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(Article begins on next page)

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 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

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

KEYWORDS

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

NOMENCLATURE

A_{ind} = Area occupied by industrial users [m²]

A_{res} = Area occupied by residential users [m²]

Ec_{eec} = Economic saving due to the energy efficiency certificates [€*year⁻¹]

Ec_{saving_gross} = Gross economic saving [€*year⁻¹]

$Ec_{saving_gross_final}$ = Gross economic saving considering the energy efficiency certificates [€*year⁻¹]

$\overline{En}_{after_turbine}$ = Electric energy consumed by the pumping station after the installation of the hydraulic turbine [MW*h]

$\overline{En}_{before_turbine}$ = Electric energy consumed by the pumping station before the installation of the hydraulic turbine [MW*h]

$\overline{En}_{electric_bill}$ = Average electricity bill consumption of the pumping station [MW*h]

$\overline{En}_{electric_pump}$ = Average electricity consumption of the pumping station [MW*h]

$\overline{En}_{electric_pump,i}$ = 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_{tCO_2} = Conversion factor from kW*h to tCO₂ [tCO₂*(kW*h)⁻¹]
- 50 F_{TOE} = Conversion factor from kW*h to TOE [TOE*(kW*h)⁻¹]
- 51 F_{ec} = Conversion factor from kW*h to € [€*(kW*h)⁻¹]
- 52 F_{eec} = Conversion factor from TOE to € [€*TOE⁻¹]
- 53 g = Gravity acceleration [m*s⁻²]
- 54 H = Head [m]
- 55 $H_{\text{available}}$ = Available head [m]
- 56 H_{loss} = Head losses [m]
- 57 H_{useful} = Useful head [m]
- 58 n_{ind} = Population density in industrial areas [person*m⁻²]
- 59 n_{res} = Population density in residential areas [person*m⁻²]
- 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 [m³*s⁻¹]
- 63 $\overline{Q}_{\text{avg_yearly}}$ = Yearly average flow rate in a gravity adduction pipeline [m³*s⁻¹]
- 64 $\overline{Q}_{\text{pump avg_monthly}}$ = Monthly average flow rate elaborated by the pumping station [m³*s⁻¹]

- 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 [m^3]
- 77 $V_{\text{monthly_ind}}$ = Monthly water volume consumption per each residential user [m^3]
- 78 $V_{\text{monthly_res}}$ = Monthly water volume consumption per each industrial user [m^3]
- 79 **tCO₂_saving** = Tonnes of CO₂ [tCO₂] saving
- 80 **TOE_{saving}** = Tonnes of Oil Equivalent [TOE] saving
- 81 $\Delta \bar{Q}$ = Relative percentage error related to the flow rate estimation [%]
- 82 η_{pump} = Total efficiency of a hydraulic pump [-]
- 83 η_{turbine} = Total efficiency of the hydraulic turbine [-]

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

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

86 ω_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 CO₂ 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⁻³ in developing countries and reach
126 values higher than 3 (kW*h)*m⁻³ 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

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

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

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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 tCO₂ emissions not released into the atmosphere, and the economic saving due to the energy
222 efficiency intervention are discussed.

223

224

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 Mm³. 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.

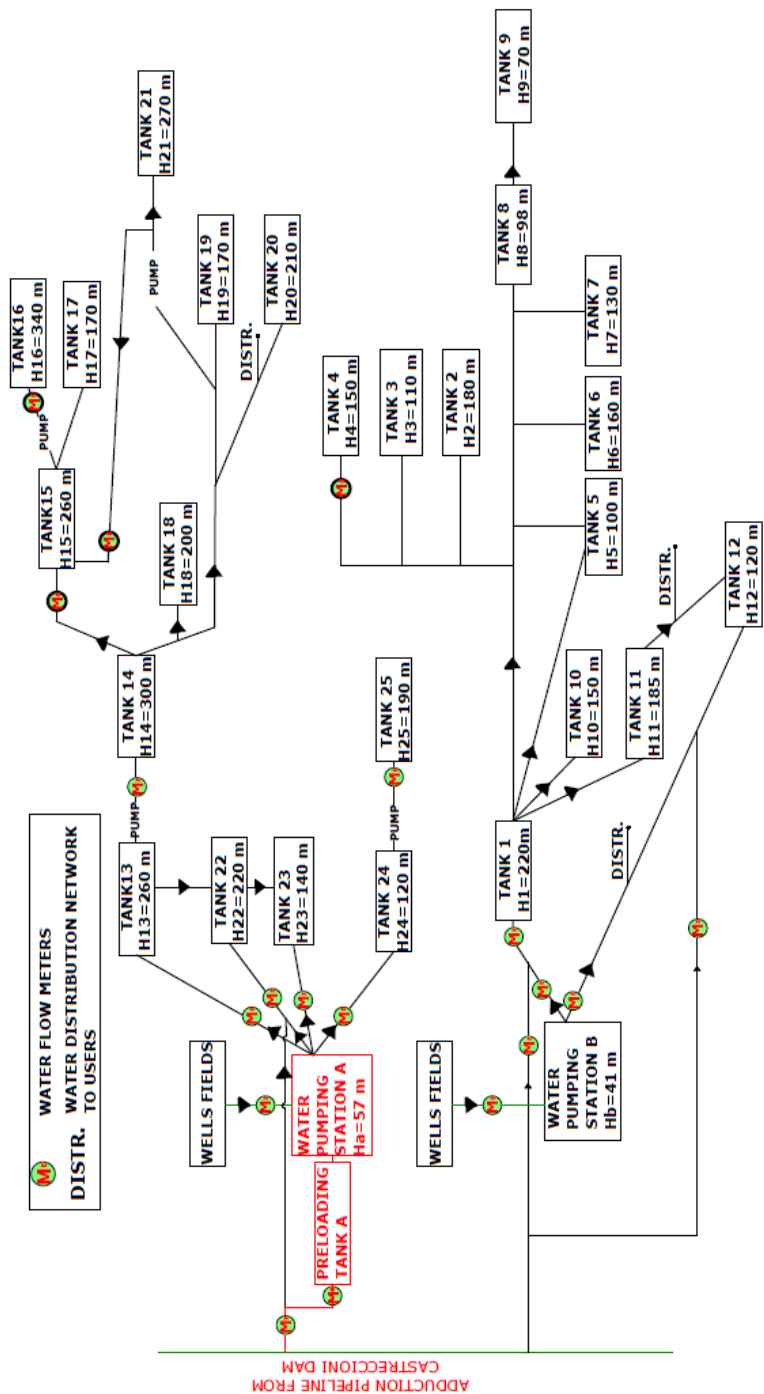
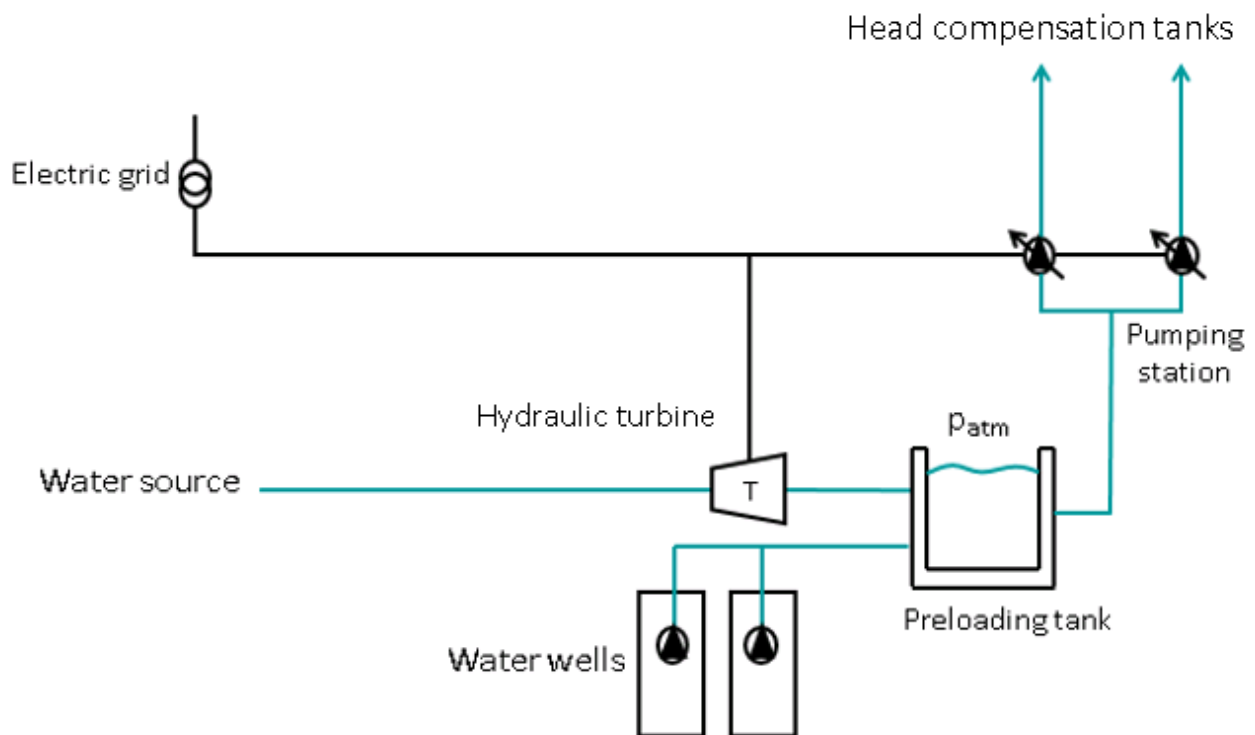


Figure 1: Layout of the analysed WSS

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

WATER SOURCE	LOADING AND PRELOADING TANK (GEODETIC HEIGHT)	HEAD COMPENSATION TANK (GEODETIC HEIGHT)	GEODETIC HEIGHT DIFFERENCE
CASTRECCIONI 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

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

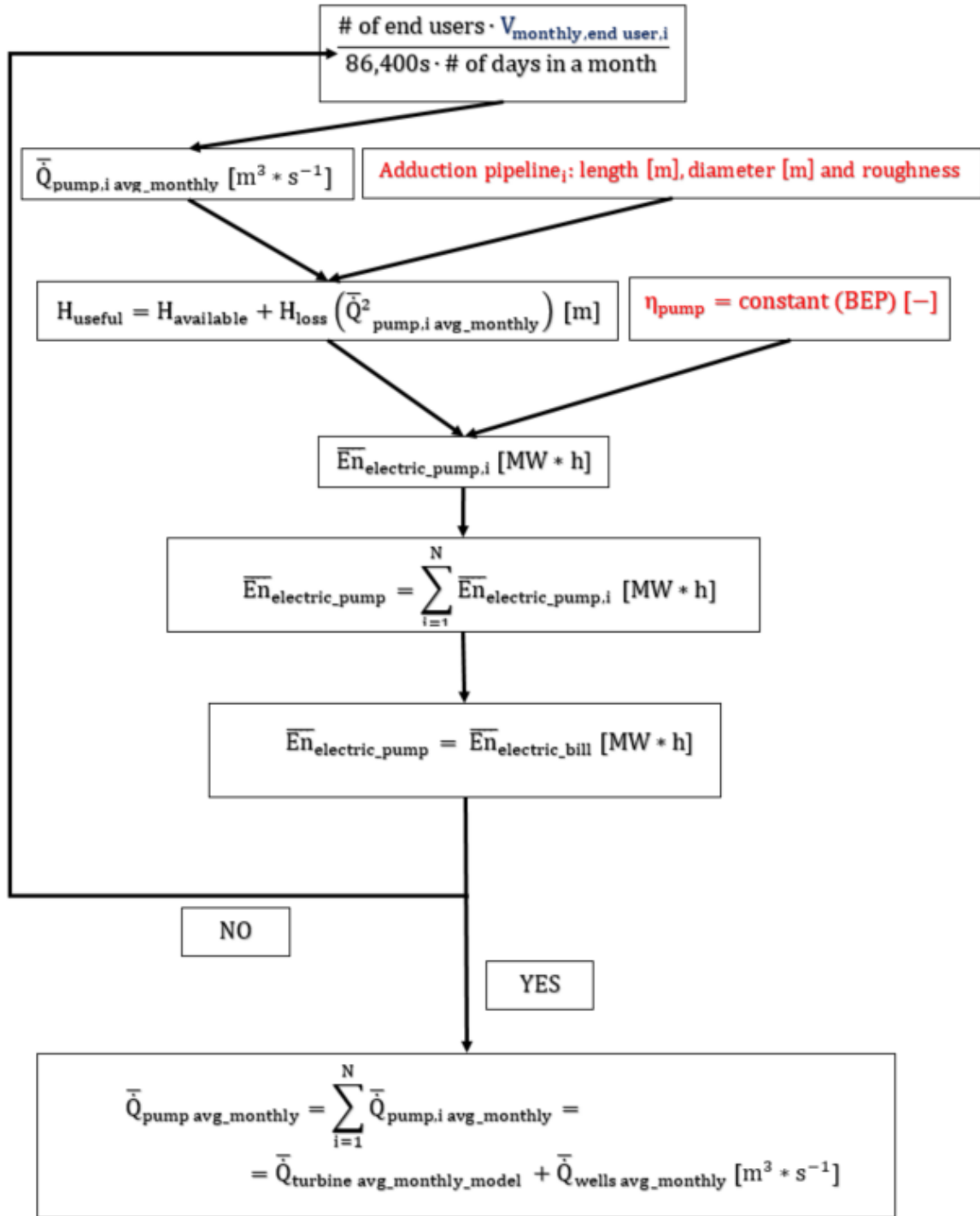
$\bar{Q}_{\text{pump},i \text{ avg_monthly}}$ [$\text{m}^3 * \text{s}^{-1}$] elaborated by each pump;

2. both dimensions and physical characteristics of the adduction pipelines that connect each pump to the respective loading/head compensation tank are known as well. The monthly average flow rate elaborated by each pump $\bar{Q}_{\text{pump},i \text{ avg_monthly}}$ [$\text{m}^3 * \text{s}^{-1}$] previously evaluated is used to calculate the head losses along each adduction pipeline, being a quadratic function of the flow rate;
3. the useful head H_{useful} [m] provided by each pump is equal to the sum of the geodetic height difference between the head compensation tank and the preloading one $H_{\text{available}}$ [m] plus the head losses along the adduction pipelines H_{loss} [m] using the one-term quadratic formula valid for fully turbulent flow regimes [29];
4. since the pumps are installed in parallel, the same hydraulic efficiency within all the operating range is assumed, since they operate close to their Best Efficiency Point (BEP) most of the time. Therefore, Eq. (2) provides the monthly average electric energy $\bar{E}n_{\text{electric_pump},i}$ [MW * h] consumed by each pump:

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

5. the sum of the electric energies consumed by each pump has to be equal to the one in the electric bill; if not, the monthly water volume consumption $\bar{V}_{\text{monthly,end user},i}$ [m^3] of each end user is modified iteratively until the solution converges;
6. finally, when the convergence of the solution is reached, the sum of the monthly average flow rates elaborated by each pump $\bar{Q}_{\text{pump},i \text{ avg_monthly}}$ [$\text{m}^3 * \text{s}^{-1}$] leads to the monthly average 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

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

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 its angular rotational speed ω [$\text{rad} \cdot \text{s}^{-1}$] that is dependent on both grid frequency and characteristics of the electric generator, allows to select the proper machine to be installed close to the preloading tank. In particular, the most important dimensionless parameter that characterizes which machine better suits the available operative conditions is the specific speed ω_s [–], as expressed by Eq. (5).

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

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

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

$$\bar{E}_{\text{electric_turbine avg_monthly}} = \bar{P}_{\text{turbine avg_monthly}} \cdot (24\text{h} \cdot \text{days in a month}) \text{ [MW} \cdot \text{h]} \quad (7)$$

3. CASE STUDY

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

As already stated in Section 2, the monthly average electric energy $\overline{E}_{\text{electric_turbine avg_monthly}}$ [MW * h] consumed by the pumping station, together with the useful head H_{useful} [m] and their efficiencies η_{pump} [–] (see Table 2), allows to estimate the monthly average flow rate elaborated by the pumping station $\overline{Q}_{\text{pump avg_monthly}}$ [m³ * s⁻¹] through Eq. (2). Furthermore, the obtained monthly average flow rate elaborated by the pumping station $\overline{Q}_{\text{pump avg_monthly}}$ [m³ * s⁻¹] has to be shortened by the the water flow rates coming from the wells $\overline{Q}_{\text{wells avg_yearly}}$ [m³ * s⁻¹]. Finally, the monthly average flow rate elaborated by the hydraulic turbine $\overline{Q}_{\text{turbine avg_monthly_model}}$ [m³ * s⁻¹] is obtained, which can be also expressed as yearly average flow rate $\overline{Q}_{\text{turbine avg_yearly_model}}$ [m³ * s⁻¹] according to Eq. (3). Table 3 sums up the numerical values of the magnitudes previously mentioned related to the year 2018.

It is worth noting that the overall efficiency of each pump η_{pump} has been set equal to 0.65, according to the point 4 of Subsection 2.2 and the available datasheets. Furthermore, the monthly water consumption of each end user $V_{\text{monthly,end user,i}}$ [m³] provided by each pump is considered the same and equal to 12 m³, taking into account an average water volume consumption of about 0.4 m³*day⁻¹ per each end user [29]. This was possible since the distribution of the end users per each pump is homogeneous in terms of both residential and industrial consumers.

364

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

# of the PUMP	# of end users	$V_{\text{monthly, end user, } i}$ [m ³]	Adduction pipeline length [km]	Adduction pipeline diameter [m]	$H_{\text{available}}$ [m]	η_{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

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

MONTH (YEAR 2018)	PUMP	$E_{\text{electric_pump, } i}$ [MW*h]	$\dot{Q}_{\text{pump, } i \text{ avg_monthly_model}}$ [m ³ *s ⁻¹]	$\dot{Q}_{\text{pump avg_monthly_model}}$ [m ³ *s ⁻¹]	$\dot{Q}_{\text{wells avg_monthly}}$ [m ³ *s ⁻¹]	$\dot{Q}_{\text{turbine avg_monthly_model}}$ [m ³ *s ⁻¹]
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			

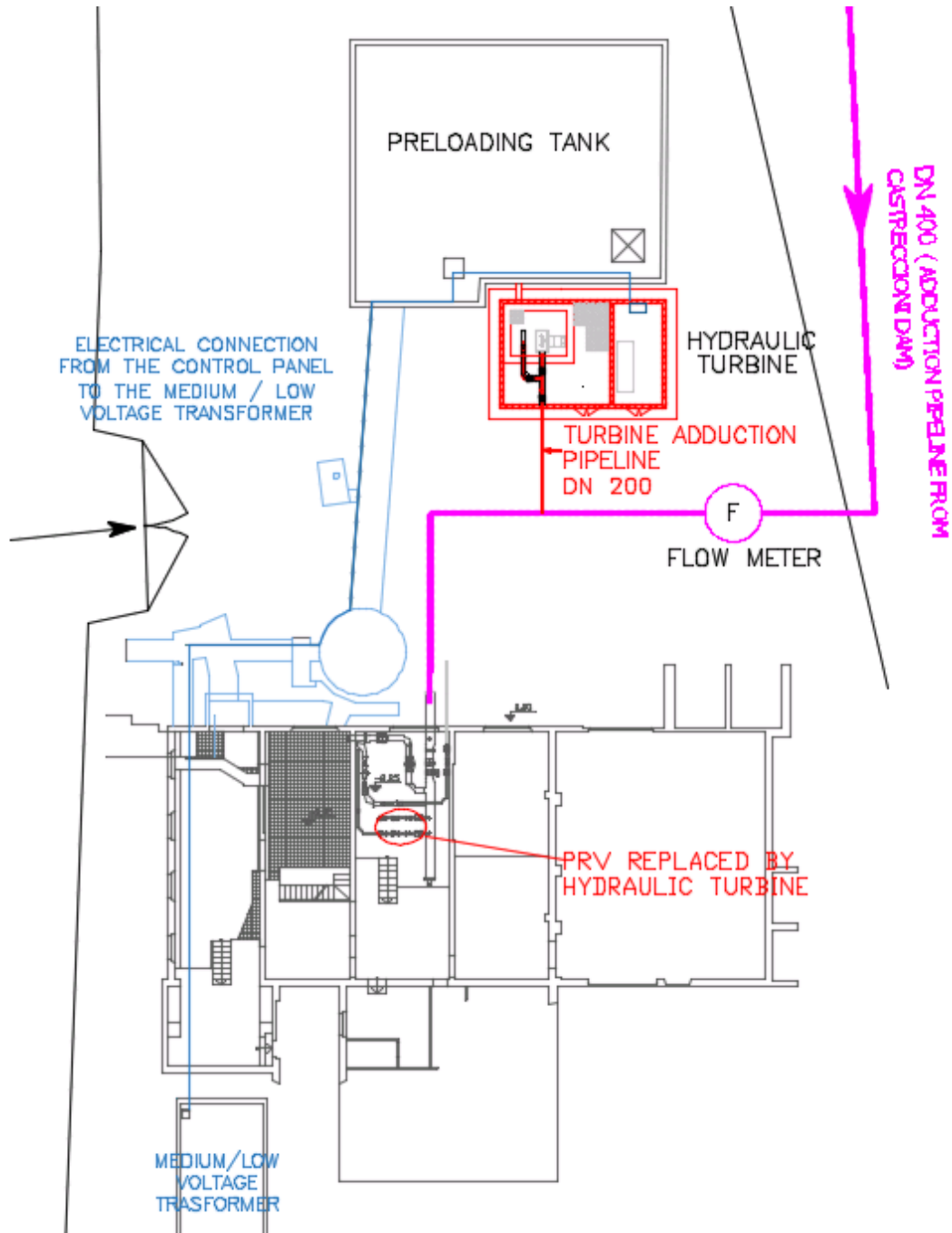
JUNE	1	91.32	0.04002	0.04977	0.0214	0.02837
	2	6.57	0.00371			
	3	1.89	0.00210			
	4	2.74	0.00394			
JULY	1	99.67	0.04227	0.05258	0.02156	0.03102
	2	7.18	0.00392			
	3	2.07	0.00222			
	4	3.00	0.00417			
AUGUST	1	101.63	0.04310	0.0536	0.02091	0.03269
	2	7.30	0.00399			
	3	2.11	0.00226			
	4	3.05	0.00425			
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 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).

$$379 \quad \Delta \bar{Q} (\%) = \frac{\bar{Q}_{\text{turbine avg_monthly_model}} - \bar{Q}_{\text{turbine avg_monthly_meas}}}{\bar{Q}_{\text{turbine avg_monthly_meas}}} [-] \quad (8)$$



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

382

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

MONTH (YEAR 2018)	$\dot{Q}_{\text{turbine avg_monthly_meas}}$ [m ³ *s ⁻¹]	$\dot{Q}_{\text{turbine avg_monthly_model}}$ [m ³ *s ⁻¹]	Δ (%)
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
2018	0.03050	0.03000	-1.64

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 $\bar{Q}_{\text{turbine avg_yearly_model}}$ [m³ * s⁻¹] 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 $\bar{Q}_{\text{turbine avg_yearly_meas}}$ [m³ * s⁻¹], which will be renamed

393 $\bar{Q}_{\text{turbine avg_yearly}}$ [$\text{m}^3 * \text{s}^{-1}$] hereinafter, the pressure losses H_{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_{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_{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

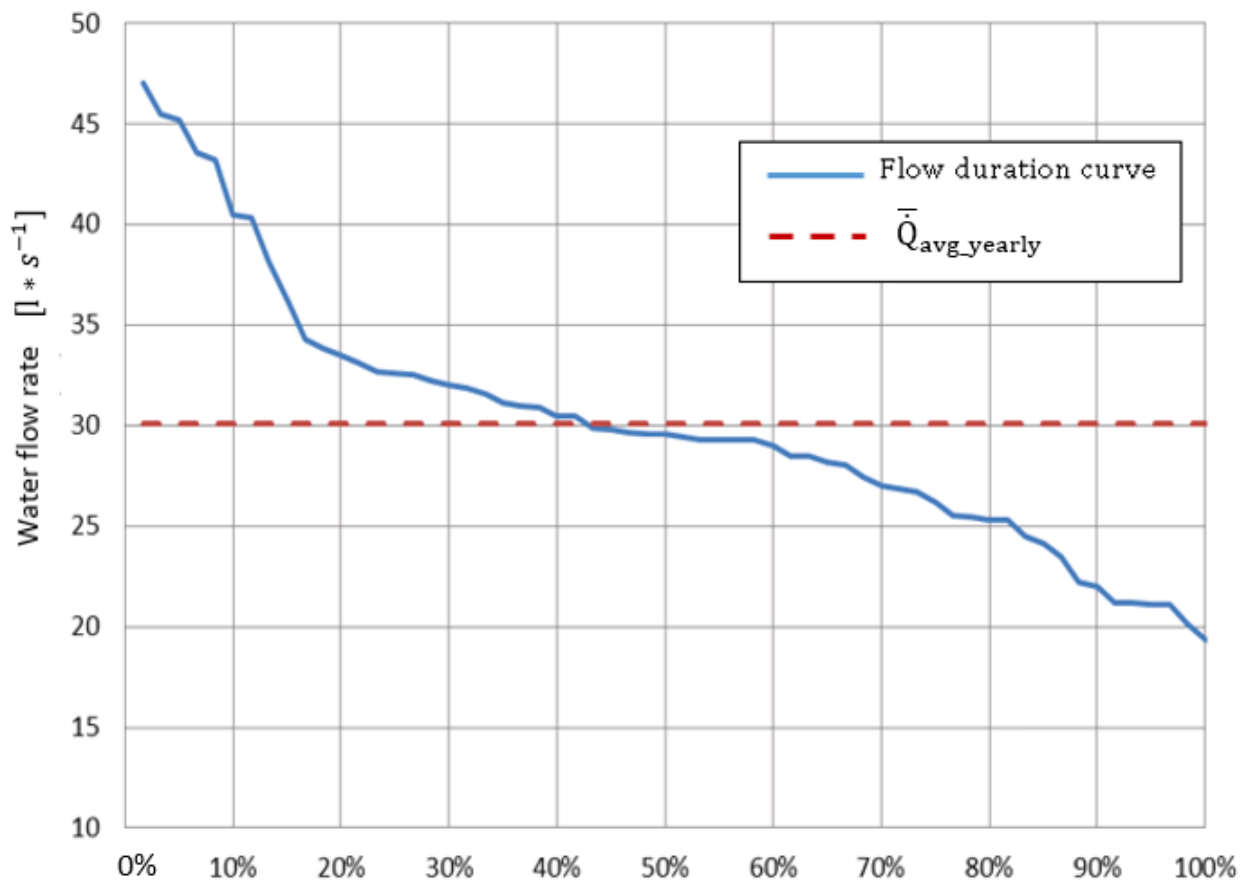
402 In Section 2, the main operating magnitudes to evaluate the performance of the hydraulic turbine to
 403 be installed in the gravity adduction pipeline of interest have been assessed. Nevertheless, the yearly
 404 average flow rate that can be exploited by the hydraulic turbine $\bar{Q}_{\text{turbine avg_yearly}}$ [$\text{m}^3 * \text{s}^{-1}$] 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 [km^3]	YEARLY AVERAGE FLOW RATE [m^3s^{-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 $\text{m}^3\cdot\text{s}^{-1}$.

3.3 Selection of the hydraulic turbine

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

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



a)

b)

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

4. ENERGY, ENVIRONMENTAL AND ECONOMIC ANALYSES

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

The energy saving $\overline{En}_{\text{saving_after_turbine}}$ [MW * h] is evaluated by the difference between the electricity consumption before, $\overline{En}_{\text{before_turbine}}$ [MW * h], and after, $\overline{En}_{\text{after_turbine}}$ [MW * h], the installation of the small-scale hydropower plant, as reported by Eq. (8).

$$\overline{En}_{\text{saving_after_turbine}} = (\overline{En}_{\text{before_turbine}} - \overline{En}_{\text{after_turbine}}) [MW * h] \quad (8)$$

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

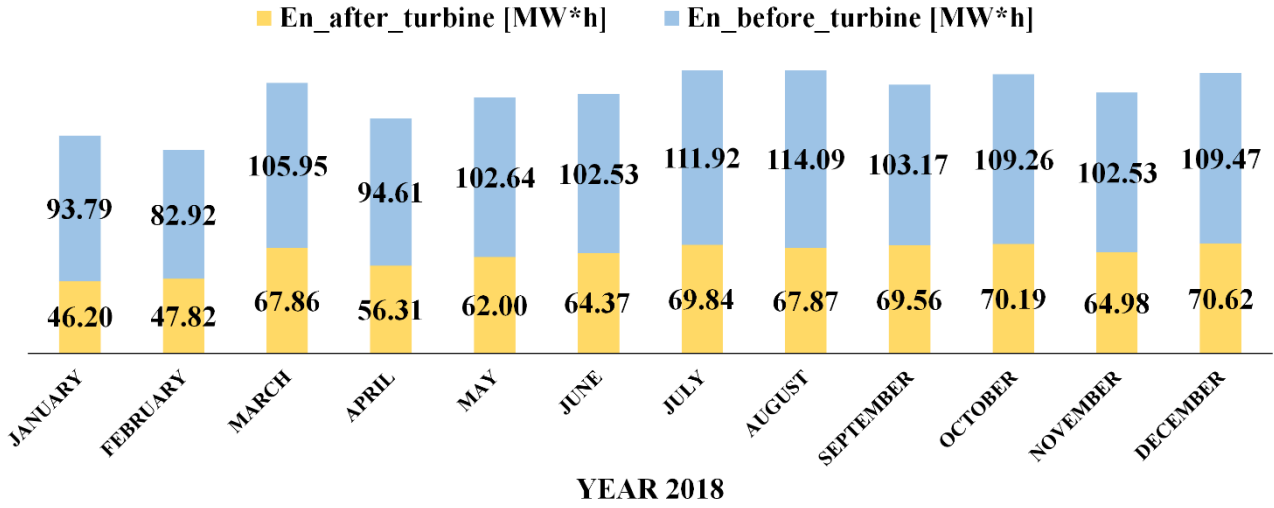


Figure 7: Electric energy consumed by the pumping station before and after the hydraulic turbine installation

It is worth noticing that the electricity consumption after the energy recovery intervention includes:

- i) the electricity withdrawn from the grid to feed the pumping station that is lowered due to the installation of the hydraulic turbine and
- ii) the electricity consumed by auxiliary devices of both pumps and turbine.

Knowing the energy saving $\overline{En}_{saving_after_turbine}$ [MW * h], 88.87 TOE are saved according to Eq. (9):

$$TOE_{saving} = \overline{En}_{saving_after_turbine} \cdot Fc_{TOE} [TOE] \quad (9)$$

Fc_{TOE} [TEP * (kW * h)⁻¹] is the conversion factor equal to 0.000187 TOE * (kW * h)⁻¹ [31] for the Italian scenario. This saving can be also expressed by means of tCO₂ not released into the atmosphere, as expressed by Eq. (10), that leads to a value of 204.36 ktCO₂:

$$tCO_{2_saving} = \overline{En}_{saving_after_turbine} \cdot Fc_{tCO_2} [tCO_2] \quad (10)$$

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 $94.29 k€*year^{-1}$:

$$Ec_{saving_gross} = \overline{En}_{saving_after_turbine} \cdot F_{ec} [€*year^{-1}] \quad (11)$$

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 $22.22 k€*year^{-1}$:

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

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*

$\overline{E}_{n_{\text{saving_after_turbine}}} \text{ [MW} \cdot \text{h]}$	$\text{TOE}_{\text{saving}}$	$\text{ktCO}_{2_{\text{saving}}}$	$\text{Ec}_{\text{saving_gross}}$ [k€*year ⁻¹]	Ec_{cert} [k€*year ⁻¹]	$\text{Ec}_{\text{saving_gross_final}}$ [k€*year ⁻¹]
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 $\text{Ec}_{\text{saving_gross}}$ [€ * year⁻¹] of 116.51
 498 k€*year⁻¹ 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

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

This methodology has been then validated using flow rates values recorded by a flow meter installed in the gravity adduction pipeline after the installation of the Pelton turbine. The validation phase has shown monthly relative percentage errors lower than 5% in six out of twelve months, a slightly higher (5-7%) in four out of twelve months in the same year, and a still acceptable relative percentage error between 7-10% in the remaining months. Nevertheless, considering the yearly average flow rate value, an absolute relative percentage error of only 1.64% with respect to measured value has been obtained. Always using the measured data, an energy saving equal to 475.26 MW*h (88.87 TOE and 204.36 ktCO₂) is obtained, which results to a gross economic saving of 94.29 k€*year⁻¹. The gross economic saving increases up to 116.51 k€*year⁻¹ if energy efficiency certificates issued by Italian Authorities are considered, leading to a PBP of 3 years and a NPV after twenty years of 1,388,000 €.

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

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

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