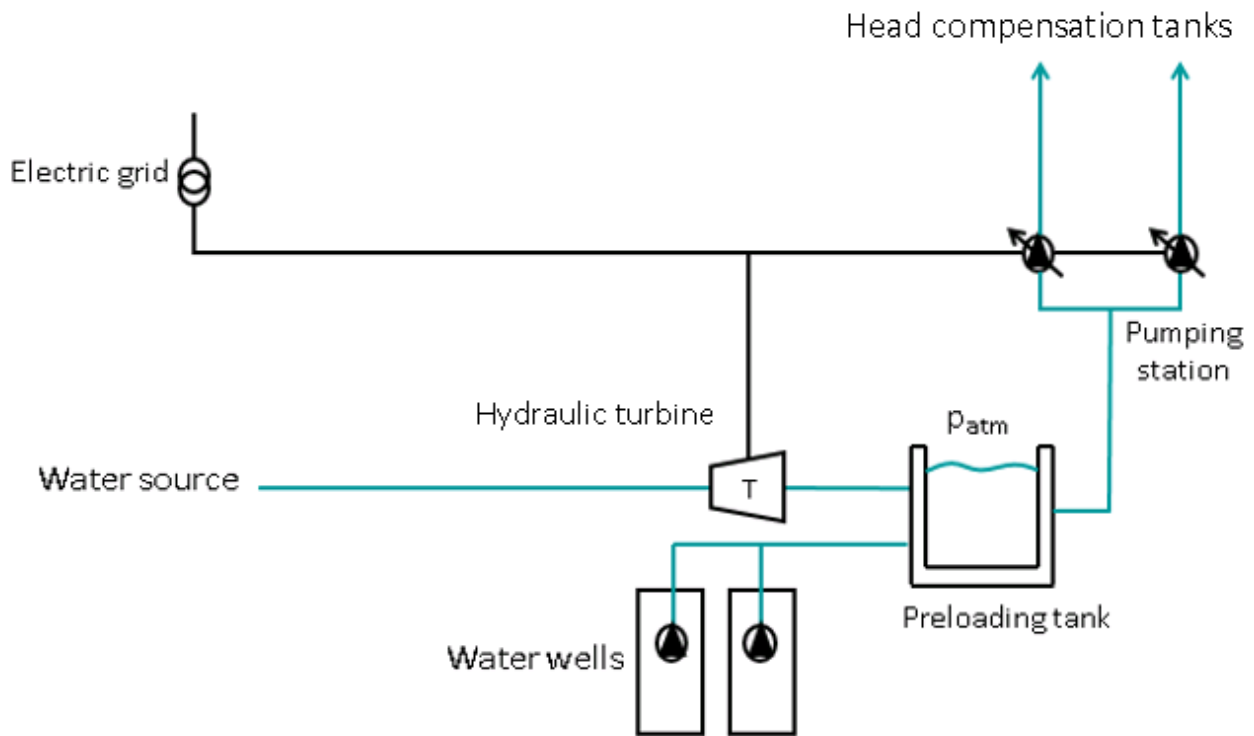
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Figure 1: Layout of the analysed WSS

232 Table 1: Water source, loading, preloading and head compensation tanks with respective geodetic heights

| <b>WATER SOURCE</b>         | <b>LOADING AND<br/>PRELOADING TANK<br/>(GEODETTIC HEIGHTH)</b> | <b>HEAD COMPENSATION TANK<br/>(GEODETTIC HEIGHTH)</b> | <b>GEODETTIC<br/>HEIGHTH<br/>DIFFERENCE</b> |
|-----------------------------|--|---|---|
| CASTRECCIONI<br>DAM (346 m) | TANK A (57 m)  | -   | 289 m                                       |
|                             | -  | TANK 1 (57 m)   | 126 m                                       |
|                             | -  | TANK 22 (220 m)                                       | 126 m                                       |
|                             | -  | TANK 12 (120 m)                                       | 226 m                                       |
|                             | TANK 13 (260 m)  | TANK 22 (220 m)                                       | 40 m  |
|                             | TANK 22 (220 m)  | TANK 23 (140 m)                                       | 80 m  |
|                             | TANK 14 (300 m)  | TANK 18 (200 m)                                       | 100 m                                       |
|                             |  | TANK 19 (170 m)                                       | 130 m                                       |
|                             |  | TANK 20 (210 m)                                       | 90 m  |
|                             |  | TANK 15 (260 m)                                       | 40 m  |
|                             | TANK 15 (260 m)  | TANK 17 (170 m)                                       | 90 m  |
|                             | TANK 1 (220 m)   | TANK 2 (180 m)  | 40 m  |
|                             |  | TANK 3 (110 m)  | 110 m                                       |
|                             |  | TANK 4 (150 m)  | 70 m  |
|                             |  | TANK 5 (100 m)  | 120 m                                       |
|                             |  | TANK 6 (160 m)  | 60 m  |
|                             |  | TANK 7 (130 m)  | 90 m  |
|                             |  | TANK 8 (98 m)   | 122 m                                       |
|                             |  | TANK 10 (150 m)                                       | 70 m  |
|                             |  | TANK 11 (185 m)                                       | 35 m  |
| TANK 11 (185 m)             | TANK 12 (120 m)  | 65 m  |   |
| TANK 8 (98 m)               | TANK 9 (70 m)  | 28 m  |   |

234 In particular, Tank A is the preloading tank that collects the water coming from both water source  
235 and wells with the aim of making it drinkable after a mixing phase process. The preloading tank  
236 presents a pumping station that supplies water to Tanks 13, 22, 23 and 24 located at higher altitudes  
237 with respect to the preloading tank itself. Figure 2 shows a simplified scheme of the site of interest,  
238 namely the preloading tank where a hydraulic turbine has been subsequently installed.



239

240 *Figure 2: Simplified scheme of the site of interest (preloading tank plus the new hydraulic turbine)*

241

## 242 **2.2 Estimation of both yearly average flow rate and useful head of the hydraulic turbine**

243 The flow rate elaborated by the hydraulic turbine can correspond either to the overall one that flows  
244 in gravity adduction pipelines or to a part of it, according to the number of deviations and design  
245 characteristics of the WSS. The evaluation of the flow rate can be done instrumentally through flow  
246 meters installed in pipelines that recreate the flow duration curve.

247 Generally, flow meters are installed in adduction pipelines that connect the pumping stations to a  
 248 loading/head compensation tank located at high altitude, while it is rare to find them in gravity  
 249 adduction pipelines since they are costly. If a gravity adduction pipeline connects the water source to  
 250 a loading/head compensation tank directly, the yearly average flow rate  $\bar{Q}_{avg\_yearly}$  [ $m^3 * s^{-1}$ ] is  
 251 evaluated through Eq. (1), which takes into account the population density  $n_{res}$  and  $n_{ind}$ , the occupied  
 252 areas and the monthly water volume consumptions  $V_{monthly\_res}$  [ $m^3$ ] and  $V_{monthly\_ind}$  [ $m^3$ ] of both  
 253 residential and industrial end users, respectively:

$$254 \quad \bar{Q}_{avg\_yearly} = \frac{(n_{res} \cdot A_{res} \cdot V_{monthly\_res} + n_{ind} \cdot A_{ind} \cdot V_{monthly\_ind}) \cdot \# \text{ of months in a year}}{86,400s \cdot \# \text{ of days in a year}} [m^3 * s^{-1}] \quad (1)$$

255

256 It is worth noting that Eq. (1) is valid when the flow rate coming from the water source is the same  
 257 of the one that flows inside a loading/head compensation tank; indeed, the balance of the water  
 258 consumption related to the end users served by a loading/head compensation tank returns the volume  
 259 of the water entered the loading/head compensation tank itself. That said, Eq. (1) can be considered  
 260 be a good starting point for estimating the flow rate of an ex-novo WSS.

261 However, when preloading tanks are located at lower geodetic heights than loading/head  
 262 compensations ones, another approach for the evaluation of the flow rate is used. In this case, the  
 263 monthly average flow rate pumped by the pumping station  $\bar{Q}_{pump\ avg\_monthly}$  [ $m^3 * s^{-1}$ ] is estimated  
 264 by knowing its monthly electricity consumption  $\bar{E}n_{electric,pump}$  [ $MW * h$ ]. The steps used in the  
 265 presented methodology are explained hereinafter:

- 266 1. the number of end users served by each pump of the pumping station, as well as the monthly  
 267 water volume consumption of each end user  $V_{monthly,end\ user,i}$  [ $m^3$ ], are known; thus, the  
 268 multiplication of the previous mentioned terms returns the water volume consumption of all  
 269 the end users. Then, this value is divided by the period of operation of the WSS equal to

270 86,400 s times the number of days in a month, leading to the monthly average flow rate

271  $\bar{Q}_{\text{pump},i \text{ avg\_monthly}} [\text{m}^3 * \text{s}^{-1}]$  elaborated by each pump;

272 2. both dimensions and physical characteristics of the adduction pipelines that connect each  
273 pump to the respective loading/head compensation tank are known as well. The monthly  
274 average flow rate elaborated by each pump  $\bar{Q}_{\text{pump},i \text{ avg\_monthly}} [\text{m}^3 * \text{s}^{-1}]$  previously  
275 evaluated is used to calculate the head losses along each adduction pipeline, being a quadratic  
276 function of the flow rate;

277 3. the useful head  $H_{\text{useful}} [\text{m}]$  provided by each pump is equal to the sum of the geodetic height  
278 difference between the head compensation tank and the preloading one  $H_{\text{available}} [\text{m}]$  plus  
279 the head losses along the adduction pipelines  $H_{\text{loss}} [\text{m}]$  using the one-term quadratic formula  
280 valid for fully turbulent flow regimes [29];

281 4. since the pumps are installed in parallel, the same hydraulic efficiency within all the operating  
282 range is assumed, since they operate close to their Best Efficiency Point (BEP) most of the  
283 time. Therefore, Eq. (2) provides the monthly average electric energy  
284  $\bar{E}n_{\text{electric\_pump},i} [\text{MW} * \text{h}]$  consumed by each pump:

285 
$$\bar{E}n_{\text{electric\_pump},i} = \frac{\rho \cdot g \cdot \bar{Q}_{\text{pump},i \text{ avg\_monthly}} \cdot H_{\text{useful}}}{\eta_{\text{pump}} \cdot 10^6} \cdot (24 \text{ h} \cdot \# \text{ of days in a month}) [\text{MW} * \text{h}] \quad (2)$$

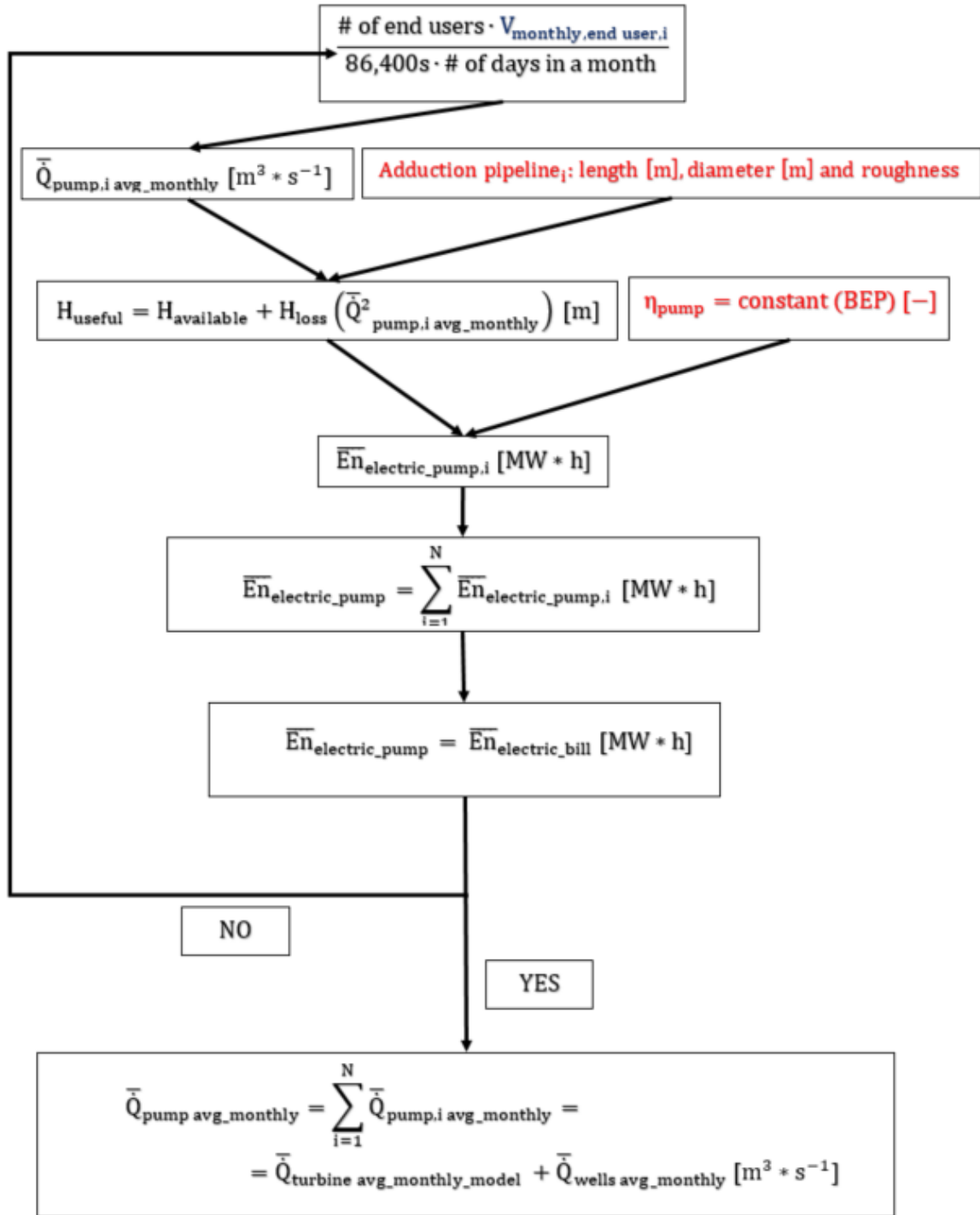
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287 5. the sum of the electric energies consumed by each pump has to be equal to the one in the  
288 electric bill; if not, the monthly water volume consumption  $\bar{V}_{\text{monthly, end user},i} [\text{m}^3]$  of each  
289 end user is modified iteratively until the solution converges;

290 6. finally, when the convergence of the solution is reached, the sum of the monthly average flow  
291 rates elaborated by each pump  $\bar{Q}_{\text{pump},i \text{ avg\_monthly}} [\text{m}^3 * \text{s}^{-1}]$  leads to the monthly average  
292 flow rate elaborated by the pumping station  $\bar{Q}_{\text{pump avg\_monthly}} [\text{m}^3 * \text{s}^{-1}]$ .



293 In order to have a better overview of the entire process, Figure 3 shows the flow diagram related to  
 294 the procedure previously explained, where the free parameter and the known values are highlighted  
 295 in dark blue and red, respectively.



296

297 *Figure 3: Flow diagram related to the estimation of the flow rate elaborated by the pumping station*

298 As reported in Figure 3, the monthly average flow rate elaborated by the pumping station  
 299  $\bar{Q}_{\text{pump avg\_monthly}} [\text{m}^3 * \text{s}^{-1}]$  is equal to the one elaborated by the hydraulic turbine  
 300  $\bar{Q}_{\text{turbine avg\_monthly\_model}} [\text{m}^3 * \text{s}^{-1}]$  plus the monthly average water flow rate coming from the  
 301 wells  $\bar{Q}_{\text{wells avg\_monthly}} [\text{m}^3 * \text{s}^{-1}]$ , which is obtained through flow meters installed in  
 302 correspondence of the wells. Using this procedure, the water mass balance in the preloading tank is  
 303 assessed; however, it is worth noting that this methodology is valid only if the variability of the flow  
 304 rate in gravity adduction pipelines is restricted close to its average value.

305 Knowing the monthly average flow rate elaborated by the hydraulic turbine  
 306  $\bar{Q}_{\text{turbine avg\_monthly\_model}} [\text{m}^3 * \text{s}^{-1}]$ , the yearly average flow rate  $\bar{Q}_{\text{turbine avg\_yearly\_model}} [\text{m}^3 * \text{s}^{-1}]$   
 307 is obtained through Eq. (3), where 12 stands for the number of months in a year:

$$308 \quad \bar{Q}_{\text{turbine avg\_yearly\_model}} = \frac{\sum_1^{12} \bar{Q}_{\text{turbine avg\_monthly\_model}}}{12} [\text{m}^3 * \text{s}^{-1}] \quad (3)$$

309

310 Then, knowing both dimensions and physical characteristics of the gravity adduction pipeline as well,  
 311 the head losses in gravity adduction pipelines are obtained according to [29]. The useful head  
 312  $H_{\text{useful}} [\text{m}]$  that the hydraulic turbine has to exploit is equal to the difference between the available  
 313 head  $H_{\text{available}} [\text{m}]$  and the pressure losses  $H_{\text{loss}} [\text{m}]$  that the water encounters along the gravity  
 314 adduction pipeline using the one-term quadratic formula valid for fully turbulent flow regimes [29],  
 315 as described by Eq. (4):

$$316 \quad H_{\text{useful}} = H_{\text{gross}} - H_{\text{loss}} \left( \bar{Q}_{\text{turbine avg\_yearly\_model}}^2 \right) [\text{m}] \quad (4)$$

317

318

### 319 2.3 Selection of the hydraulic turbine together with power and energy calculations

320 The values of both flow rate  $\dot{Q}$  [ $\text{m}^3 \cdot \text{s}^{-1}$ ] and head  $H$  [m] of the hydraulic turbine, along with  
321 its angular rotational speed  $\omega$  [ $\text{rad} \cdot \text{s}^{-1}$ ] that is dependent on both grid frequency and  
322 characteristics of the electric generator, allows to select the proper machine to be installed close  
323 to the preloading tank. In particular, the most important dimensionless parameter that  
324 characterizes which machine better suits the available operative conditions is the specific speed  
325  $\omega_s$  [-], as expressed by Eq. (5).

$$326 \quad \omega_s = \omega \cdot \frac{\dot{Q}^{0.5}}{(gH)^{0.75}} \quad [-] \quad (5)$$

327

328 However, a machine capable to operate in a quite wide range of flow rates has to be selected,  
329 preferably with a quite flat efficiency trend. Among traditional turbines, the Pelton one could be  
330 the best choice according to what previously said: indeed, the efficiency trend is quite flat close  
331 to the BEP, thus being suitable for this case study. Nevertheless, attention must be paid at strong  
332 part-load conditions, since a consistent efficiency drop occurs. This situation mainly happens in  
333 the summer season, when the water availability could be low [30]. The monthly average power  
334 that can be produced by the hydraulic turbine  $\bar{P}_{\text{turbine avg\_monthly}}$  [MW] is evaluated through Eq.  
335 (6), while the potential monthly average energy recovery  $\bar{E}n_{\text{electric\_turbine avg\_monthly}}$  [MW \* h]  
336 is evaluated using Eq. (7), where a WSS operation of 24 h times the number days in a month has  
337 been considered. The results can be widened to a yearly basis with equations similar to Eq. (3).

$$338 \quad \bar{P}_{\text{turbine avg\_monthly}} = \frac{\eta_{\text{turbine}} \cdot \rho \cdot g \cdot \bar{Q}_{\text{turbine avg\_monthly}} \cdot H_{\text{useful}}}{10^6} = \frac{\eta_{\text{turbine}} \cdot \bar{P}_{\text{hydraulic avg\_monthly}}}{10^6} \quad [MW] \quad (6)$$

339

$$340 \quad \bar{E}n_{\text{electric\_turbine avg\_monthly}} = \bar{P}_{\text{turbine avg\_monthly}} \cdot (24h \cdot \text{days in a month}) \quad [MW \cdot h] \quad (7)$$

341

## 342 3. CASE STUDY

### 343 3.1 Evaluation and assessment of the yearly average flow rate in gravity adduction pipelines

344 As already stated in Section 2, the monthly average electric energy  
345  $\overline{E}n_{\text{electric\_turbine avg\_monthly}}$  [MW \* h] consumed by the pumping station, together with the useful  
346 head  $H_{\text{useful}}$  [m] and their efficiencies  $\eta_{\text{pump}}$  [-] (see Table 2), allows to estimate the monthly  
347 average flow rate elaborated by the pumping station  $\overline{Q}_{\text{pump avg\_monthly}}$  [ $\text{m}^3 * \text{s}^{-1}$ ] through Eq. (2).  
348 Furthermore, the obtained monthly average flow rate elaborated by the pumping station  
349  $\overline{Q}_{\text{pump avg\_monthly}}$  [ $\text{m}^3 * \text{s}^{-1}$ ] has to be shortened by the the water flow rates coming from the wells  
350  $\overline{Q}_{\text{wells avg\_yearly}}$  [ $\text{m}^3 * \text{s}^{-1}$ ]. Finally, the monthly average flow rate elaborated by the hydraulic  
351 turbine  $\overline{Q}_{\text{turbine avg\_monthly\_model}}$  [ $\text{m}^3 * \text{s}^{-1}$ ] is obtained, which can be also expressed as yearly  
352 average flow rate  $\overline{Q}_{\text{turbine avg\_yearly\_model}}$  [ $\text{m}^3 * \text{s}^{-1}$ ] according to Eq. (3). Table 3 sums up the  
353 numerical values of the magnitudes previously mentioned related to the year 2018.

354 It is worth noting that the overall efficiency of each pump  $\eta_{\text{pump}}$  has been set equal to 0.65,  
355 according to the point 4 of Subsection 2.2 and the available datasheets. Furthermore, the monthly  
356 water consumption of each end user  $V_{\text{monthly,end user},i}$  [ $\text{m}^3$ ] provided by each pump is considered  
357 the same and equal to  $12 \text{ m}^3$ , taking into account an average water volume consumption of about  
358  $0.4 \text{ m}^3 * \text{day}^{-1}$  per each end user [29]. This was possible since the distribution of the end users per  
359 each pump is homogeneous in terms of both residential and industrial consumers.

360

361

362

363

364

Table 2: Input and known values used in the proposed methodology

| # of the PUMP         | # of end users | $V_{\text{monthly,end user},i}$<br>[m <sup>3</sup> ] | Adduction pipeline length<br>[km] | Adduction pipeline diameter<br>[m] | $H_{\text{available}}$ [m] | $\eta_{\text{pump}}$ [-] |
|-----------------------|----------------|--|-----------------------------------|------------------------------------|----------------------------|--------------------------|
| 1 (TANK A to TANK 13) | 7203           | 12   | 2.94                              | 0.25                               | 203                        | 0.65                     |
| 2 (TANK A to TANK 22) | 668            | 12   | 2.65                              | 0.15                               | 163                        | 0.65                     |
| 3 (TANK A TO TANK 23) | 379            | 12   | 2.02                              | 0.15                               | 83                         | 0.65                     |
| 4 (TANK A TO TANK 24) | 710            | 12   | 2.84                              | 0.15                               | 63                         | 0.65                     |

365

366

367 Table 3: Estimated monthly average flow rates in the analysed gravity adduction pipelines (year 2018)

| MONTH (YEAR 2018) | PUMP | $E_{\text{electric\_pump},i}$<br>[MW*h] | $\dot{Q}_{\text{pump},i \text{ avg\_monthly\_model}}$<br>[m <sup>3</sup> *s <sup>-1</sup> ] | $\dot{Q}_{\text{pump avg\_monthly\_model}}$<br>[m <sup>3</sup> *s <sup>-1</sup> ] | $\dot{Q}_{\text{wells avg\_monthly}}$<br>[m <sup>3</sup> *s <sup>-1</sup> ] | $\dot{Q}_{\text{turbine avg\_monthly\_model}}$<br>[m <sup>3</sup> *s <sup>-1</sup> ] |
|-------------------|------|---|---|---|---|--|
| JANUARY           | 1    | 83.55                                   | 0.03543   | 0.04406   | 0.00793   | 0.03613  |
|                   | 2    | 6.00                                    | 0.00328   |   |   |  |
|                   | 3    | 1.73                                    | 0.00186   |   |   |  |
|                   | 4    | 2.51                                    | 0.00349   |   |   |  |
| FEBRUARY          | 1    | 73.86                                   | 0.03468   | 0.04313   | 0.007763  | 0.03537  |
|                   | 2    | 5.31                                    | 0.00321   |   |   |  |
|                   | 3    | 1.53                                    | 0.00182   |   |   |  |
|                   | 4    | 2.22                                    | 0.00342   |   |   |  |
| MARCH             | 1    | 94.37                                   | 0.04002   | 0.04977   | 0.02241   | 0.02736  |
|                   | 2    | 6.79                                    | 0.00371   |   |   |  |
|                   | 3    | 1.96                                    | 0.00210   |   |   |  |
|                   | 4    | 2.83                                    | 0.00394   |   |   |  |
| APRIL             | 1    | 84.27                                   | 0.03693   | 0.04593   | 0.01791   | 0.02802  |
|                   | 2    | 6.06                                    | 0.00342   |   |   |  |
|                   | 3    | 1.75                                    | 0.00194   |   |   |  |
|                   | 4    | 2.53                                    | 0.00364   |   |   |  |
| MAY               | 1    | 91.42                                   | 0.03877   | 0.04822   | 0.01917   | 0.02905  |
|                   | 2    | 6.57                                    | 0.00359   |   |   |  |
|                   | 3    | 1.90                                    | 0.00204   |   |   |  |
|                   | 4    | 2.75                                    | 0.00382   |   |   |  |

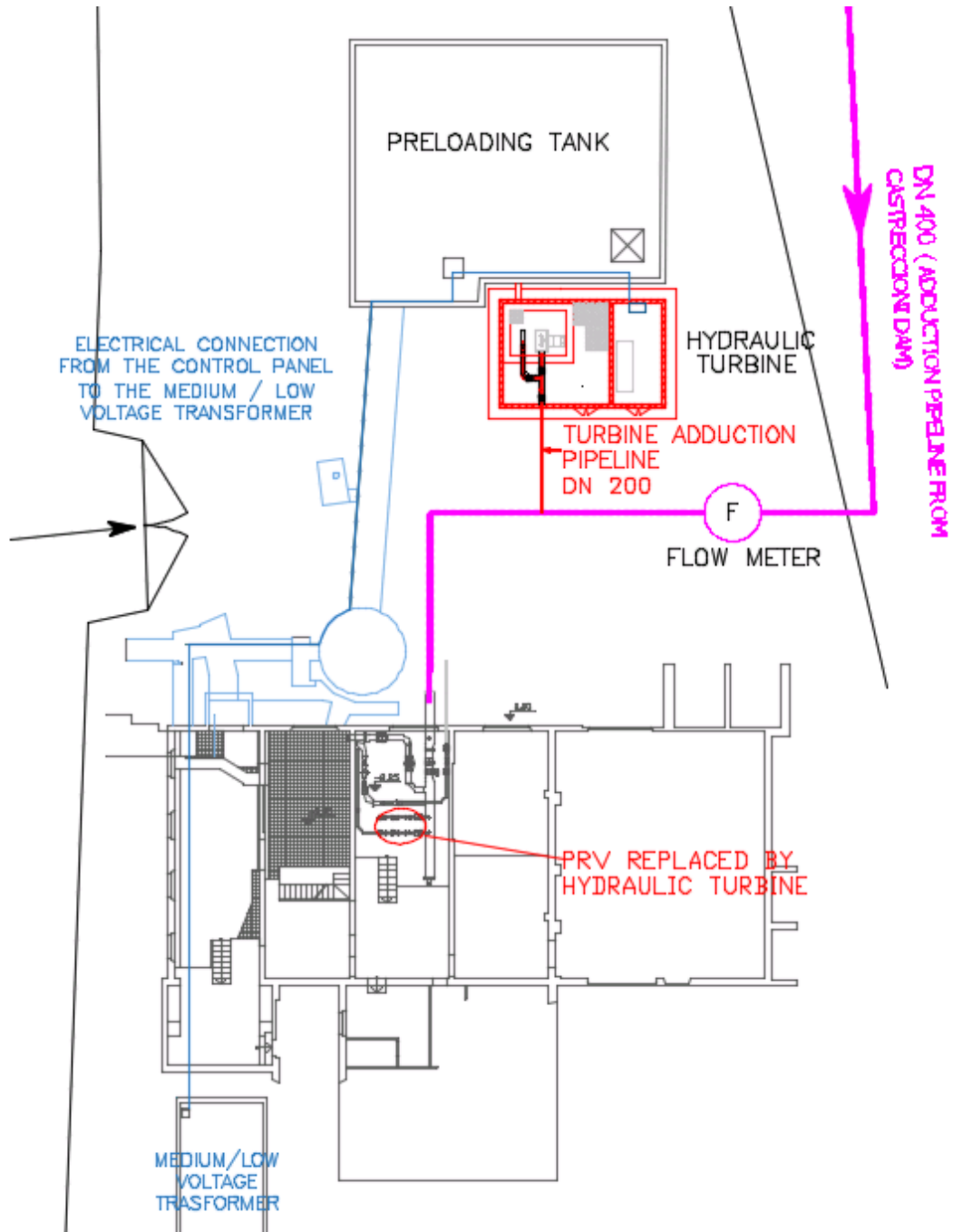
|           |   |        |         |         |         |         |
|-----------|---|--------|---------|---------|---------|---------|
| JUNE      | 1 | 91.32  | 0.04002 | 0.04977 | 0.0214  | 0.02837 |
|           | 2 | 6.57   | 0.00371 |         |         |         |
|           | 3 | 1.89   | 0.00210 |         |         |         |
|           | 4 | 2.74   | 0.00394 |         |         |         |
| JULY      | 1 | 99.67  | 0.04227 | 0.05258 | 0.02156 | 0.03102 |
|           | 2 | 7.18   | 0.00392 |         |         |         |
|           | 3 | 2.07   | 0.00222 |         |         |         |
|           | 4 | 3.00   | 0.00417 |         |         |         |
| AUGUST    | 1 | 101.63 | 0.04310 | 0.0536  | 0.02091 | 0.03269 |
|           | 2 | 7.30   | 0.00399 |         |         |         |
|           | 3 | 2.11   | 0.00226 |         |         |         |
|           | 4 | 3.05   | 0.00425 |         |         |         |
| SEPTEMBER | 1 | 91.89  | 0.04027 | 0.05009 | 0.02254 | 0.02755 |
|           | 2 | 6.61   | 0.00373 |         |         |         |
|           | 3 | 1.91   | 0.00212 |         |         |         |
|           | 4 | 2.76   | 0.00397 |         |         |         |
| OCTOBER   | 1 | 97.32  | 0.04127 | 0.05133 | 0.02258 | 0.02875 |
|           | 2 | 6.99   | 0.00382 |         |         |         |
|           | 3 | 2.02   | 0.00217 |         |         |         |
|           | 4 | 2.93   | 0.00407 |         |         |         |
| NOVEMBER  | 1 | 91.32  | 0.04002 | 0.04977 | 0.0229  | 0.02687 |
|           | 2 | 6.57   | 0.00371 |         |         |         |
|           | 3 | 1.89   | 0.00210 |         |         |         |
|           | 4 | 2.74   | 0.00394 |         |         |         |
| DECEMBER  | 1 | 97.50  | 0.04135 | 0.05143 | 0.02211 | 0.02932 |
|           | 2 | 7.01   | 0.00383 |         |         |         |
|           | 3 | 2.02   | 0.00217 |         |         |         |
|           | 4 | 2.93   | 0.00408 |         |         |         |

368

369 After the estimation of the monthly average flow rate that can be elaborated by the hydraulic turbine  
370  $\bar{Q}_{\text{turbine avg\_monthly\_model}} [\text{m}^3 * \text{s}^{-1}]$ , the management of the WSS decided to install a flow meter  
371 in the gravity adduction pipeline that connects the water source to the preloading tank. The flow  
372 meter allows to evaluate the exact flow rate values that can be elaborated by the hydraulic turbine  
373 and, at the same time, to validate the estimated results obtained with the proposed methodology.  
374 Figure 4 shows the hydraulic turbine installation site highlighted in red and connected to the  
375 gravity adduction pipeline highlighted in magenta. The location of the PRV to be dismissed is

376 also present. Table 4 lists the estimated monthly average flow rate  $\bar{Q}_{\text{turbine avg\_monthly\_model}}$  [ $\text{m}^3 \cdot$   
 377  $\text{s}^{-1}$ ] and the measured ones  $\bar{Q}_{\text{turbine avg\_monthly\_meas}}$  [ $\text{m}^3 \cdot \text{s}^{-1}$ ], along with the relative percentage  
 378 errors expressed by Eq. (8).

379 
$$\Delta\bar{Q} (\%) = \frac{\bar{Q}_{\text{turbine avg\_monthly\_model}} - \bar{Q}_{\text{turbine avg\_monthly\_meas}}}{\bar{Q}_{\text{turbine avg\_monthly\_meas}}} [-] \quad (8)$$



380  
 381 *Figure 4: Detailed view of the hydraulic turbine installation site*

Table 4: Monthly average flow rates elaborated by the hydraulic turbine (model. vs meas.)

| MONTH<br>(YEAR 2018) | $\bar{Q}_{\text{turbine avg\_monthly\_meas}}$<br>[m <sup>3</sup> *s <sup>-1</sup> ] | $\bar{Q}_{\text{turbine avg\_monthly\_model}}$<br>[m <sup>3</sup> *s <sup>-1</sup> ] | $\Delta$ (%) |
|----------------------|---|--|--------------|
| JANUARY              | 0.03600   | 0.03613  | 0.36         |
| FEBRUARY             | 0.02940   | 0.02674  | -9.05        |
| MARCH                | 0.02881   | 0.02736  | -5.03        |
| APRIL                | 0.02994   | 0.02802  | -6.41        |
| MAY                  | 0.03074   | 0.02905  | -5.50        |
| JUNE                 | 0.02983   | 0.02837  | -4.89        |
| JULY                 | 0.03183   | 0.03102  | -2.54        |
| AUGUST               | 0.03497   | 0.03269  | -6.52        |
| SEPTEMBER            | 0.02628   | 0.02755  | 4.83         |
| OCTOBER              | 0.02955   | 0.02875  | -2.71        |
| NOVEMBER             | 0.02935   | 0.02687  | -8.45        |
| DECEMBER             | 0.02939   | 0.02932  | -0.24        |
| <b>2018</b>          | <b>0.03050</b>  | <b>0.03000</b>   | <b>-1.64</b> |

383

384 Table 4 shows that the relative percentage errors related to the monthly average flow rates in the year  
385 2018 are lower than 5% in six out of twelve months, while they are slightly higher (5-7%) in four out  
386 of twelve months in the same year. The remaining months present relative percentage errors between  
387 7-10%, which are still acceptable. Nevertheless, it is pointed out that the relative percentage error  
388 referred to the yearly average flow rate potentially exploited by the hydraulic turbine  
389  $\bar{Q}_{\text{turbine avg\_yearly\_model}}$  [m<sup>3</sup> \* s<sup>-1</sup>] is sensibly lower than 5%, namely 1.64% in absolute value. It can  
390 be stated that the methodology presented in this paper is anyway a good approach for estimating the  
391 yearly average flow rate in gravity adduction pipelines when flow meters are not installed. Knowing  
392 the measured yearly average flow rate  $\bar{Q}_{\text{turbine avg\_yearly\_meas}}$  [m<sup>3</sup> \* s<sup>-1</sup>], which will be renamed



393  $\bar{Q}_{\text{turbine avg\_yearly}}$  [ $\text{m}^3 * \text{s}^{-1}$ ] hereinafter, the pressure losses  $H_{\text{loss}}$  [m] between the water source and  
 394 the preloading tank is calculated, being equal to 68.1 m. Therefore, the useful head that can be  
 395 exploited by the hydraulic turbine  $H_{\text{useful}}$  [m], considering the respective geodetic heights of the  
 396 water source (346 m) and the preloading tank (57 m), is equal to 220.9 m. Finally, the operative yearly  
 397 average measured flow rate  $\bar{Q}_{\text{turbine avg\_yearly}}$  [ $\text{m}^3 * \text{s}^{-1}$ ] of  $0.0305 \text{ m}^3 * \text{s}^{-1}$  and the useful head  
 398 exploited by the hydraulic turbine  $H_{\text{useful}}$  [m] of 220.9 m allow to evaluate the available yearly  
 399 average hydraulic power  $\bar{P}_{\text{hydraulic avg\_yearly}}$  [kW], which is approximately equal to 66 kW.

400

### 401 3.2 Flow duration curve

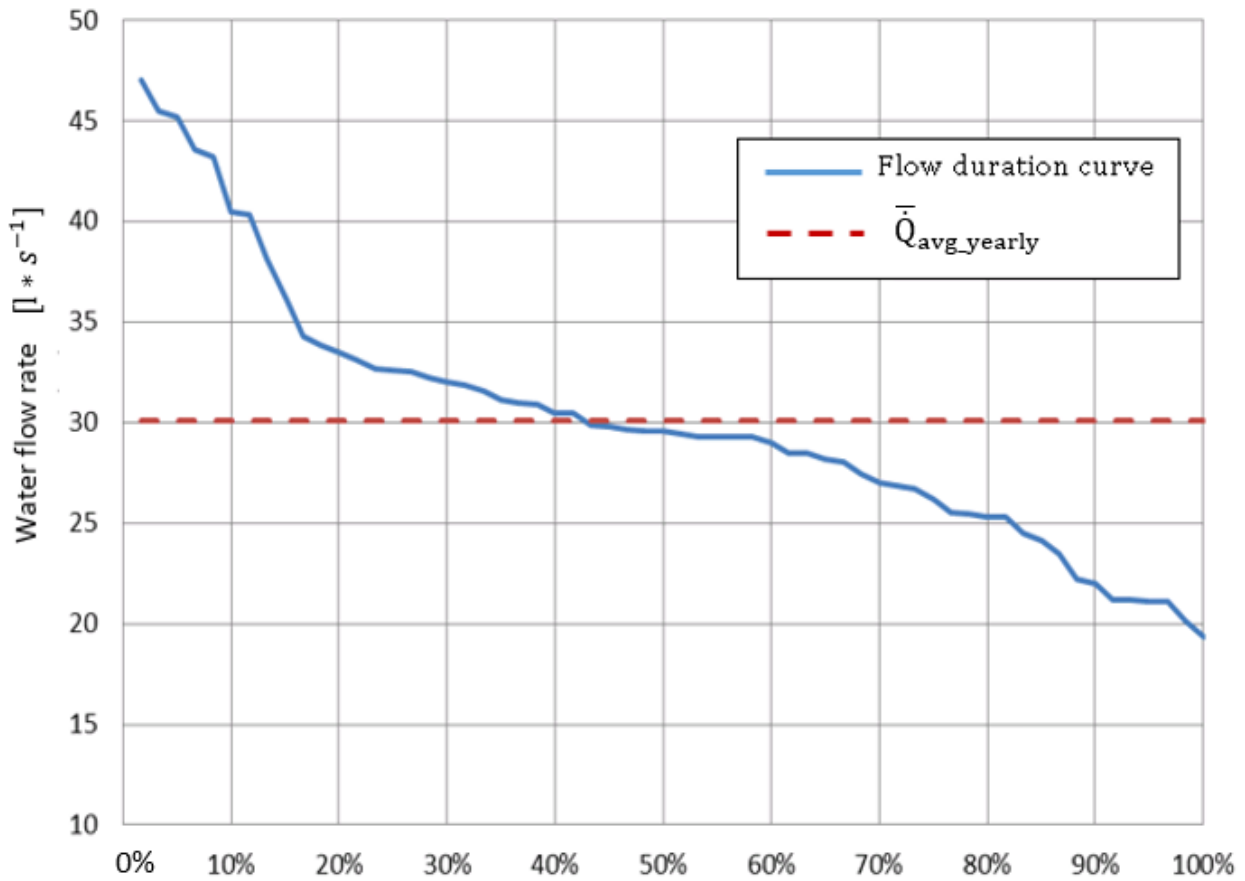
402 In Section 2, the main operating magnitudes to evaluate the performance of the hydraulic turbine to  
 403 be installed in the gravity adduction pipeline of interest have been assessed. Nevertheless, the yearly  
 404 average flow rate that can be exploited by the hydraulic turbine  $\bar{Q}_{\text{turbine avg\_yearly}}$  [ $\text{m}^3 * \text{s}^{-1}$ ] must  
 405 be checked through the flow duration curve, which is fundamental to obtain the flow rate value that  
 406 leads to the highest energy recovery. Immediately downstream the water reservoir, a flow meter is  
 407 installed. Using data measured by this flow meter between the years 2012 and 2016 (see Table 5),  
 408 both yearly average water volumes and flow rates coming from the water source are determined.

409 *Table 5: Yearly average water volumes and flow rates coming from the water reservoir (2012-2016)*

| YEAR          | WATER VOLUMES [ $\text{km}^3$ ] | YEARLY AVERAGE FLOW RATE [ $\text{m}^3 * \text{s}^{-1}$ ] |
|---------------|---------------------------------|---|
| 2016          | 946.08                          | 0.03000   |
| 2015          | 1151.56                         | 0.03652   |
| 2014          | 923.39                          | 0.02928   |
| 2013          | 898.77                          | 0.02850   |
| 2012          | 911.16                          | 0.02889   |
| AVERAGE VALUE | 966.19                          | 0.03064   |

410

411 The maximum and minimum monthly average flow rates in the five years of measurements reported  
 412 in Table 5 are approximately  $0.047 \text{ m}^3\cdot\text{s}^{-1}$  and  $0.019 \text{ m}^3\cdot\text{s}^{-1}$ , respectively. However, all the flow rates  
 413 recorded in the five years of measurements provided the flow duration curve reported in Figure 5.



414

415 *Figure 5: Flow duration curve of the gravity adduction pipeline of interest*

416

417 Figure 5 clearly shows that the monthly average flow rate of about  $0.03064 \text{ m}^3\cdot\text{s}^{-1}$  occurred more  
 418 than 40% of the measured time period. That said, if a flow rate range of  $\pm 0.005 \text{ m}^3\cdot\text{s}^{-1}$  is  
 419 considered during the operation of the hydraulic turbine, flow rates that occur up to 60% of the  
 420 measured time period can be elaborated, thus further maximizing the energy recovery potential  
 421 since the hydraulic turbine will be designed to have the maximum efficiency at almost  $0.03064$   
 422  $\text{m}^3\cdot\text{s}^{-1}$ .

423

### 424 3.3 Selection of the hydraulic turbine

425 After the flow duration curve analysis, which confirmed the correct evaluation of the yearly average  
426 flow rate  $\bar{Q}_{\text{turbine avg\_yearly}}$  [ $\text{m}^3 * \text{s}^{-1}$ ] of  $0.0305 \text{ m}^3 * \text{s}^{-1}$ , this value and the useful head  $H_{\text{useful}}$  [m]  
427 of 220.9 m, together with the rotational speed of the hydraulic turbine equal to 1000 rpm that is  
428 imposed by the electric generator, are used to evaluate the specific speed value, which is equal to  
429 0.057, in order to select the proper hydraulic machine by means of Eq. (5). It is worth noting that this  
430 value is within the range of Pelton turbines (0.05-0.35); for this reason, this kind of hydraulic machine  
431 with two jets has been chosen for being installed in the WSS site of interest. Pelton turbines have a  
432 wide range of operation in terms of flow rates; indeed, the efficiency curve is quite flat and constant  
433 down to 30% of the maximum load and between  $\pm 40\%$  with respect to the design flow rate [30]. For  
434 this reason, quite sensible flow rate variations from the design one do not affect too much the  
435 efficiency of this machine. The efficiency of the turbine is always constant during its operation  
436 since a Proportional-Integral-Derivative (PID) controller switch its functioning from one nozzle  
437 to two according to the operative flow rate by monitoring the water level of the preloading tank.  
438 Table 6 resumes the main characteristics of the Pelton turbine at its BEP, while Figure 6 shows the  
439 hydraulic machine installed in the site of interest.

440 *Table 6: Pelton turbine characteristics at its BEP*

| MAGNITUDE                                  | VALUE  |
|--|--------|
| Flow rate [ $\text{m}^3 * \text{s}^{-1}$ ] | 0.0305 |
| Useful Head [m]                            | 220.9  |
| Rotational speed [rpm]                     | 1000   |
| Total efficiency [-]                       | 0.82   |
| Power [kW]                                 | 54.19  |

441



442

443

a)

b)

444

*Figure 6: Pelton turbine installed close to the preloading of the analysed WSS*

445

#### 446 **4. ENERGY, ENVIRONMENTAL AND ECONOMIC ANALYSES**

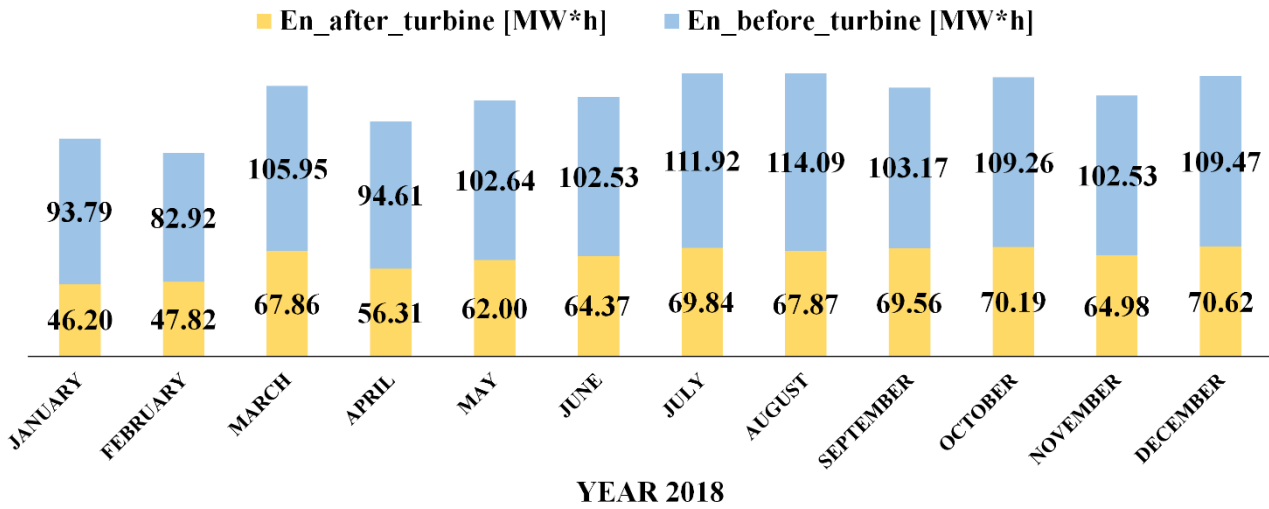
447 The values listed in Table 6 related to the Pelton turbine have been used to carry on the energy analysis  
 448 deriving by the installation of a small-scale hydropower plant in WSSs. It is worth noting that the  
 449 measured flow rate value at BEP has been used in these analyses.

450 The energy saving  $\overline{E}n_{\text{saving\_after\_turbine}}$  [MW \* h] is evaluated by the difference between the  
 451 electricity consumption before,  $\overline{E}n_{\text{before\_turbine}}$  [MW \* h], and after,  $\overline{E}n_{\text{after\_turbine}}$  [MW \* h], the  
 452 installation of the small-scale hydropower plant, as reported by Eq. (8).

$$453 \overline{E}n_{\text{saving\_after\_turbine}} = (\overline{E}n_{\text{before\_turbine}} - \overline{E}n_{\text{after\_turbine}}) [MW * h] \quad (8)$$

454

455 Precisely, 475.25 MW\*h per year are saved. To better highlight this aspect, Figure 7 shows the energy  
 456 consumed by the pumping station before and after the energy recovery intervention, where the  
 457 produced electric power is used for supplying electric energy to the pumping station.



458

459 Figure 7: Electric energy consumed by the pumping station before and after the hydraulic turbine installation

460

461 It is worth noticing that the electricity consumption after the energy recovery intervention includes:  
 462 i) the electricity withdrawn from the grid to feed the pumping station that is lowered due to the  
 463 installation of the hydraulic turbine and ii) the electricity consumed by auxiliary devices of both  
 464 pumps and turbine. Knowing the energy saving  $\overline{En}_{saving\_after\_turbine}$  [MW \* h], 88.87 TOE are saved  
 465 according to Eq. (9):

$$466 \quad TOE_{saving} = \overline{En}_{saving\_after\_turbine} \cdot FC_{TOE} [TOE] \quad (9)$$

467

468  $FC_{TOE}$  [TEP \* (kW \* h)<sup>-1</sup>] is the conversion factor equal to 0.000187 TOE \* (kW \* h)<sup>-1</sup> [31] for the  
 469 Italian scenario. This saving can be also expressed by means of tCO<sub>2</sub> not released into the atmosphere,  
 470 as expressed by Eq. (10), that leads to a value of 204.36 ktCO<sub>2</sub>:

471  $tCO_{2\_saving} = \overline{En}_{saving\_after\_turbine} \cdot Fc_{tCO_2} [tCO_2]$  (10)

472

473  $Fc_{tCO_2} [tCO_2 * (kW * h)^{-1}]$  is the conversion factor equal to  $0.43 tCO_2 * (kW * h)^{-1}$  [32]. Finally,  
 474 the gross economic saving is then obtained using Eq. (11), being equal to  $94.29 k€*year^{-1}$ :

475  $Ec_{saving\_gross} = \overline{En}_{saving\_after\_turbine} \cdot F_{ec} [€*year^{-1}]$  (11)

476

477  $F_{ec} [€*year^{-1}]$  is the gross electricity cost in 2018 for non-residential consumers with an overall  
 478 consumption of  $20-500 MW*h$  [33]. The gross economic saving  $Ec_{saving\_gross} [€ * year^{-1}]$  has to be  
 479 reduced by the Operation & Management (O&M) costs that have not been taken into account in this  
 480 work. Nevertheless, the Italian Authorities introduced incentives for energy efficiency interventions:  
 481 in this regard, energy efficiency certificates are issued according to the amount of saved TOE. In this  
 482 case, the possible economic income is calculated through Eq. (12) and it is equal to  $22.22 k€*year^{-1}$ :

483  $Ec_{eec} = TOE_{saving} \cdot F_{eec} [€*year^{-1}]$  (12)

484

485  $F_{eec} [€*TOE^{-1}]$  corresponds to the economic income obtained per each saved TOE, considering  
 486 a maximum value of  $250 €*TOE^{-1}$  [34]. Then,  $Ec_{eec} [€*year^{-1}]$  is summed to the net economic  
 487 saving  $Ec_{saving\_gross} [€*year^{-1}]$ , obtaining  $116.51 k€*year^{-1}$  that is the new economic saving  
 488  $Ec_{saving\_gross\_final} [€*year^{-1}]$ . This value is sensibly high and it is expected to keep such interesting  
 489 results also in the upcoming years since the flow rate elaborated by the Pelton turbine is almost  
 490 constant throughout the year. Table 7 resumes main energy and economic items reported in this  
 491 section.

492

493 *Table 7: Resume of energy, environmental and economic analyses of the energy efficiency intervention*

| $\bar{E}n_{\text{saving\_after\_turbine}}$ [MW * h] | $TOE_{\text{saving}}$ | $ktCO_{2\_saving}$ | $Ec_{\text{saving\_gross}}$<br>[k€*year <sup>-1</sup> ] | $Ec_{\text{cert}}$<br>[k€*year <sup>-1</sup> ] | $Ec_{\text{saving\_gross\_final}}$<br>[k€*year <sup>-1</sup> ] |
|---|-----------------------|--------------------|---|--|--|
| 475.26  | 88.87                 | 204.36             | 94.29   | 22.22  | 116.51   |

494

495 The management of the WSS under investigation have calculated that the construction of the civil,  
 496 hydraulic, and electromechanical works to build and install the hydraulic turbine are equal to 130 k€,  
 497 while the yearly operating cost is 20 k€. Thus, considering an  $Ec_{\text{saving\_gross}}$  [€ \* year<sup>-1</sup>] of 116.51  
 498 k€\*year<sup>-1</sup> and a discount rate of 2%, a Payback Period (PBP) of 3 years is achieved, as well as a Net  
 499 Present Value (NPV) equal to 1,388,000 € in 20 years.

500

## 501 **5. CONCLUSIONS**

502 This paper proposes a novel methodology capable of estimating the average flow rate in a gravity  
 503 adduction pipeline, upstream the preloading tank of a WSS, to evaluate a possible energy recovery  
 504 intervention.

505 Since the installation of flow meters in gravity adduction pipelines is quite rare and the knowledge of  
 506 the average flow rate is necessary to maximize the exploitation of the recoverable energy, a simple  
 507 methodology for flow rate evaluation is necessary. This methodology is based on the electric energy  
 508 consumption of the pumping station, since the sum of flow rates supplied by each pump is equal to  
 509 the one flowing in the gravity adduction pipeline reduced by the flow rate coming from wells. It is  
 510 worth noting that this methodology is valid only if the variability of the flow rate in gravity adduction  
 511 pipelines is restricted close to its average value. The energy recovery intervention is evaluated for a  
 512 WSS located in a mid-town in the Center of Italy. A Pelton turbine has been selected for recovering

513 the water energy content, supplying electricity to the pumping station. The useful head exploited by  
514 the hydraulic turbine is evaluated by knowing the flow rates and the dimensions, as well as the  
515 physical characteristics, of the gravity adduction pipeline in which it can be installed.

516 This methodology has been then validated using flow rates values recorded by a flow meter installed  
517 in the gravity adduction pipeline after the installation of the Pelton turbine. The validation phase has  
518 shown monthly relative percentage errors lower than 5% in six out of twelve months, a slightly higher  
519 (5-7%) in four out of twelve months in the same year, and a still acceptable relative percentage error  
520 between 7-10% in the remaining months. Nevertheless, considering the yearly average flow rate  
521 value, an absolute relative percentage error of only 1.64% with respect to measured value has been  
522 obtained. Always using the measured data, an energy saving equal to 475.26 MW\*h (88.87 TOE and  
523 204.36 ktCO<sub>2</sub>) is obtained, which results to a gross economic saving of 94.29 k€\*year<sup>-1</sup>. The gross  
524 economic saving increases up to 116.51 k€\*year<sup>-1</sup> if energy efficiency certificates issued by Italian  
525 Authorities are considered, leading to a PBP of 3 years and a NPV after twenty years of 1,388,000 €.

526 This study confirmed that energy recovery interventions improve the efficiency of a WSS when a  
527 proper methodology for the evaluation of the flow rates in gravity adduction pipelines is performed,  
528 which is fundamental for assessing its profitability when flow meters are not present.

529 In terms of future developments of this research, it would be interesting to increase the flexibility of  
530 the proposed methodology by extending the validity of the estimation of water flows, also when the  
531 flow rate to the preload tank is distributed discontinuously and not close to the yearly average one.  
532 For instance, the operation of the water pumping station could be regulated according to the average  
533 set-point level in the preloading tank by means of inverters that modulate the flow rate supplied by  
534 the pumps. Another possible development could be the evaluation of strategies that increase the self-  
535 consumption of the energy produced by the turbine (ideally up to 100%) to feed the pumping station,  
536 and modulate the pumps that feed the preload tank via inverters. Finally, another point of reflection



537 concerns the chance of increasing the energy produced by the turbine by varying the set-point level  
538 in the preload tank and thus optimizing the regulation of the spear valve.

539

## 540 **REFERENCES**

541 [1] W. Hickman, A. Muzhikyan, A.M. Farid, The synergistic role of renewable energy integration  
542 into the unit commitment of the energy water nexus, *Renewable Energy*, Year 2017, Vol. 108, Pages  
543 220-229.

544 [2] E. Ahmadi, B. McLellan, T. Tezuka, The economic synergies of modelling the renewable energy-  
545 water nexus towards sustainability, *Renewable Energy*, Year 2020, Vol. 162, Pages 1347-1366.

546 [3] J.C. Alberizzi, M. Renzi, M. Righetti, G.R. Pisaturo, M. Rossi, Speed and Pressure Controls of  
547 Pumps-as-Turbines Installed in Branch of Water-Distribution Network Subjected to Highly Variable  
548 Flow Rates, *Energies*, Year 2019, Vol. 12(24), Article 4738.

549 [4] M. Stefanizzi, T. Capurso, G. Balacco, M. Binetti, S.M. Camporeale, M. Torresi, Selection,  
550 control and techno-economic feasibility of Pumps as Turbines in Water Distribution Networks,  
551 *Renewable Energy*, Year 2020, Vol. 162, Pages 1292-1306.

552 [5] N.F. Tumen Ozdil, A. Tantekin, Exergy and exergoeconomic assessments of an electricity  
553 production system in a running wastewater treatment plant, *Renewable Energy*, Year 2016, Vol. 97,  
554 Pages 390-398.

555 [6] M. Renzi, P. Rudolf, D. Štefan, A. Nigro, M. Rossi, Installation of an axial Pump-as-Turbine  
556 (PaT) in a wastewater sewer of an oil refinery: A case study, *Applied Energy*, Year 2019, Vol. 250,  
557 Pages 665-676.

- 558 [7] T. Lydon, P. Coughlan, A. McNabola, Pressure management and energy recovery in water  
559 distribution networks: Development of design and selection methodologies using three pump-as-  
560 turbine case studies, *Renewable Energy*, Year 2017, Vol. 114, Pages 1038-1050.
- 561 [8] A. Strazzabosco, S.A. Conrad, P.A. Lant, S.J. Kenway, Expert opinion on influential factors  
562 driving renewable energy adoption in the water industry, *Renewable Energy*, Year 2020, Vol. 162,  
563 Pages 754-765.
- 564 [9] C.M. Papapostolou, E.M. Kondili, D.P. Zafirakis, G.T. Tzanes, Sustainable water supply systems  
565 for the islands: The integration with the energy problem, *Renewable Energy*, Year 2020, Vol. 146,  
566 Pages 2577-2588.
- 567 [10] X. Liu, Y. Tian, X. Lei, H. Wang, Z. Liu, J. Wang, An improved self-adaptive grey wolf  
568 optimizer for the daily optimal operation of cascade pumping stations, *Applied Soft Computing*, Year  
569 2019, Vol. 75, Pages 473-493.
- 570 [11] W. Chen, T. Tao, A. Zhou, L. Zhang, L. Liao, X. Wu, K. Yan, C. Li, T.C. Zhang, Z. Li, Genetic  
571 optimization toward operation of water intake-supply pump stations system, *Journal of Cleaner*  
572 *Production*, Year 2021, Vol. 279, Article 123573.
- 573 [12] X. Zou, H. Huang, L. Li, Z. Liu, An Improved Energy-Saving Design Method for Drive System  
574 with Multi Motor-Pumps by Using Genetic Algorithm, *Procedia CIRP*, Year 2019, Pages 79-83.
- 575 [13] C. Zhang, L. Wang, H. Li, Optimization method based on process control of a new-type  
576 hydraulic-motor hybrid beam pumping unit, *Measurement*, Year 2020, Vol. 158, Article 107716.
- 577 [14] A. Mamade, D. Loureiro, D. Covas, H. Alegre, Energy Auditing As a Tool for Improving Service  
578 Efficiency of Water Supply Systems, *Procedia Engineering*, Vol. 89, Year 2014, Pages 557-564.

579 [15] C. Huang, Y. Li, X. Li, H. Wang, J. Yan, X. Wang, J. Wu, F. Li, Understanding the water-energy  
580 nexus in urban water supply systems with cities features, *Energy Procedia*, Vol. 152, Year 2018,  
581 Pages 265-270.

582 [16] M.R. Nogueira Vilanova, J.A. Perrella Balestieri, Energy and hydraulic efficiency in  
583 conventional water supply systems, *Renewable and Sustainable Energy Reviews*, Year 2014, Vol.  
584 30, Pages 701-714.

585 [17] G. Meirelles Lima, B. Melo Brentan, E. Luvizotto, Optimal design of water supply networks  
586 using an energy recovery approach, *Renewable Energy*, Year 2018, Vol. 117, Pages 404-413.

587 [18] S. Kucukali, Hydropower potential of municipal water supply dams in Turkey: a case of study  
588 in Ulutan Dam, *Energy Policy*, Year 2010, Vol. 38, Pages 6534-6539.

589 [19] A. McNabola, P. Coughlan, A.P. Williams, Energy recovery in the water industry: an assessment  
590 of the potential of micro-hydropower, *Water Environmental Journal*, Year 2013, Vol. 27, Pages 1-11.

591 [20] J. Saldarriaga, C.A. Salcedo, Determination of Optimal Location and Settings of Pressure  
592 Reducing Valves in Water Distribution Networks for Minimizing Water Losses, *Procedia*  
593 *Engineering*, Year 2015, Vol. 119, Pages 973-983.

594 [21] F. García-Ávila, A. Avilés-Añazco, J. Ordoñez-Jara, C. Guanuchi-Quezada, L. Flores del Pino,  
595 L. Ramos-Fernández, Pressure management for leakage reduction using pressure reducing valves.  
596 Case study in an Andean city, *Alexandria Engineering Journal*, Year 2019, Vol. 58, Pages 1313-1326.

597 [22] C. Van den Berg, The Drivers of Non-Revenue Water: How Effective Are Non-Revenue Water  
598 Reduction Programs?, *Policy Research Working Paper*, 6997, Year 2014. Available at:  
599 <http://documents1.worldbank.org/curated/en/949281468161359020/pdf/WPS6997.pdf> (last  
600 accessed on the 05/07/2021).

- 601 [23] F. Vieira, H.M. Ramos, Hybrid solution and pump-storage optimization in water supply system  
602 efficiency: a case of study, *Energy Policy*, Year 2008, Vol. 36, Pages 4142-4148.
- 603 [24] Z. Xu, L. Yao, X. Chen, Urban water supply system optimization and planning: Bi-objective  
604 optimization and system dynamics methods, *Computers & Industrial Engineering*, Year 2020, Vol.  
605 142, Article 106373.
- 606 [25] S. Kucukali, Municipal water supply dams as a source of small hydropower in Turkey,  
607 *Renewable Energy*, Vol. 35, Year 2010, Pages 2001-2007.
- 608 [26] L-T. Wong, K-W Mui, A Review of Demand Models for Water Systems in Buildings including  
609 a Bayesian Approach, *Water*, Volume 10(8), Year 2018, Article 1078.
- 610 [27] L.K. Letting, Y. Hamam, A.M. Abu-Mahfouz, Estimation of Water Demand in Water  
611 Distribution Systems Using Particle Swarm Optimization, *Water*, Volume 9(8), Year 2017, Article  
612 593.
- 613 [28] G. Balacco, A. Carbonara, A. Gioia, V. Iacobellis, A.F. Piccinini, Evaluation of Peak Water  
614 Demand Factors in Puglia (Southern Italy), *Water*, Volume 9(2), Year 2017, Article 96.
- 615 [29] V. Milano, *Acquedotti Guida alla progettazione* (in Italian), HOEPLI, Year 2012, Pages 650.
- 616 [30] H. Jeon, J. Hoon Park, Y. Shin, M. Choi, Friction loss and energy recovery of a Pelton turbine  
617 for different spear positions, *Renewable Energy*, Year 2018, Vol. 123, Pages 273-280.
- 618 [31] Autorità Regolazione Energia Reti e Ambiente (ARERA), *Deliberazione dell’Autorità*  
619 *618/2013/R/EFR* (in Italian). Available at: <https://www.arera.it/allegati/docs/13/618-13.pdf> (last  
620 accessed on the 05/07/2021).
- 621 [32] Agenzia nazionale per le nuove tecnologie, l’energia e lo sviluppo economico sostenibile  
622 (ENEA), *Rapporto Energia e Ambiente 2002* (in Italian). Available at:  
623 [http://old.enea.it/com/web/pubblicazioni/REA\\_02/analisi\\_02.pdf](http://old.enea.it/com/web/pubblicazioni/REA_02/analisi_02.pdf) (last accessed on the 05/07/2021).

624 [33] European Statistical Office (EUROSTAT). Available at:  
625 <https://ec.europa.eu/eurostat/web/energy/data/database> (last accessed on the 05/07/2021).

626 [34] Gestore dei Servizi Energetici (GSE), Certificati bianchi (in Italian). Available at:  
627 <https://www.gse.it/servizi-per-te/efficienza-energetica/certificati-bianchi> (last accessed on the  
628 05/07/2021).