UNIVERSITÁ POLITECNICA DELLE MARCHE
Master's Degree in Environmental Engineering

# SUSTAINABLE ENERGY GENERATION: DESIGNING A 100 kW MICRO HYDROPOWER PLANT UTILIZING REPURPUSED FISH FARMING TANKS

Supervisor: Prof. Eng. Postacchini Matteo
Co-supervisor: Eng. Margione Diego

Student:
Natalie Bianchi

A.Y. 2023-2024

# Abstract

Hydropower is crucial for Europe's energy landscape. The EU has binding targets to promote renewable energy expansion and reduce $CO_2$ emissions. By 2030, renewables are expected to account for at least 45% of the electricity sector. Hydropower is currently the number one renewable energy source in Europe, contributing significantly to achieving these targets. Its potential relies in making the most of the geographical resources as well as modernising existing facilities, pioneering innovative small-scale and run-of-river projects, and advancing pumped storage systems. The success of European hydropower development depends on a robust framework supporting an ambitious energy transition. While solar and wind energies have challenges due to the high variability of sun and wind, the hydropower potential can be a catalyst for the renewables' success thanks to its flexibility, efficiency, and environmental acceptance. Europe's energy transition towards carbon neutrality by 2050 is a monumental endeavour, and hydropower can lead the way. The scope of this project has been that to plan a micro hydropower plant (around 100kW) with the intent to produce electricity to be transferred to the grid operator with almost no impacts on the hydraulic regime of the river of interest, the Burano River in the "Foci" locality in the Marche Region. The project is based on the restoration of an existing counter-bridle system and a dismissed concrete offshoot which used to be a fish farming until the 1980s. Hence, the project consists of the adaptation of the existing channel used for feeding the fishponds, by reprofiling and constructing special spillway inlets. The plan involves the installation of sluice gates for channel feeding, the construction of a hydroelectric power plant with a spiral chamber in the area currently occupied by the old fishponds with access from the flat area adjacent to the ponds, and the construction of the Enel delivery substation in the area of access to the plant.

# Abstract (Italian)

L'energia idroelettrica è fondamentale per il panorama energetico europeo. L'UE ha definito obiettivi vincolanti per promuovere l'espansione delle energie rinnovabili e ridurre le emissioni di $CO_2$. Entro il 2030, le energie rinnovabili dovranno rappresentare almeno il 45% del settore elettrico. L'energia idroelettrica è attualmente la prima fonte di energia rinnovabile in Europa e contribuisce in modo significativo al raggiungimento di questi obiettivi. Il suo potenziale si basa sullo sfruttamento delle risorse geografiche, sull'ammodernamento degli impianti esistenti, sulla sperimentazione di progetti innovativi su piccola scala e di tipo run-of-river e sul progresso dei sistemi di pompaggio. Il successo dello sviluppo dell'energia idroelettrica in Europa dipende da un quadro normativo solido che sostiene una transizione energetica ambiziosa. Mentre da un lato le energie solare ed eolica presentano delle sfide a causa della elevata variabilità di sole e vento, il panorama idroelettrico può essere un catalizzatore per il raggiungimento del successo nell'ambito delle energie rinnovabili grazie alla sua flessibilità ed efficienza, oltre che per la semplicità legata

alla richiesta delle autorizzazioni ambientali. La transizione energetica europea verso la neutralità delle emissioni di carbonio entro il 2050 è un'impresa monumentale e l'energia idroelettrica può fare da apripista. Lo scopo di questo progetto è stato quello di progettare una microcentrale idroelettrica (intorno a 100kW) con l'intento di produrre energia elettrica da cedere al gestore di rete con un impatto pressoché nullo sul regime idraulico del fiume di interesse, il fiume Burano, sito in località “Foci” nella Regione Marche. Il progetto si basa sul ripristino di un sistema di controbriglia già esistente, nonchè di una derivazione in cemento armato per un’attività d’itticoltura dismessa negli anni ’80. Il progetto consiste quindi nell'adeguamento di un canale già esistente utilizzato per l'alimentazione delle vasche adibite all’itticolutra, attraverso la riprofilatura e la costruzione di apposite paratoie. Il piano prevede l'installazione di paratoie per l'alimentazione del canale, la costruzione di una centrale idroelettrica con camera a spirale nell'area attualmente occupata dalle vasche dismesse, con accesso dalla zona pianeggiante adiacente, e infine la realizzazione della cabina di consegna Enel nell'area di accesso alla centrale.

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# INTRODUCTION

The project aims to design a 100kW micro hydropower plant placed along the Burano River in the municipality of Cagli, in the Pesaro-Urbino Province in the Marche Region.

The project is motivated by the rapidly evolving energy landscape, which compels innovative companies to produce clean energy from renewable sources in order to meet the $CO_2$ reduction commitments outlined in the Kyoto Protocol. Additionally, the liberalization of the energy market has encouraged the development of small-scale plants distributed across the European territory.

The primary aim is that of restoring an existing counter-bridle system and a disused concrete offshoot, previously used for fish farming until the 1980s. The project includes adapting the existing channel that fed the fishponds by reprofiling the tanks, installing sluice gates for the channel feeding, building the hydroelectric power plant with a spiral chamber in the area of the old fishponds, and constructing an Enel delivery substation near the access area of the plant.

This thesis is structured as follows:

- The first chapter provides an overview of the hydroelectric sector, detailing its applications globally, in Europe, and in Italy. It also categorizes hydropower plants based on their capacity and functionality. Additionally, it includes a brief introduction to the different types of hydropower plants, with a particular focus on micro hydropower applications (100kW).
- The second chapter, which is the core of the thesis, meticulously outlines the authorization steps. It details the initial project attempt from 2012, the subsequent rejected project from 2020, and finally the new current project. It also covers the software used to design and model the entire hydroelectric power plant, encompassing both civil and mechanical components. Finally, it provides an in-depth study of all the plant's components.
- The third chapter concerns the most technical part of the thesis, it presents the technical, the hydraulic and the energy output analyses on which the whole project was based on.

# 1 HYDROELECTRIC POWER PLANTS

Hydropower generation has been exploited since the late 19th century and since then they have been continuously improving by simply exploiting the simple concept of converting the gravitational energy of the water into mechanical energy and then electrical energy. Basically, the flow of the water is able to activate and turn a turbine, which is in turn connected to a generator. Hence, the generated electricity flows into a substation, where the voltage is increased, and the electricity is finally distributed to the end user or fed into the power grid.

## 1.1 WORLDWIDE HYDROPOWER OUTLOOK

The headline of 2024 is the growth in the global hydropower fleet to 1,416GW (Figure 1 and Figure 2). Conventional hydropower capacity grew by 7.2GW reaching 1,237GW, while pumped storage hydropower grew by 6.5GW reaching 179GW. In 2023 there was a decrease in generation of up to 4,185TWh which reflects drought conditions in some significant hydropower markets. The nature of developments in each region is different given their differing circumstances and history with hydropower.

The abundance of natural resources in North and Central America makes this region highly suited for renewable energy production, with a significant portion of the electricity market supported by hydropower. Hydropower also plays a crucial role in South America, supplying approximately 45% of the continent's electricity, despite encountering temporary drops in generation due to drought conditions. In Africa about 90% of the continent's potential has yet to be tapped, even though hydropower already provides 40% of Sub-Saharan Africa's power.

Europe boasts a mature fleet of hydropower stations, which play a crucial role in supporting the region's ambitions for wind and solar development (Figure 3). The EU's Renewable Energy Directive sets ambitious targets, aiming for a minimum of 42.5% renewable energy contribution to total consumption by 2030. In 2023, Europe witnessed minimal movement in commissioning new greenfield hydropower projects. The need for system flexibility is driving interest in PSH, and modernizing Europe's existing hydropower fleet presents a significant opportunity to increase capacity and enhance performance. Despite drought-related challenges in 2022, hydropower generation rebounded in 2023, reaching 637.23TWh, nearly reaching the 2020 and 2021 averages of 666.5TWh. (World Hydropower Outlook, Opportunities to advance net zero, 2024)

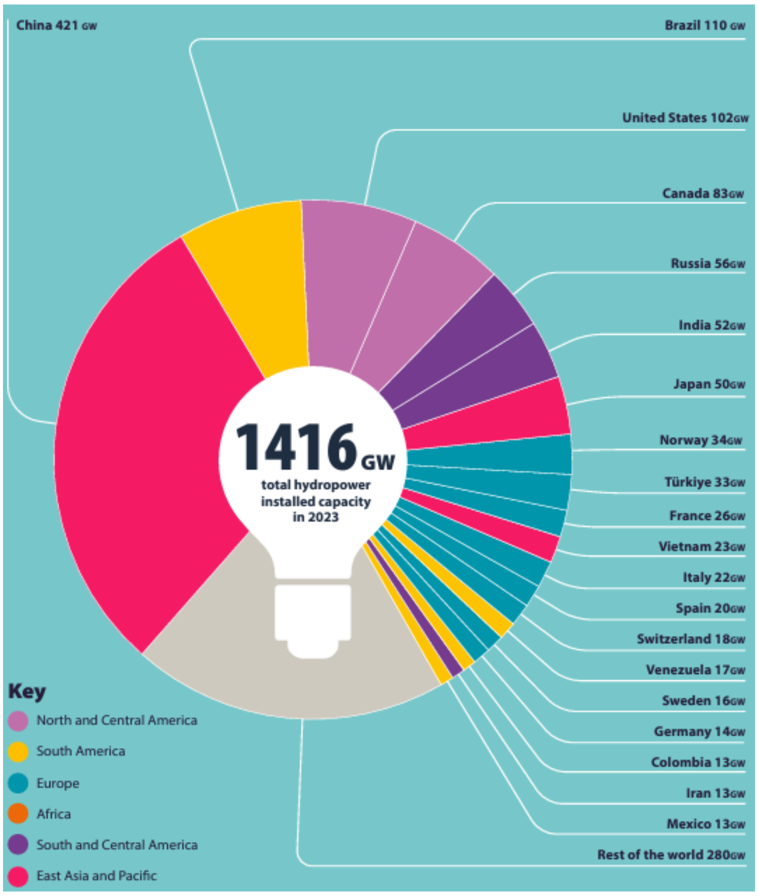


**FIGURE 1: WORLD HYDROPOWER INSTALLED CAPACITY IN 2023 (SOURCE: WORLD HYDROPOWER OUTLOOK, OPPORTUNITIES TO ADVANCE NET ZERO, 2024)**

## World

| | Total installed capacity including pumped storage (MW) | Pumped (MW) | Generation (TWh) |
|---|---|---|---|
| Total | 1,416,398 | 179,132 | 4,202 |

**FIGURE 2: WORLD HYDROPOWER OUTLOOK (SOURCE: WORLD HYDROPOWER OUTLOOK, OPPORTUNITIES TO ADVANCE NET ZERO, 2024)**

## Europe

| Country/Territory | Total installed capacity including pumped storage (MW) | Pumped storage (MW) | Generation (TWh) |
|---|---|---|---|
| Albania | 2,153 | 0 | 7 |
| Andorra | 46 | 0 | <1 |
| Austria | 11,821 | 3,485 | 44 |
| Belarus | 96 | 0 | <1 |
| Belgium | 1,494 | 1,308 | 2 |
| Bosnia and Herzegovina | 2,263 | 420 | 6 |
| Bulgaria | 2,916 | 1,403 | 3 |
| Croatia | 1,855 | 281 | 8 |
| Cyprus | 0 | 0 | 0 |
| Czechia | 2,285 | 1,172 | 3 |
| Denmark | 7 | 0 | <1 |
| Estonia | 8 | 0 | <1 |
| Faroe Islands (Denmark) | 41 | 0 | <1 |
| Finland | 3,190 | 0 | 15 |
| France | 25,534 | 5,051 | 59 |
| Germany | 14,428 | 9,379 | 20 |
| Greece | 3,423 | 699 | 4 |
| Greenland (Denmark) | 91 | 0 | <1 |
| Hungary | 61 | 0 | <1 |
| Iceland | 2,114 | 0 | 14 |
| Ireland | 508 | 292 | 1 |
| Italy | 22,149 | 7,156 | 40 |
| Kosovo | 115 | 0 | 1 |
| Latvia | 1,558 | 0 | 4 |
| Liechtenstein | 35 | 15 | <1 |
| Lithuania | 1,028 | 900 | <1 |
| Luxembourg | 1,332 | 1,296 | <1 |
| Macedonia | 644 | 0 | 1 |
| Malta | 0 | 0 | 0 |
| Moldova | 64 | 0 | <1 |
| Montenegro | 649 | 0 | 2 |
| Netherlands | 38 | 0 | <1 |
| Norway | 33,897 | 1,441 | 137 |
| Poland | 2,506 | 1,591 | 4 |
| Portugal | 8,196 | 3,707 | 12 |
| Romania | 6,730 | 92 | 18 |
| San Marino | 0 | 0 | 0 |
| Serbia | 3,178 | 1,017 | 11 |
| Slovakia | 2,476 | 1,017 | 5 |
| Slovenia | 1,309 | 180 | 5 |
| Spain | 20,425 | 5,650 | 25 |
| Sweden | 16,391 | 91 | 66 |
| Switzerland | 17,533 | 4,055 | 37 |
| Türkiye | 32,529 | 0 | 66 |
| Ukraine | 6,600 | 1,963 | 10 |
| United Kingdom | 4,723 | 2,833 | 5 |
| **Total** | **258,845** | **54,174** | **637** |

**FIGURE 3: EUROPE HYDROPOWER OUTLOOK (SOURCE: WORLD HYDROPOWER OUTLOOK, OPPORTUNITIES TO ADVANCE NET ZERO, 2024)**

The EU electrical power market has the aim to reach all the emission levels established during the Paris Climate Agreement that will lead the future of the electrical sector until 2050.

The new targets will lead to big investments in the fields of research and development of new renewable energy technologies, they will induce the projection of the several new power plants. There are three application scenarios which EU can reach based on the investment's costs and the set limits, these are listed in

Table 1.

| Scenario | Cost (Billion €) | Description |
|---|---|---|
| Green | 6645 | 80% Of the energy generated from renewable energies. |
| Clean | 6255 | 40-45% of the energy generated from renewable energies |
| Lean | 5730 | Conventional fossil generation would be prioritized. The emissions would be higher than 1990 |

**TABLE 1: PARIS AGREEMENTS EUROPEAN UNION ACTION PLANS 2050 (SOURCE: CALVO, 2020)**

Although the *Green* and *Clean* scenarios are very promising, to reach the *Green* scenario an improvement of the grid connection is required to make accessible any geographic location with a feasible potential in renewable energies. In *Lean* scenarios, the objective is that to prioritize another energy system like gas or coal. (Calvo, 2020)

## 1.2 APPLICATIONS IN ITALY

In Italy the hydropower source ranks first in renewable energy generation thanks to 4860 plants and an installed capacity of 21.73 GW. In 2021 this source covered 39% of the total energy production despite all the difficulties. These difficulties come from both natural and human factors, accounting for example for climate change conditions, infrastructure related issues, stricter environmental regulations and geological risks. The physical conformation of the Italian territory characterized by many steep slopes is very suitable for the hydroelectric resource exploitation.

In 2022, the renewable sources collectively covered 31.1% of the national electricity demand, 6% less than in the same period in 2021, according to the Green Italy 2023 report. This decline was mainly due to a lower contribution from hydropower, which saw a 37.7% slump due to long droughts throughout the year (Lisi, 2024).

Almost 4000 of the total plants (which represent the 81.3%) are located in Northern Italy (Figure 4), while only 572 and 334 facilities are operating in the Centre and South, respectively. The Piemonte region is the first in terms of the number of plants, it hosts 1092 hydroelectric power plants which are more than one-fifth of the total. In second and third place in the ranking are Trentino Alto Adige and Lombardia regions, with 891 and 749 facilities, respectively. The number of plants located in Italy is a steadily growing number: in 2022, the number was 4702, which is 158 fewer than in 2024 (4860 plants). Going back another 13 years, in 2009, this number was almost half and amounted to only 2249.

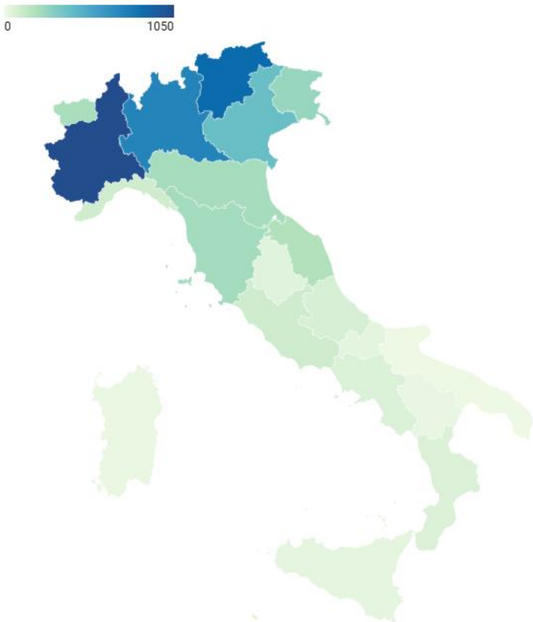


**FIGURE 4: HYDROELECTRIC POWER PLANTS IN ITALY (SOURCE: GEOPOP, 2024)**

Looking at the latest available data for 2022, in total, Italy was able to produce about 30,291 GWh of energy annually, or about 50% of the entire production coming from renewable sources that year. Table 2 provides a good overview of the number of plants per each Italian region as well as the produced MW.

| Region | Number of plants | MW |
|---|---|---|
| Valle d'Aosta | 220 | 1106 |
| Piemonte | 1092 | 3103 |
| Liguria | 101 | 112 |
| Lombardia | 749 | 5694 |
| Trentino-Alto Adige | 891 | 3804 |
| Veneto | 408 | 1391 |

| | | |
|---|---|---|
| Friuli-Venezia Giulia | 269 | 620 |
| Emilia-Romagna | 223 | 407 |
| Toscana | 233 | 432 |
| Umbria | 49 | 717 |
| Marche | 189 | 311 |
| Lazio | 101 | 482 |
| Abruzzo | 78 | 1267 |
| Molise | 40 | 94 |
| Campania | 63 | 394 |
| Basilicata | 21 | 157 |
| Puglia | 10 | 4 |
| Calabria | 74 | 915 |
| Sicilia | 31 | 155 |
| Sardegna | 18 | 566 |

**TABLE 2: ITALIAN PLANTS, NUMBER AND MW (SOURCE: GEOPOP, 2024)**

## 1.3 HYDROPOWER GENERATION

Hydropower projects have both positive and negative impacts on the environment and society. The physical structures, such as dams and weirs, alter the river hydrology and disrupt both the sediment transport and the fish migration. Socially, hydropower projects affect land use, local economies, and community health and safety. However, they also offer benefits like electricity generation, irrigation, tourism, and flood protection. Addressing challenges like ecological continuity, water quality, environmental flow, hydropeaking, and biodiversity mitigation is crucial, on the same note the Run-of-river hydropower plants maintain a river's natural flow, while reservoir-based projects significantly change the surrounding environment.

Each hydroelectric power plant has to be tailored and designed considering site-specific features, such as local hydrology, topography and geology. However, while the design changes according to local conditions, the plants are composed of basic conventional components.

To provide a clearer understanding of all the components of a hydropower plant, a general scheme is provided in Figure 5.

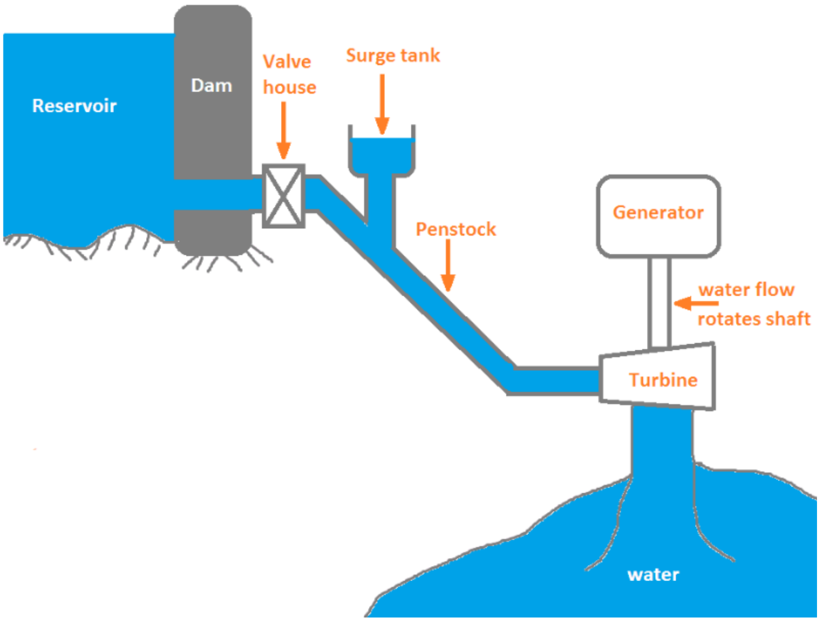


**FIGURE 5: HYDROPOWER PLANT LAYOUT (SOURCE: SHARMA, WORJING PRINCIPLE OF HYDROELECTRIC POWER PLANT)**

The *gates* allow the flow discharge regulation, this aim is achieved by using fixed wheel gates, sliding gates, radial gates, caterpillar gates, and spillway gates. The opening of the gates releases the water which flows towards the turbine through the penstock.

The *penstock* is a conduit that allows the water to flow from the intake of the power plant towards the turbine placed inside the powerhouse. These pipes are conventionally made of steel, and they must bear high pressure on the inside surface on occasion of sudden increase and decrease in the load, the so-called water hammer. In case the powerhouse location is far from the dam and the reservoir, the water is transferred through open channels, tunnels under pressure, or pressure shafts designed considering the rock mass features. In order to avoid the formation of vortices which may carry air into the penstock and cause in problems to the turbine, a sufficient water head should be provided above the intake entrance.

Between the water intake and the powerhouse, the *surge tank* is often introduced with the aim to absorb any water surges caused inside the penstock or pressure tunnel due to possible loading and unloading of the generator with opening and closing of *inlet valve* and *wicket gates*. The wicket gates of the turbine allow to regulate the amount of water that flows into the turbine.

The *turbine* is the machine that converts the kinetic or potential energy of the water into mechanical energy, a shaft connects it to the *generator* which is what actually transforms the mechanical energy of the turbine into the final product, electric energy. The electricity is generated by the rotating magnetic field created by the spinning of the rotor, a series of large electromagnets, inside a stator, a tightly wound coil of copper wire. The alternating current thus produced is transferred to the transformer, which converts it into higher voltage. Finally, the high voltage electricity is transmitted to the power line.

The exploited water, that entered the hydropower plant and passed through the powerhouse, finally flows through the draft tube into the tailrace channel and re-enters the river downstream. After serving its purpose in generating electricity, the water from a hydropower plant is released back into the river, this process completes the cycle, allowing the water to flow downstream and continue its natural course. (Andrej Misech, 2021)

The generation of power coming from falling water exploits the potential energy which is characterized by a specific elevation of the water. The power is therefore related to the elevation, as well as the availability of water coming and the efficiency of the considered plant. The power generated from falling water, *P*, can be calculated by applying the following equation:

$$P = \int_{\Omega} (v \cdot n)\, \rho g\, H\, d\Omega$$

where:

- $\Omega$ is the cross section,
- $v$ is the fluid velocity,
- $n$ is the unit vector normal to the cross section Ω,
- $\rho g$ is the specific weight of water,
- $H$ is the total head.

The balance of the energy flux extraction is provided using the following equation, which ensures that all forms of energy are accounted for, maintaining the principle of energy conservation.

$$P_{in} = P_{out} + P_{diss} + P_e$$

where:

- $P_{in}$ is the input power, which is the total energy available from the water,
- $P_{out}$ is the output power, which is the useful electrical energy generated,
- $P_{diss}$ is the power dissipated due to inefficiencies such as friction and turbulence,
- $P_e$ is the extracted power.

The efficiency of a hydropower plant can be evaluated using two different formulas, listed below, depending on the specific parameters being considered.

The first formula essentially measures how effectively the *HPP* converts the input power, $P_{in}$, from the falling water into electrical power, accounting for losses in the system. The higher the efficiency coefficient, $C_p$, the more efficient the power plant is.

$$C_p = \frac{P_e}{P_{in} - P_{out}}$$

where:

- $C_p$ is the efficiency coefficient.
- $P_{in}$ is the input power,
- $P_{out}$ is the output power,
- $P_e$ is the extracted power.

The second formula provides a measure of the overall efficiency of the *HPP* by comparing the extracted power to the available hydraulic power.

$$\eta = \frac{Pe}{Pw} = \eta_{hydr}\,\eta_t\,\eta_e$$

where:

- $P_e$ is the extracted electrical power,
- $P_w$ is the available power of the water (hydraulic power),
- $\eta_{hydr}$ is the efficiency related to the hydraulic losses,
- $\eta_t$ is the efficiency related to the turbine,
- $\eta_e$ is the electromechanical efficiency.

Both formulas are essential for understanding different aspects of the *HPP*'s performance. The first one focuses on the conversion efficiency considering the losses, while the second one gives a broader view of the overall efficiency.

## 1.4 HYDROELECTRIC POWER PLANTS CLASSIFICATION

Hydroelectric power plants are mainly classified depending on the functioning type and based on the capacity of the plant, therefore on the installed power.

The classification done accordingly to the capacity of the plants, although it depends on every country, it is based on a standard range of the installed power. It is considered that the plants are connected to the grid when the power installed is above 100KW. The revenue and grants per kWh generated, has an independent price in every country of the European Union.

The following Table 3 describes the standard European classification of the hydropower plants based on the installed power capacity.

| CLASSIFICATION | POWER | DESCRIPTION |
|---|---|---|
| Large-Hydro | 100MW | Installed into a large grid |
| Medium-Hydro | 15-100MW | Feeds into a grid |
| Small-Hydro | 1-15MW | feeds into a grid |
| Mini-Hydro | 0.1-1MW | Isolated or feeding into grid |
| Micro-Hydro | 5-100kW | Small community or industrial applications |
| Pico-Hydro | Up to 5kW | Isolated applications |

**TABLE 3: HYDROPOWER PLANTS CLASSIFICATION BASED ON THE MAXIMUM CAPABILITY**

Conversely, the classification based on the functioning system is done distinguishing these two types of plants, the run-of-rivers power plants with a very brief residence time, and the plants which on the other hand are equipped with a storage reservoir such as storage power plants and pumped storage power plants. In-stream technology refers to the use of hydrokinetic turbines to harvest the energy of naturally flowing water, such as stream, but also tidal or open ocean flows, without impounding the water.

### 1.4.1 STORAGE HYDROPOWER PLANTS

Storage hydropower plants, *SHPPs*, benefit from the storage of water behind a dam, in order to produce the energy, the water is released from the reservoir and led towards the turbine. *SHPPs* rely on a storage reservoir to enhance the available head, $\Delta H$, and regulate the flow rate, $Q$. These plants do not depend on the water availability as the run-of-river power plants, on the contrary they are able to operate independently of the hydrological flow according to their storage capacity, they collect the water during wet seasons and exploits it during dry seasons. Basically, their flexibility is due to the ability to store the potential energy and convert it into electrical energy when needed.

The power generation facilities are typically situated at the base of the dam or further downstream, and they are linked to the reservoir via tunnels or pipelines. The design and the type of reservoirs involved vary based on the terrain, often resulting in the flooding of river valleys to form artificial lakes or expand existing ones. *SHPPs* are highly efficient and capable of producing significant power, but they can also have substantial social, economic, and environmental impacts on the surrounding area.

The dam is a structure that blocks the natural flow of the river, creating a reservoir, offering both storage capacity and additional potential energy. The type of dam chosen depends significantly on the local topography and geotechnical conditions, they can be classified as embankment dams, concrete dams, or other types.

A clear representation of the components of a *SHPP* is given in the image below (Figure 6), it schematises a general *SHPP* and its basic related parameters.

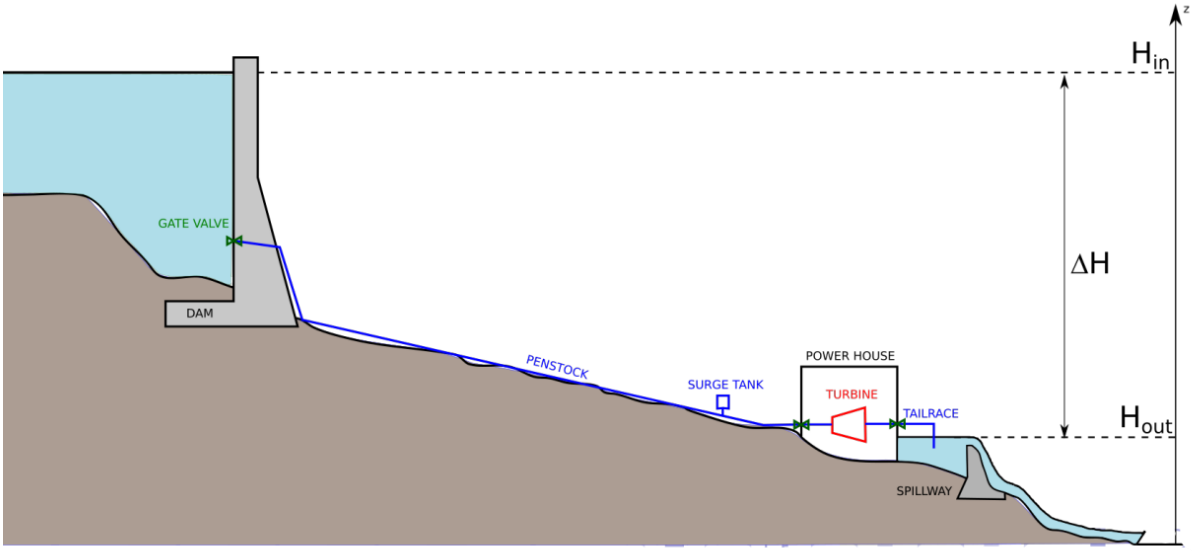


**FIGURE 6: STORAGE HYDROPOWER PLANT**

The flow rate which can be considered as suitable for the power production in a S*HPP*, i.e. $Q_w$, depends on the river discharge, $Q_r$, and on the time variation of the volume of water in the storage basin $V_S$:

$$\frac{d}{dt} V_s\,(t) = Q_r\,(t) - Q_w\,(t) - Q_s\,(t)$$

where:

- $Q_r(t)$ is the inflow river discharge, which mainly depends on the precipitation, the watershed area, the evapotranspiration and the groundwater discharge,
- $Q_w(t)$ is the flow rate inside the *HPP*,
- $Q_s(t)$ is the spillway discharge (when $V_S\,(t) > V_{max}$).

*SHPPs* efficiency mainly depends on two contributions, which are the hydraulic efficiency, that depends on the hydraulic losses in the hydraulic grid of the plant, and it is evaluated as a reduction in water head; and the turbine efficiency, that depends on the functioning of the turbomachinery, depending on the hydraulic regime of the flow.

Essentially the electrical power output, $P_e$, is the product of the system's efficiency and the waterpower input at any given time, as shown in the next equation:

$$P_e\,(t) = \eta(t)\,P_w(t)$$

where:

- $P_e(t)$ is the electrical power output at time (t),
- $\eta(t)$ is the efficiency of the system at time (t), depending on the hydraulic losses and the functioning of the turbomachinery,
- $P_w(t)$ is the waterpower input at time (t).

### 1.4.2 RUN-OF-RIVERS HYDROPOWER POWER PLANTS

Run-of-rivers power plants, *RoR*, exploit the natural flow of the water in the riverbed without using any storage equipment, their operation depends on the water availability in terms of water level at the intake, therefore the performance of the plant is directly affected by the variability of the flow. The design of these plants is usually optimized in case of large flow rates with small head on large rivers and in the case of small flow rates with high head in mountain rivers.

*RoR HPPs* divert a portion of the river flow in order to generate energy, utilizing nearly the entire flow. The generation of power is influenced by the precipitation and the runoff, leading to significant daily, monthly, or seasonal variations. While *RoR HPPs* may include some short-term storage (e.g., hourly, daily), their generation profile is primarily determined by local river flow conditions. These plants are relatively inexpensive to install and generally have lower environmental impacts compared to similarly sized Storage *HPPs*. A schematic representation of a possible *RoR HPP* layout is visible in Figure 7.

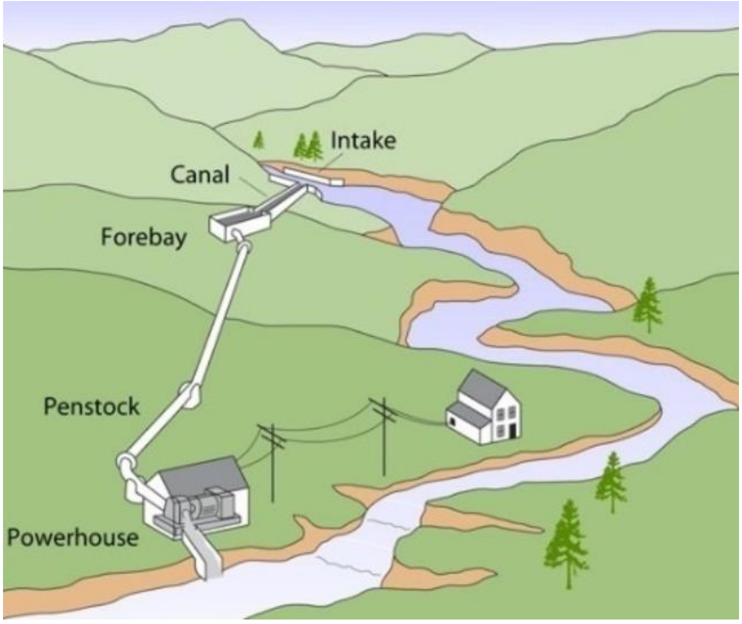


**FIGURE 7: RUN-OF-RIVER SCHEMATIC REPRESENTATION (SOURCE: PICKERING, PRACTICAL SUSTAINABILITY, RUN-OF-THE-RIVER)**

In *RoR HPPs* the basin management is of secondary importance, the primary focus is instead on the unregulated run-of-river flow. These types of plants utilize a large water head, *H(t)*, and they work with a variable water flow, $Q_w(t)$, which in turn depends on the river flow, $Q_r(t)$. Typically, the operation of such plants is characterized by a water flow which is proportional to the stream flow of the river. The annual river discharge, $Q_r$, is represented by the river flow duration curve, which actually influences the efficiency of RoR *HPPs*.

*In RoR HPPs* the intake structure diverts the water from the river into the system. This structure has the aim of directing the necessary amount of water into a canal or into following penstocks, therefore, transitioning from a variable unstable flow into a more controlled and uniform one. While intakes are designed to minimize the floating debris, a sediment trap may sometimes be required downstream. In small hydropower plants, intakes are often equipped with gates and valves to facilitate maintenance. The location and orientation of the intake are crucial to minimizing debris accumulation, the intake can be lateral, frontal or of drop-type.

The spillway is an overflow device designed to manage floods that greatly exceed normal flow conditions in natural streams, serves as a diversion structure that channels the required flow into a conveyance system.

In *RoR HPPs'* context a crucial role is played by the duration curves both in the design and in the operating process of the plant. By using duration curves, engineers can design *RoR HPPs* that are both efficient and resilient to the possible variations of the river flow. The use of this curve that represents the relationship between the flow rate and the percentage of time that the flow rate has been matched or exceeded helps in understanding the variability and availability of water flow over time. The shape of the duration curve influences the optimal capacity and helps determining the maximum flow that the plant can process by still ensuring an efficient operation. The curves are also used to assess the hydrological characteristics of the river, essential for the feasibility and sustainability of the hydropower project. In addition, the analysis of these curves may help assessing the impact of the climate variability on river flows and, therefore, adapting the plant's design to ensure reliable power generation under changing conditions.

Given a significantly long time series of flow discharges, at least one curve a year should be extracted in order to obtain a good analysis. Then, the typical year is represented by closest duration curve to the average duration curve.

It is worth mentioning that in most hydro-projects, environmental regulation set a minimum non-usable flow to bypass the hydropower plant to limit damages to the ecosystem; there are several hydrological-based environmental flows methods, which allow estimating this minimum flow, one of them is described in detail in Section 3.1.2.

### 1.4.3 Pumped storage hydropower plants

*Pumped storage* hydropower plants, *PSH*, operate using two connected reservoirs into which water flows (Figure 8). The water is released from the upper reservoir to generate electricity using the turbine. The energy is stored by pumping the water from the lower reservoir to the upper one when the electricity demand is low (i.e., at night), on the other hand when the demand increases the stored water is released back to the lower reservoir, flowing through turbines in order to generate electricity. Basically, pumped storage plants function as storage devices rather than energy sources. Although the pumping process results in energy losses, making the plant a net energy consumer, still offers significant benefits as a large-scale energy storage system.

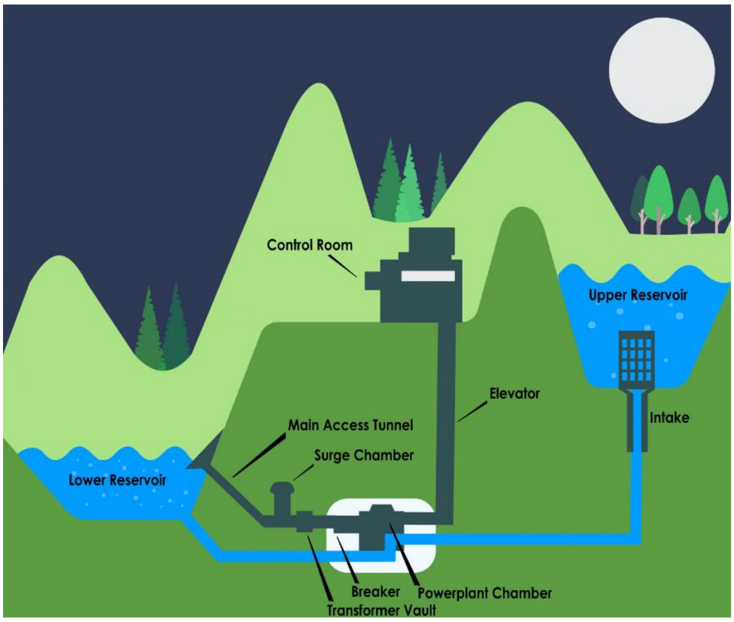


**FIGURE 8: PUMPED STORAGE HYDROPOWER PLANT SCHEMATIC REPRESENTATION (SOURCE: TECHNICAL REVIEW OF PUMPED STORAGE HYDROPOWER)**

The *PSH* typically boasts a long lifespan, ranging from 50 to 100 years. It offers a round-trip efficiency of 70–85% and it can respond within seconds or minutes. Pumping and generation can occur daily, weekly, or even seasonally in extensive networks.

While it involves very high site-specific and capital costs, its operational and maintenance expenses are relatively low, due to the fact that the technology involved is relatively simple, involving water movement between reservoirs, it does not rely on expensive raw materials for operation, additionally the components are robust and does not experience significant wear and tear issues.

More in detail, in the generation phase, the water from the upper reservoir flows down onto the turbine, which rotating generates electrical energy, following the conventional hydropower method. During the pumping mode, in case of reversible pump-turbines, the same turbine is used to pump water from the lower reservoir back up to the upper one. This cycle is repeated under optimal conditions to maximize the plant's efficiency and profitability.

*PSH* plants are designed to primarily take advantage of the fluctuating electricity rates. While it might seem that the energy used to pump the water up would negate the benefits, the *PSH* plants assure a profit by operating during peak hours when electricity rates are high. During these times, they generate electricity to meet the high demand, effectively bridging the gap between production and consumption.

The most favourable conditions to install a pumped storage plant must include the presence of a significant elevation difference between the two reservoirs, a reliable water source, the proximity to the electrical grid, a minimal environmental impact, and regulatory and community support. In addition, the climate must be mild and humid, in order to maintain under control, the potential energy losses due to evaporation and absorption.

The installation of a *PSH* plant on hilly or mountainous regions results in extremely high investments costs due to the location management, on the other hand totally plain areas are unsuitable for pumped storage hydropower plants, since the elevation difference would not be guaranteed. Therefore, it is crucial to analyse the surrounding conditions of the proposed location when deciding to plan a *PSH*, as well as the effect that the plant itself would have on the population and landscape. Similarly, during periods of low electricity consumption, such as at night, pumped storage systems use cheaper electricity to pump water back to the upper reservoir. This strategy not only generates profits but also stabilizes the region's energy supply by serving as backup plants. (Technical Review of Pumped Storage Hydropower)

## 1.5 RENPOWER GROUP SRL

The Renpower Group is one of the two corporate organizations, together with the Ergon Group, started in 2016 as product of a pathway for the development of photovoltaic and hydroelectric potential.

The Ergon Group owns several hydroelectric and photovoltaic plants in Italy, with a total capacity of 10 MW for photovoltaic plants and 200 kW for hydroelectric ones. It also owns the Palazzo Cortesi, an 18th-century historic palace located in Macerata in the Marche Region, which includes apartments, offices, a cafe, a restaurant, and room rentals. The Ergon Group manages these above-listed properties as well as the renewable energy facilities, ensuring they generate stable and predictable cash flows over time.

The Renpower Group s.r.l. is one of the most experienced companies in the renewables field at a worldwide scale, it guarantees the use of state-of-the-art technologies, the manageability and maintenance of all the plants via remote control systems, the maximum energy efficiency and design already oriented to the disassembly of entire plants and their total recycling or reuse of the involved materials.

The company is highly experienced in consulting, mechanical and electrical design in both environmental and technical-urban assessments for the photovoltaic and energy storage sector for major market players, including ENEL and Iren. The company owns a considerable wealth of knowledge for the design, permitting process, construction, and subsequent management of plants.

The Renpower Group focuses on the following listed business units:

- *RES* Project (Renewable Energy Systems) related to harnessing renewable energy sources such as solar, wind, hydro, or geothermal. The design and development of RES projects involve creating efficient systems for generating clean energy;

- Green Field Project which applies to building something new from scratch, typically in undeveloped or unused area. In the context of renewable energy, a green field project could involve setting up a new solar farm, wind turbine installation, or other clean energy infrastructure;
- design of weirs and electromechanical works for hydroelectric power plants;
- environmental assessments;
- technical-urban assessment;
- asset management;
- operation and maintenance of photovoltaic plants, hydroelectric plants and electromechanical equipment;
- administrative and financial management of plants from *RES*;
- design of photovoltaic plants and *CERs* (Renewable Energy Communities).

The organigram of the corporate shown in the next image, provides a good representation of the society along with their fields of interest (Figure 9).

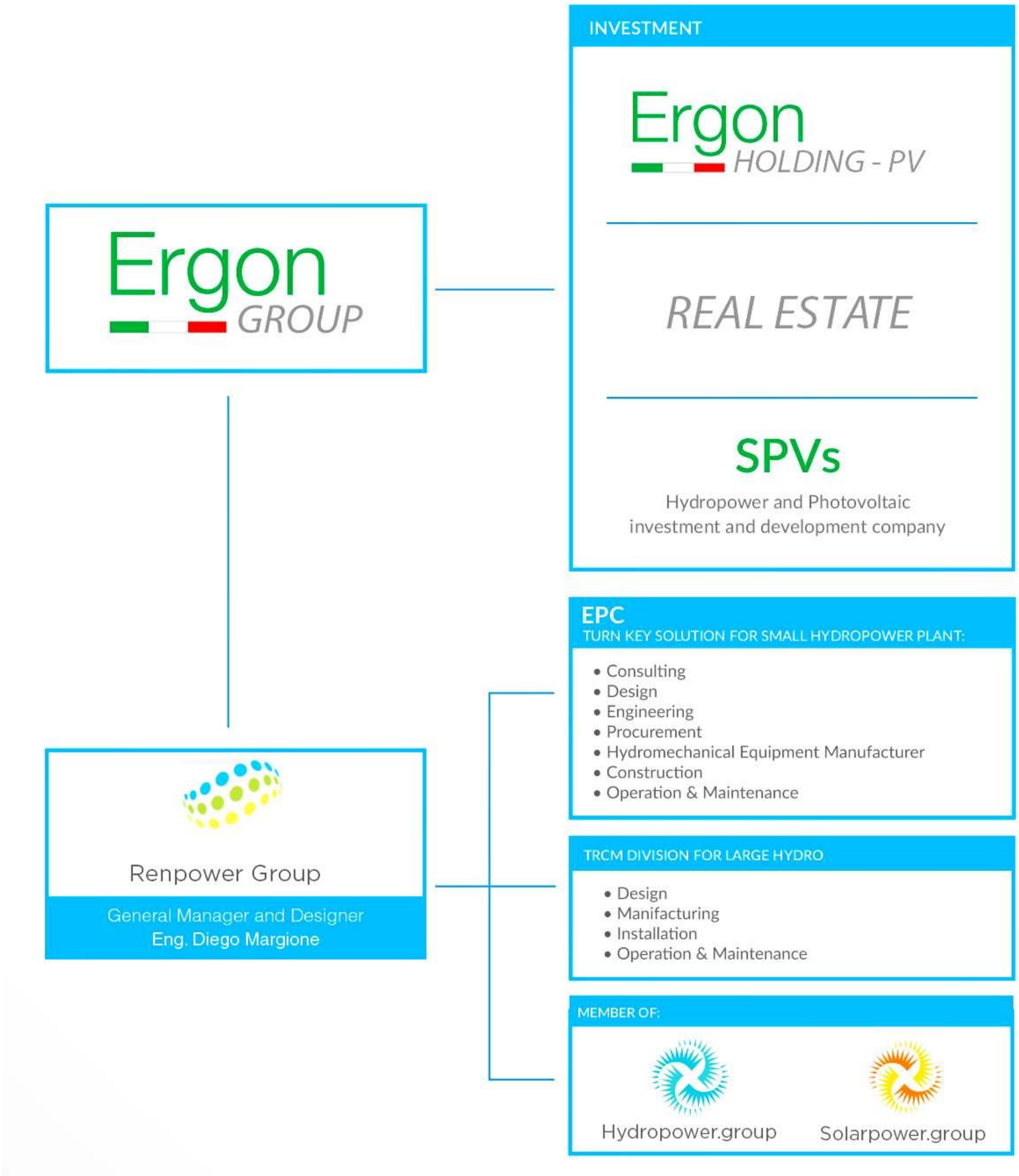


**FIGURE 9: CORPORATE ORGANIGRAM**

# 2 PROJECT

Today's energy landscape is changing rapidly due to many factors, including the need to produce clean energy from renewable sources in order to meet the $CO_2$ reduction commitments made in the ratification of the *Kyoto Protocol*[*], and the liberalization of the energy market that favours the construction of small-scale plants distributed throughout the territory. As a result, current legislation has introduced important facilities that produce electricity from renewable sources.

In such a scenario, the company Renpower Group s.r.l. intends to produce electricity to be sold to the grid operator with almost no impact on the hydraulic regime of the Burano River, in the "Foci" locality. The company proposes a plant with intake and release just below the existing system of bridle and counter-bridle, with a slight subtraction of natural riverbed for about 90 m, restoring the existing derivation in the area for fish farming, decommissioned in the 1980s, which drew and returned water in the same locations as the present initiative.

The new project schematically consists of the following works:

- Construction of an access road to the plant with inert stabilized quarry material.
- Adaptation and reprofiling of the existing channel for feeding the fishponds.
- Installation of sluice gates for channel feeding and de-icing, an oil-driven water gutter for cleaning the water just before it enters the power plant.
- Construction of a micro hydroelectric power plant with a spiral chamber in the area currently occupied by the old fishponds, with an easy access point from the flat area adjacent to the ponds.
- Laying of a discharge diffuser to the river that can also recover, in terms of hydraulic performance, the natural hydraulic pressure drops in the section between turbine and the discharge to the river.
- Construction of the ENEL delivery substation in the area of access to the plant, in the area of plot 144, as agreed with the ENEL company, to facilitate the commissioning also of a secondary transformer which feeds the inhabited area and that is currently a *PTP* (Transformation Point on Pole) with continuous disservices.
- Reclamation of the entire area, consisting of the removal of the heavily degraded iron and concrete artifacts of the old plant.

The produced electricity will be fed into the Local Electricity Distribution Grid, while the connection of the micro-hydroelectric power plant will take place in a medium voltage. The plant will have a power output of about 100 kW, and it will therefore be classified as a micro hydropower plant.

## 2.1 AUTHORIZATIONS

The construction project of the micro hydroelectric power plant on the Burano River in the municipality of Cagli started off in 2009, the year in which the first conference of services was held.

In that year the proposing company, the Expandi Energia, has followed the procedural process with the aim to verify the subjectivity in accordance with the Regional Law 7/2004 (described in detail in the Annex I – Regulation of reference, page 98) and the Legislative Decree 152/2006 (described in detail in the Annex I – Regulation of reference, page 98), and to grant a landscape authorization.

The procedure was completed on November 16, 2012, the process was able to assure the exclusion of the project from the Environmental Impact Assessment, *EIA*, procedure as long as in the subsequent design, authorization and operation phases of the plant the conditions and the requirements set in the Decree No. 107/VAA are met.

The process was also able to issue the landscape permit in accordance with the Article 146 of the Legislative Decree No. 42/2004 (described in detail in the Annex I – Regulation of reference, page 98) as long as the requirements set in the Decree No. 107/VAA are met.

On February 28, 2017, the Single Authorization process was also concluded with the Decree dated February 27, 2017, for the plant characterized by 211.90 kW.

During 2019, the company Expandi Energia S.a.s. of Acqualagna (PU) was acquired by the company Ergon Group S.a.s. with the intention of completing the project. Considering that the start of work had not been communicated within one year from the issuance of the authorization, as prescribed, the PF Reclamation, Energy Sources, Waste, Quarries and Mines of the Marche Region issued a Decree of Revocation of the Single Authorization.

At the same time, Expandi Energia purchased all the areas on which the project is located, and resubmitted, under the Single Authorization, the project for the construction of the micro hydroelectric power plant, with similar characteristics to the project already approved, with some functional and technical adjustments necessary for the proper construction and operation of the plant.

With the memo identified by the protocol No. 78388 of January 21, 2020, the Marche Region, the PF Reclamation, Energy Sources, Waste, Quarries and Mines and the PF Environmental Assessments and Authorizations, Air Quality and Nature Protection, requested that the project would be resubmitted for an additional environmental impact assessment review.

The project presented and examined in this thesis is the one that the Ergon Group S.a.s. will use to resubmit the authorizations requests. The modifications addressed from the previous unapproved version of 2020 have been meticulously analysed in the following Sections 2.5, 2.6 and 3.

## 2.2 BURANO RIVER AND SPECIFICATIONS ON THE PLANT ACCOMMODATION

The power plant will be built in the Municipality of Cagli, about 3 km upstream of the main town, in the locality "Foci", along the via Flaminia sud, which connects Cagli to Cantiano. The following image (Figure 10) provides an overview of the location as seen from Google Maps, offering a clear representation of the area's layout and surroundings. More in detail is the Google Earth view (Figure 11) which illustrates the proposed location for the hydropower plant, highlighting where the plant would be situated.

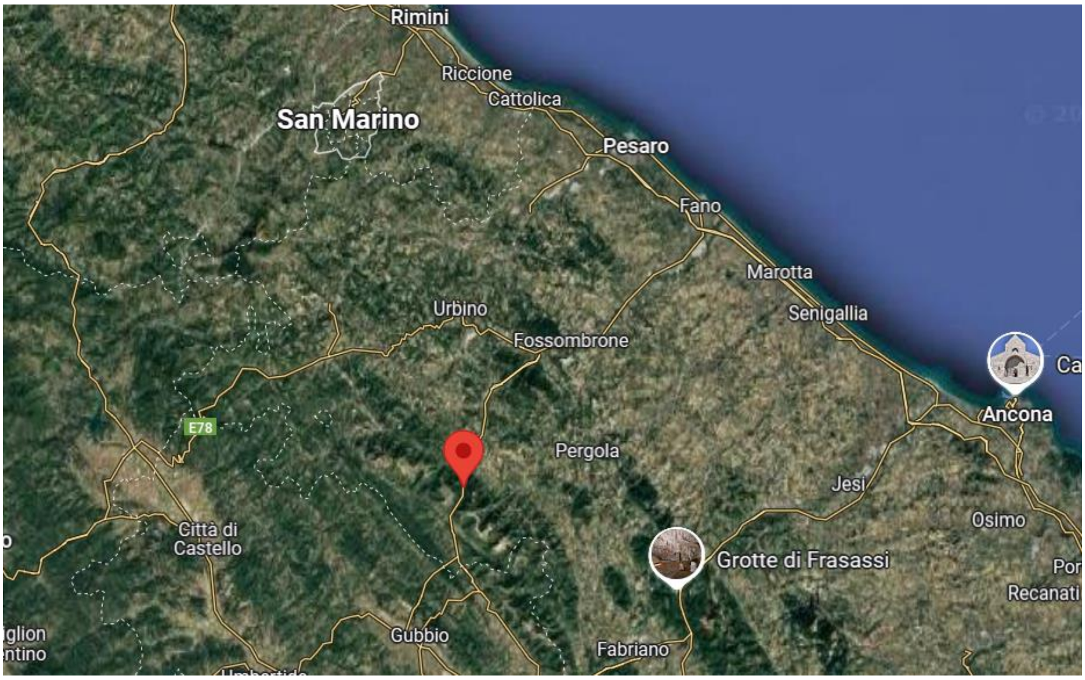


FIGURE 10: GOOGLE MAPS VIEW OF THE LOCATION


**FIGURE 11: GOOGLE EARTH VIEW OF THE SITE LOCATION WITH AN OVERLAY INDICATING THE PROPOSED PLANT PLACEMENT**

In the CTR of the Marche Region the area is mapped within the section n. 290080 (Figure 12), in the upper Metauro valley, on the right bank of the Burano River, entirely within the municipal territory of Cagli.

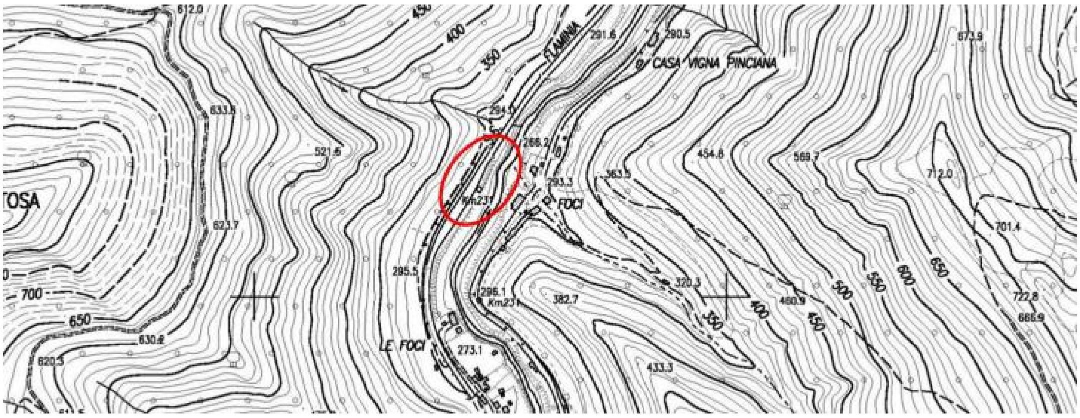


**FIGURE 12: CTR MARCHE REGION, SECTION 290080 CAGLI**

The Burano River constitutes one of the most important tributaries of the Candigliano River, its source is located at 874 m a.s.l., near Monte Cerrone in the province of Perugia, and it flows for about 40 km. The catchment area of about 124 km$^2$ (Figure 13), measured at the height of the examined area. The permeable surface can be estimated at 35% of the total, which is equal to 44 $km^2$, and coincides with the carbonate massifs present found from Cantiano to the closure station of the area.

Near Cagli, the Burano River takes in the waters of the Bosso Stream, and then before reaching Acqualagna they flow back into the Candigliano River, as a right tributary. Therefore, the main tributary is the Bosso Stream whose confluence with the Burano River is located just upstream from the closure section of the analysed catchment area. Its minor network presents characteristic factors, such as frequency and density of drainage, closely related to the geological substrate.

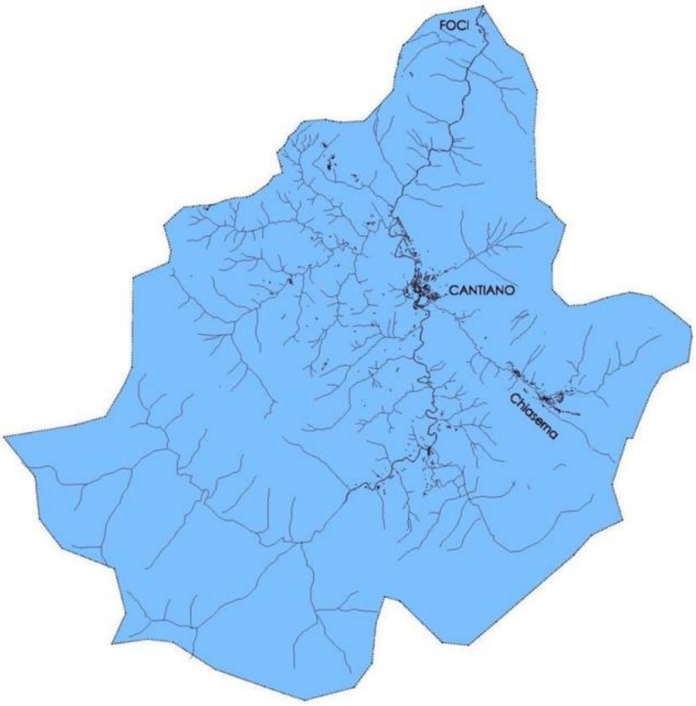


**FIGURE 13: WATERSHED OF THE BURANO RIVER, FOCI IS THE CLOSURE SECTION**

The next framework image (Figure 14) provides a good representation of the current condition of the site of concern, showing the precise location of the existing weirs, the existing and dismissed intake structure and the old concrete walls. This plant view also provides useful elevation information. Upstream of the first weir, the free water surface is about 272.90 m a.s.l., while downstream of the second weir, at the point of discharge, it is about 267.36 m a.s.l.

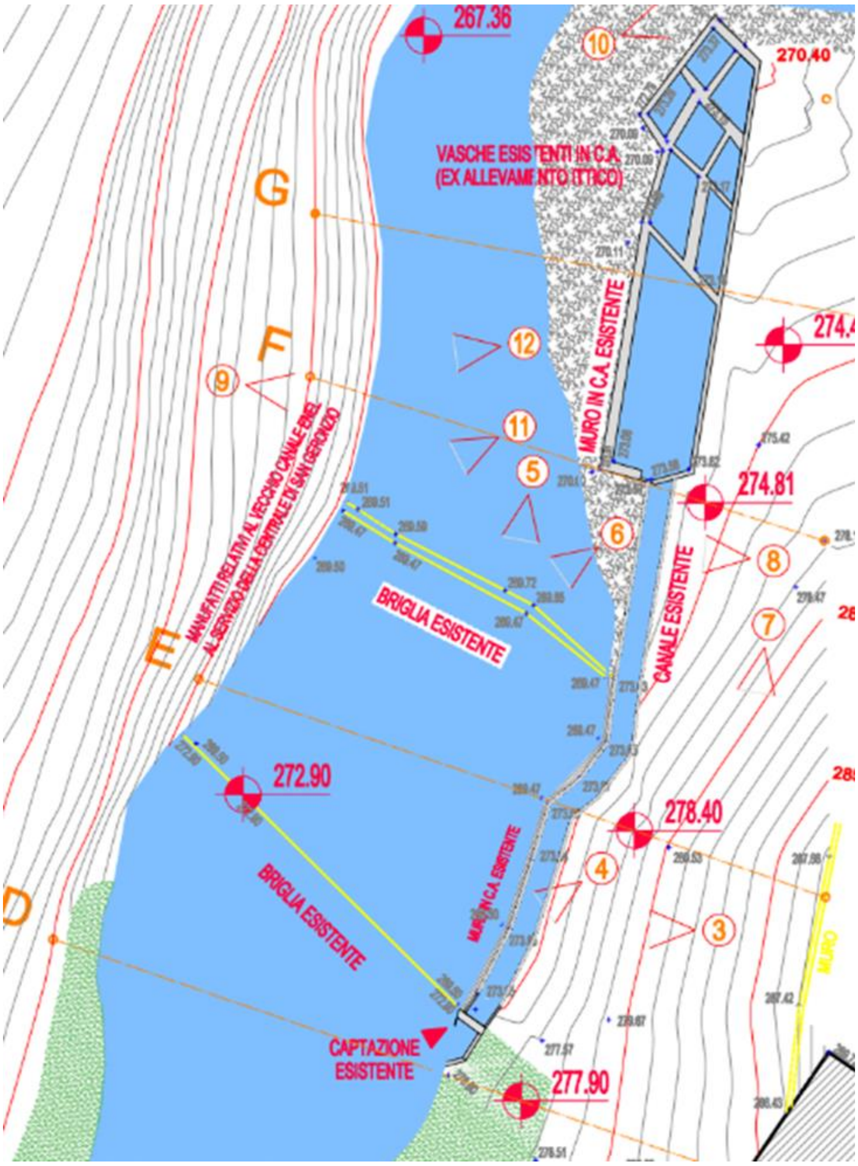


FIGURE 14:TOP VIEW OF THE CURRENT CONDITIONS OF THE SITE

At the elevation of concern, the river is crossed by two old weirs. The first upstream weir (Figure 15) creates a small reservoir, from which, in the past, the water was captured and brought throughout a canal towards a series of tanks intended for trout fish breeding. Figure 16 shows the second downstream weir. Nowadays, the fish breeding tanks have been dismissed and the disused concrete tanks will be used as constraints for the hydropower plant project. Until the old fish-farming facility was decommissioned, the plant received water from the Burano River via an artificial diversion canal of about 90m that went from the artificial reservoir created from the upstream first weir to the following rearing tanks, downstream of the second weir.

The dismissed concrete tanks, although overgrown with vegetation and in an advanced state of decay, are still clearly visible (Figure 17, Figure 18 and Figure 19).

**FIGURE 15: FIRST REGULAR UPSTREAM WEIR**

**FIGURE 16: SECOND IRREGULAR DOWNSTREAM WEIR**

**FIGURE 17: DISMISSED FISH FARMING CANAL**


**FIGURE 18: VIEW FROM THE TOP OF THE EXISTING TANKS**

**FIGURE 19: EXISTING TANKS DETAIL**

The project involves placing the hydroelectric power plant on the hydraulic right at the most downstream point of return to the river, coinciding with the most downstream old tank, thus configuring a rectangular channel of about 90 m through the adaptation of the existing concrete walls. The intent is that to adapt the existing canal and take advantage of the natural head of about 5.54 m in order to be able to install a vertical axis Kaplan-type turbine with a concrete spiral chamber.

From the geological point of view, the entire western part is characterized by the siliciclastic - clastic deposits of the “Formazione Marnoso Arenacea”, which affect more than 120 $km^2$ of the entire catchment area. The Mesozoic limestone lithotypes outcrop in the northeastern part constitutes an elongated band in the Apennine direction on the Catria - Nerone axis, this limestone massifs play an important regulating function in the water reserves guaranteeing the lean flow of the two rivers. In fact, the Burano River shows an increase in flow downstream of the Ridge due to the presence of more linear springs in the riverbed.

As for Quaternary cover, alluvium gravel is confined to narrow bands in the majority of the drainage area. Extensive areas are characterized by a coarse detrital cover of the "stratified detritus" and "chaotic detritus" types, which are located at the foot of the major limestone reliefs where they form a continuous band especially in the Chiaserna-Cantiano area (Catria and Acuto).

The area of interest is mostly covered by holm oak forest on the hydraulic right and hornbeam forest on the left, with subordinate anthropized areas. Along the river there is a predominantly shrub-like vegetation typical of river basins, riverine garrigue consisting mainly of Saxifrago Australis and Trisetetum Betolonii, with widespread tall vegetation consisting mostly of downy oak, maple, European hornbeam, black hornbeam and domestic rowan.

The examined area was surveyed accurately during the planning process dated back to the first project attempt in 2012. More specifically, plano-altimetric surveys were carried out through the use of GPS instrumentation and Total Stations, in addition all the relevant planimetric and altimetric information was taken in site. Once the field surveys were completed, all the acquired data were processed creating a set of plano-altimetric tables, oriented on the basis of the cornerstone ST.10.59M, in order to obtain a detailed representation of all the surveyed points of interest.

## 2.3 First project (2012)

The first project presented dates back to the 2012, it involved the construction of the hydroelectric power plant with an estimated average rated power of 67.49 kW and a maximum power of 211.90 kW.

This project was approved and met all the authorizations requirements set at the time. However, the works did not officially start on time and the authorization was annulled by the relevant regional authority.

The plan was that to carry out the following works:

- Construction of a stabilized access road to the plant.
- Decommissioning of the old canal and burying of a pipe to allow for the water supply to the plant.
- Replacement of the old manual sluice gate with a new intake structure.
- Construction of a building that would host the turbine, in the area currently occupied by the old fish tanks.
- Laying of an underground pipe, equivalent to that used for adduction, for the return of the water to the river.
- Construction near the end of the canal of a building intended for the panel control, measurements and for hosting the Enel cabin, replacing the old building serving the fish plant.
- Reclamation of the entire area, consisting of the removal of the artifacts of the old iron plant and concrete which is heavily degraded.

As visible from the following image (Figure 20) showing a longitudinal section of the plant, the new conduit would have been completely underground, parallel to the existing retaining wall, and sized to be able to derive a maximum flow rate of 4 $m^3/s$.

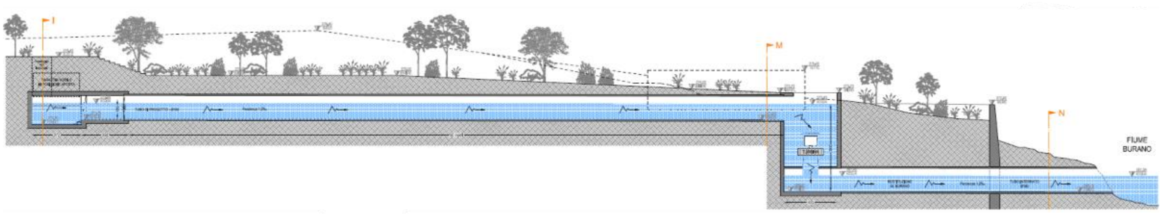


**FIGURE 20: LONGITUDINAL SECTION OF THE PLANT (2012)**

Figure 21 shows a sectioned top view of the hydropower plant layout. The channel, which runs underground, is represented as follows in order to illustrate its routing beneath the surface. The sectioned view allows for a clearer visualization of the channel's placement in relation to the surrounding landscape.

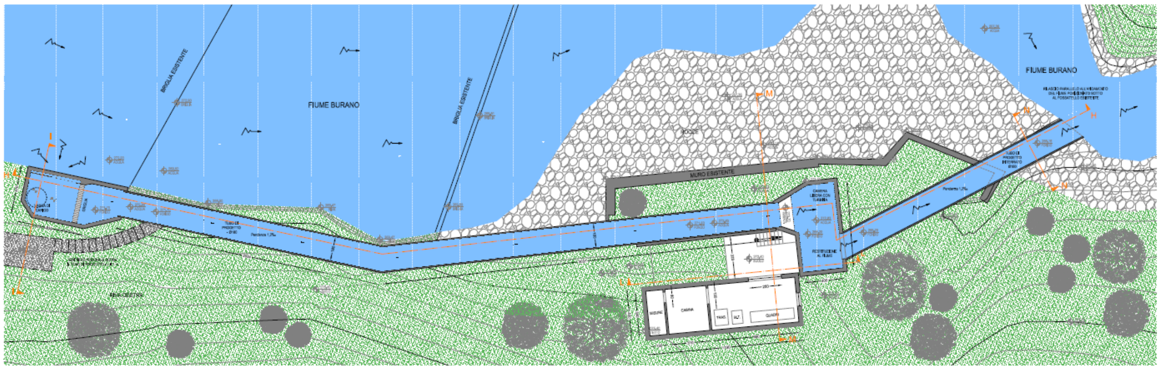


**FIGURE 21: TOP VIEW PLAN OF THE PLANT (2012)**

The water supply conduit planned to have a circular cross section with a diameter of 180cm, a length of about 50 meters to the free chamber, and a constant slope of about 1.2‰.

On the other hand, the discharge conduit planned to have a circular cross section with same diameter but length of about 20 meters, this return conduit would have ended up at an elevation of 267.36 m a.s.l., which is equal to that of the river.

Notice that all calculations will be better explained in the hydraulic analysis in section 3.1.

The gross water available in the year 2012 resulted from the calculations as equal to $63.24 \cdot 10^6$ $m^3$, this value was obtained based on the consideration of a derivation of a maximum of 4 $m^3/s$, which at that time was available for 78 days a year.

The gross water available must take into account a flow rate which is defined as the minimum vital flow for the river, also called *DMV* (in Italian: "Deflusso Minimo Vitale"), and a flow rate required for the fish ladder, these rates must therefore be subtracted to the previous one. Hence, obtaining the net water available value, which was found as equal to $40.17 \cdot 10^6$ $m^3$ a year, or an average net flow rate of 1,274 $m^3/s$.

The intake structure consisted of an underground loading tank equipped with a reinforced concrete sluice gate with an automated up and down sluice gate.

The fish ladder artifact, showed in the next two images (Figure 22 and Figure 23), was supposed to be located on the hydraulic right and it was planned on the model of a natural stream with 11 steps and a total length of about 23 m, with the use of large aggregates to be found directly on site, with a width of 100 cm and a maximum slope of 17% and water depth of about 40 cm each step.

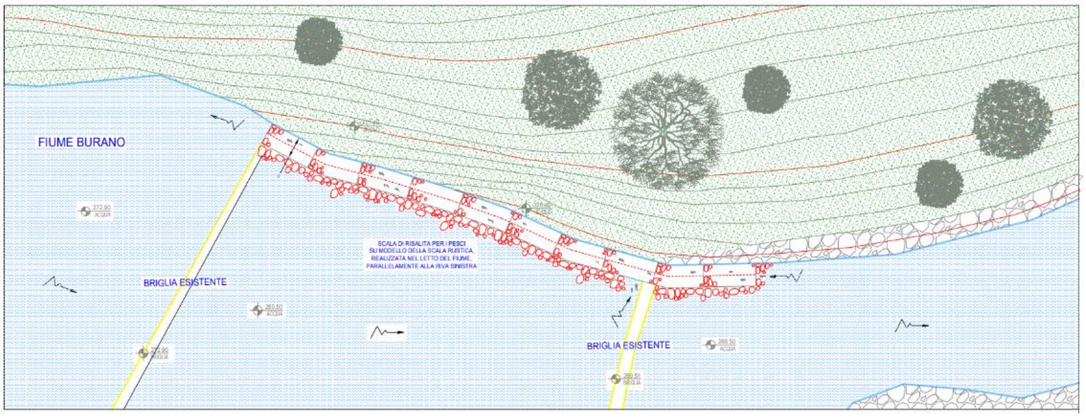


**FIGURE 22: PLANIMETRY OF THE FISH LADDER LOCATED ON THE HYDRAULIC LEFT (2012)**

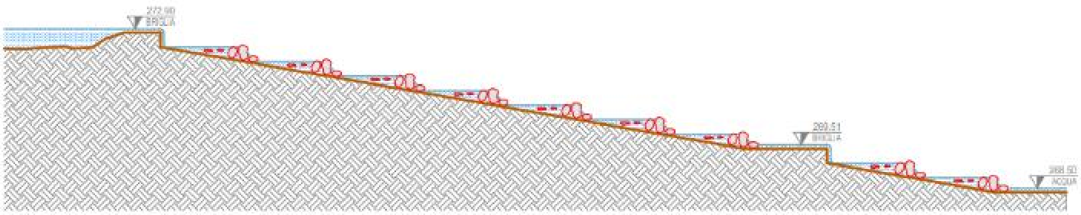

**FIGURE 23: LONGITUDINAL SECTION OF THE FISH LADDER (2012)**

As for the turbine, the plan involved the use of a cochlea, also called Archimedes screw, choice was made in order to avoid the production of waste for disposal, to have the maximum simplicity of installation and maintenance, have low operating costs and being able to exploit the very small available jump and flow rate.

## 2.4 SECOND PROJECT (2020)

In 2020, the Marche Region, requested a resubmission of the project in order to allow for an additional environmental impact assessment review.

The project presented in 2020 proposed some variations to the original old project, which represented improvements in terms of land consumption, of visual and environmental impact and in terms of functionality for the construction and implementation of the hydroelectric plant itself.

This second project involved the construction the hydroelectric power plant with an estimated average rated power of 78.48 kW and a maximum power of 217.39 kW.

The key modification proposed was that to move the central building closer to the river. This adjustment would have allowed for a significant reduction in rock excavations during the construction operations. In this 2020 project, the building was located much further back towards the existing tanks, without the necessity to have an extensive excavation. By relocating it closer to the river, the need for excavation in a challenging and unsafe area was greatly minimized.

Among other things, in the examined area where the power plant was to be planned, the reused fish farming tanks already had a vertical cut-out that housed a small turbine which used to feed the auxiliary services of an hotel located above; therefore, most of the excavations would have already been adequate, and that would have significantly reduced the impact on the construction site.

Figure 24 illustrates a sectioned view of the hydropower plant designed in 2020. In this configuration, the canal is covered but remains at ground level rather than being buried underground, as per the 2012 project. The image shows a visible decrease in the necessary rock excavations as well as the feasibility and greater safety of the possible interventions.

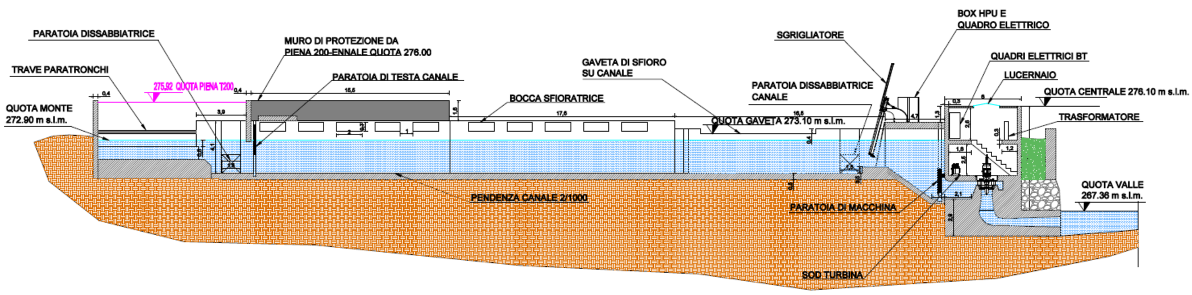


**FIGURE 24: LONGITUDINAL SECTION OF THE PLANT (2020)**

Figure 25 presents a sectioned top view of the hydropower plant layout, where the covered canal is again depicted to show its path at ground level. This sectional perspective provides a clearer understanding of how the channel is integrated into the terrain and highlights its relationship with the surrounding infrastructure.

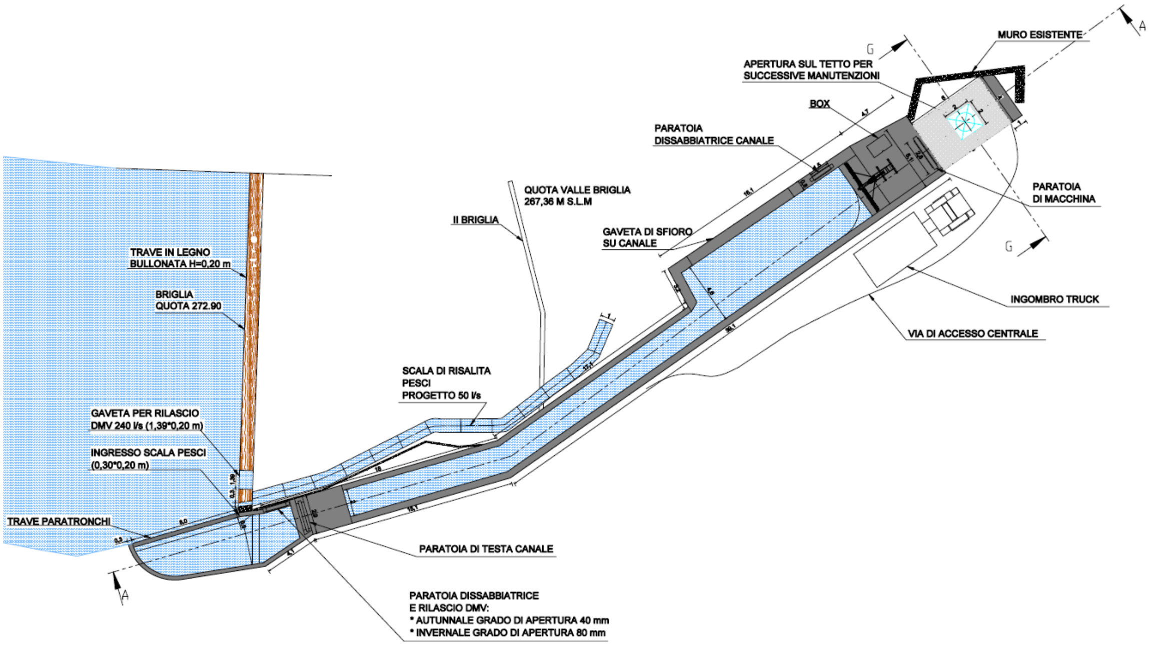


**FIGURE 25: TOP VIEW PLAN OF THE PLANT (2020)**

It was also decided to propose moving the fish ladder to the hydraulic right, since the previous position proposed on the hydraulic left would have strongly put at risk its functionality, precisely because the hydraulic left cannot be reached even on foot without crossing the river from the right bank. This means that, in the event of floods obstructing the passage of the ladder with branches or stones, the fish ladder could not work properly until a vehicle would cross the river to clean it up, this being possible only during low-flow conditions.

The passage for the fish on the hydraulic right was extended to more than 30 m, with 14 steps and 30-cm depth. With this configuration, the motion of the water would have been less turbulent, and the formed length of the step would have stretched beyond 2 m, which is a size considered by experts as ideal for allowing any fish species to go up the river without consequences from the generated turbulence.

The original project from 2012 included an intake mouth without any screening system and with passage sections incompatible with the expected derivation capacity. The new intake structure would have been adequate both for the derivation of a maximum of 3.5 $m^3/s$, and with the possibility of guaranteeing the solid transport through the use of the gravel removal gate and the provided hydrodynamic curb.

The next two images show the design of the fish ladder (Figure 26 and Figure 27).

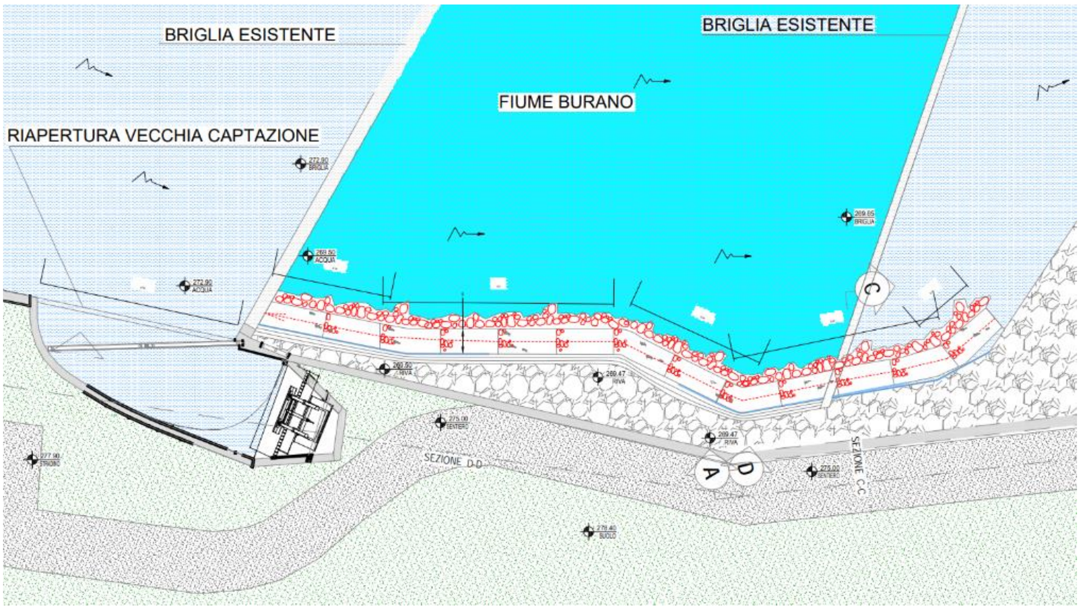


**FIGURE 26: PLANIMETRY OF THE FISH LADDER LOCATED ON THE HYDRAULIC RIGHT (2020)**

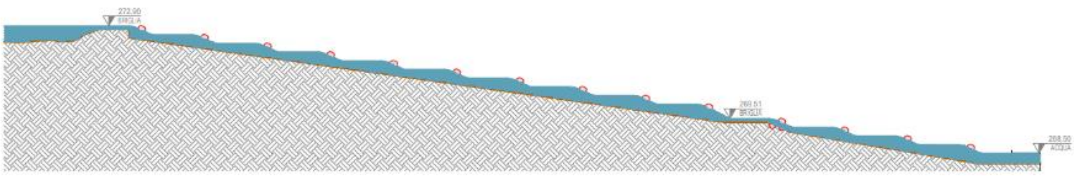

**FIGURE 27: LONGITUDINAL SECTION OF THE FISH LADDER (2020)**

During 2020, a series of hydraulic verifications were carried out in some relevant sections of the river, the aim was that to determine the flood water levels with the return year of 30, 100 and 200 years. To do such calculations, the *HEC-RAS* Software was used.

The HEC-RAS Software is a mathematical computational model created by the U.S. Army Corps of Engineering based on iterative resolution of the energy equation in one dimension. This method is widely used to model river flows, floodplains, and other water bodies. It is an engineering tool that aims at helping the design and the analysis of structures such as dams, levees, and channels.

More specifically, the one-dimensional energy equation is used to describe the flow of water in a channel, and it accounts for various factors like the velocity, the pressure, and the elevation. The equation is typically written as follows:

$$\frac{dE}{dx} = \frac{d}{dx}\left(\frac{v^2}{2g} + z + \frac{p}{\rho g}\right)$$

where:

- *E* is the energy per unit weight of water,
- *v* is the velocity,
- *g* is the acceleration due to gravity,
- *z* is the elevation,
- *p* is the pressure,
- $\rho$ is the density of water.

The above-mentioned equation is solved using an iterative process until the solution converges to a stable result. Basically, the iterative process starts by setting an initial guess of the water surface profile, calculating the energy at each point along the examined channel, adjusting the profile based on the obtained results in order to reduce the difference between the calculated values and actual energy. The process has to be repeated until the changes in the water surface profile are within an acceptable tolerance, therefore the iterative process continues until the difference between the successive iterations is smaller than a predefined threshold. (HEC-RAS River Analysis System)

The *HEC-RAS* Software is able to simulate the behaviour of the current in subcritical, supercritical or mixed regimes handling an entire network of channels. The program schematizes the river as a straight channel between two consecutive sections and finds the solution of the previously explained one-dimensional energy equation.

For slow current motion, boundary conditions are applied to the downstream section, while for fast current motion, they are applied to the upstream section. In cases of mixed-stream motion, both boundary conditions are necessary. Energy losses are determined using the Manning roughness coefficient (coefficient described in detail in the Section 2.5.1.4) and the effects of section variation, including contraction and expansion coefficients.

In particular, the verifications for the Burano River were based on the assumption of a steady flow conditions, the analysis was done on a 700-meter stretch, both upstream and downstream of the bridleway where the diversion channel begins.

The analysis was conducted on the following highlighted sections, showed in the next image (Figure 28), more specifically the sections highlighted with a red colour indicate those sections which have been provided by the Regional Basin Authority of the Marche Region, those ones marked with the blue colour are the section were drawn based on the survey conducted for this study and appropriately scaled to match the elevations indicated in the Marche Region survey at the bridleway. Each section has been identified with a number going from 1 to 0.8, from an upstream location towards a downstream one). This identification has then been used to describe the results in terms of flow rates and water elevation.

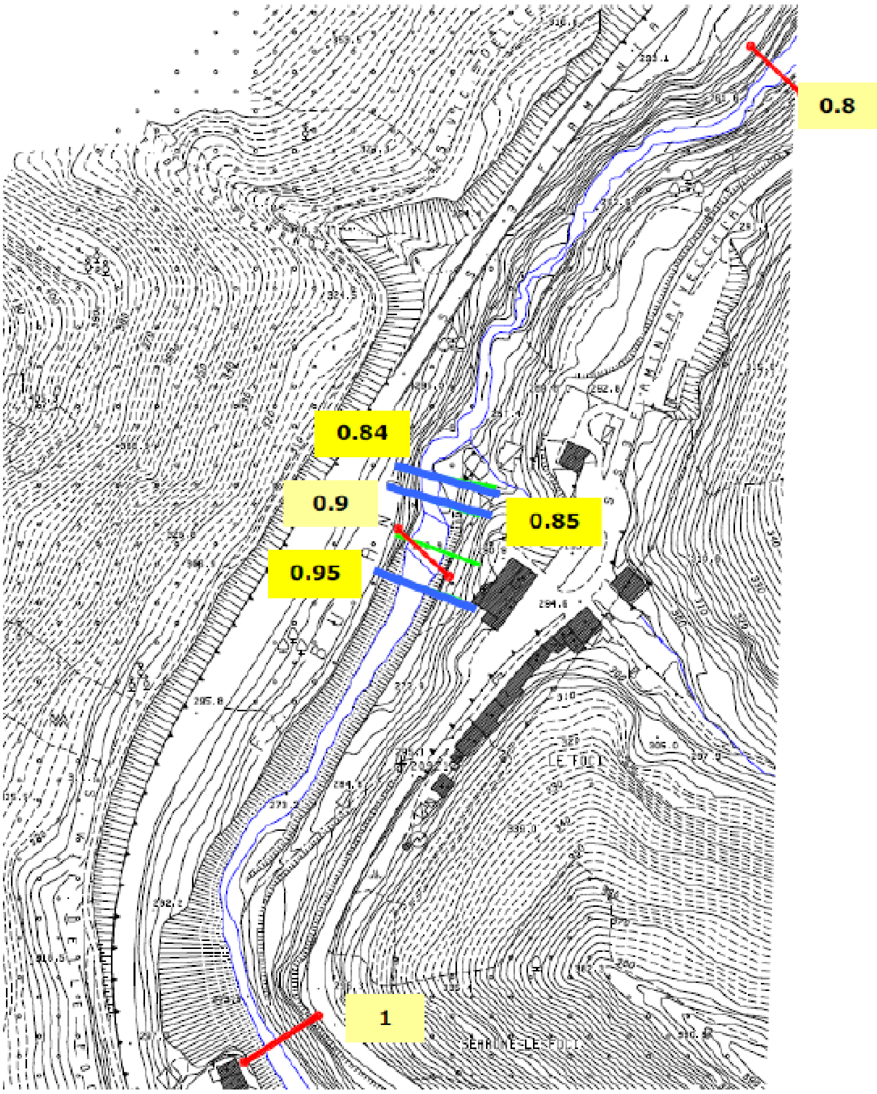


**FIGURE 28: LOCATION OF THE VERIFIED SECTIONS DONE WITH THE HEC-RAS SOFTWARE, THE RED COLOUR INDICATES THE SECTIONS PROVIDED BY THE MARCHE REGION, IN BLUE THE SECTION OBTAINED BY SURVEYING THE AREA.**

The hydraulic model is drawn by an operator who creates a schematic representation of the river system of concern and subsequent input of data on the different sections such as the Manning roughness coefficient values. The next steps involve the entering of more specific information related to the current.

For the Burano River case the current has been defined as in the condition of a steady state. In particular, the model has been implemented with the maximum flow rates values with return times of $T_{30}$, $T_{100}$ and $T_{200}$, calculated on the basis of a 26-year history retrieved from the Acqualagna station. By processing the given data with the Gumbel's method, the $T_{200}$ provided a value of the maximum flow rate, $Q_{max}$, of about 1080 $m^3/s$ over an overall area of 617 $km^2$.

Hence, considering this specific water supply, there would have been a flow rate of 216 $m^3/s$ for $T_{200}$, of 196 $m^3/s$ for $T_{100}$, and finally 162 $m^3/s$ for $T_{30}$, in correspondence of the closure section.

The *HEC-RAS* results provide important insights into various hydraulic parameters across different stations and for selected return periods, these parameters include:

- Water Surface Elevation, *WSE*, height of the water surface above a reference point (sea level). Higher return periods (e.g., $T_{200}$) typically have higher *WSEs*, indicating the possibility of having more severe flood events.
- Flow Velocity, speed at which water is moving through the river channel. Higher velocities indicate a more erosive power of the flow and therefore a higher potential for damage.
- Flow Rate, volume of water passing a point per unit time (usually cubic meters per second). Higher return periods are usually related to higher flow rates values, reflecting the possibility of having more significant flood events.
- Flood Extent Areas, areas that will be covered by water during a possible flood event. The larger the inundation areas are related to higher return periods since they indicate a more widespread flooding.
- Cross-Sectional Profiles, graphical representations of the river channel at specific locations. It is crucial to visually examine these profiles to understand how the water surface interacts with the channel geometry, the areas that could be affected by a flood are the ones whose water surface values exceeds the bank full stage.
- Hydraulic Parameters, metrics such as shear stress, energy grade line, and Froude number; parameters that provide insights related to the flow characteristics and the potential impacts on the river channel and the surrounding areas.

The next following graphs (Figure 29 and Figure 31) display the elevation of the riverbed and banks at various stations along the river reach, providing a visual representation of the cross-sectional shape of the river at different locations. The red lines represent the water surface elevation for the specific return period of $T_{200}$, basically it shows the level the water is expected to reach during a flood event with a 200-year return period.

For the station No. 0.95, represented in the next couple images (Figure 29 and Figure 30), the $T_{200}$ provides values of *WSE* equal to 275.92 m, with a flow velocity of 2.55 m/s and a discharge of 216.00 $m^3/s$. The elevation of the water surface exceeded the maximum elevation of the project, therefore, to avoid a possible flooding event it seemed appropriate to a concrete wall where the underground channel begins, arriving at an elevation of 276.00 m, ensuring both the safety of the plant and the entire environment.

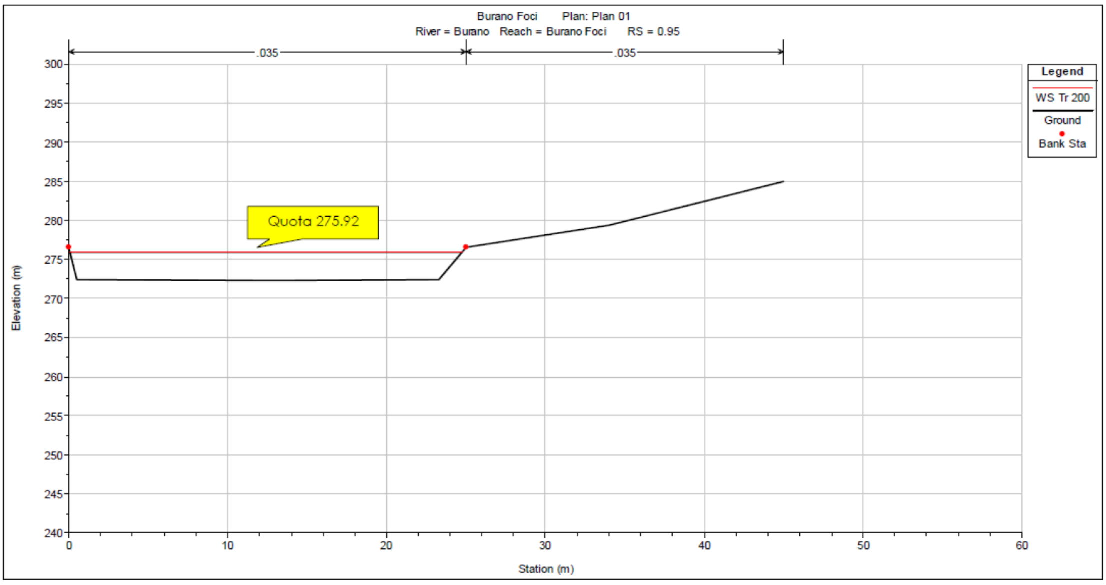


**FIGURE 29: CROSS-SECTION PROFILE OF THE SECTION 0.95**

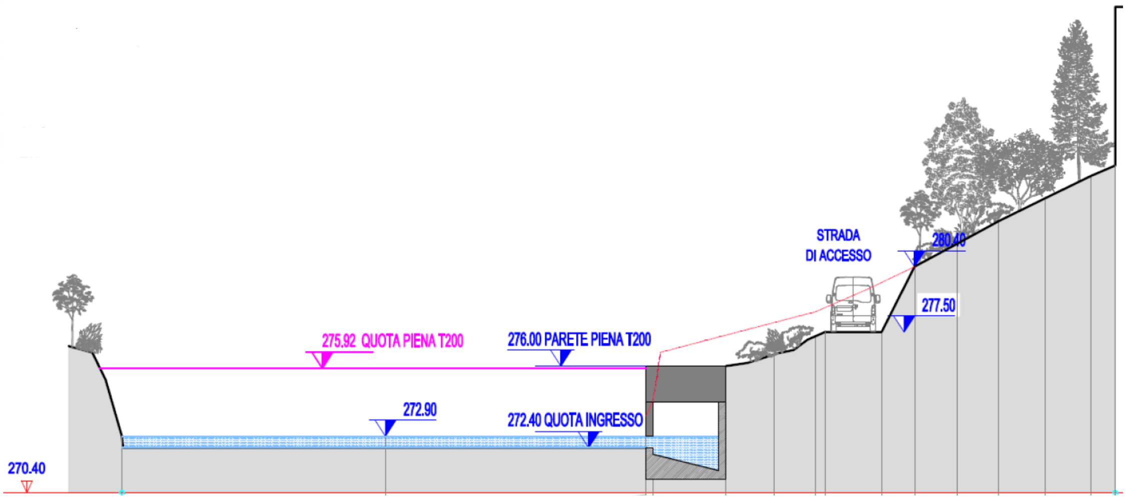


**FIGURE 30: ADDITION OF A CONCRETE WALL**

For the station No. 0.9, represented in the next couple images (Figure 31 and Figure 32), the $T_{200}$ provides values of *WSE* equal to 276.09 m, with a flow velocity of 1.30 m/s and a discharge of 216.00 $m^3$/s. In this section the basin becomes narrower, this is the reason why the project involved the raise of the wall on the hydraulic left that leads to an elevation of 276.20, excluding therefore the possibility to be inundated in case of a flooding events.

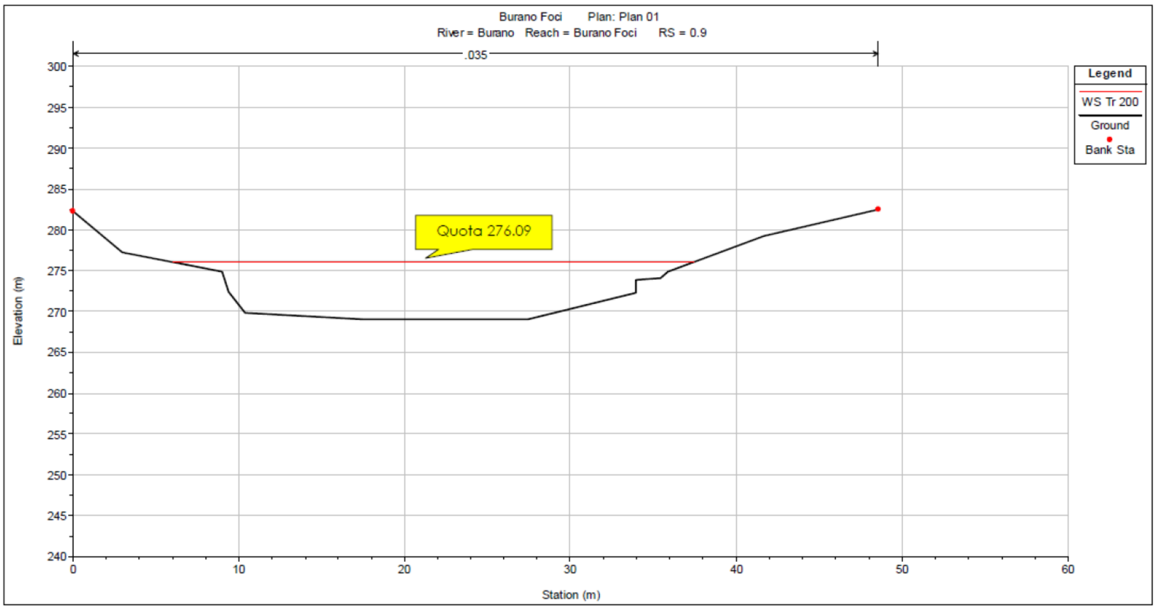


**FIGURE 31: CROSS-SECTION PROFILE OF THE SECTION 0.9**

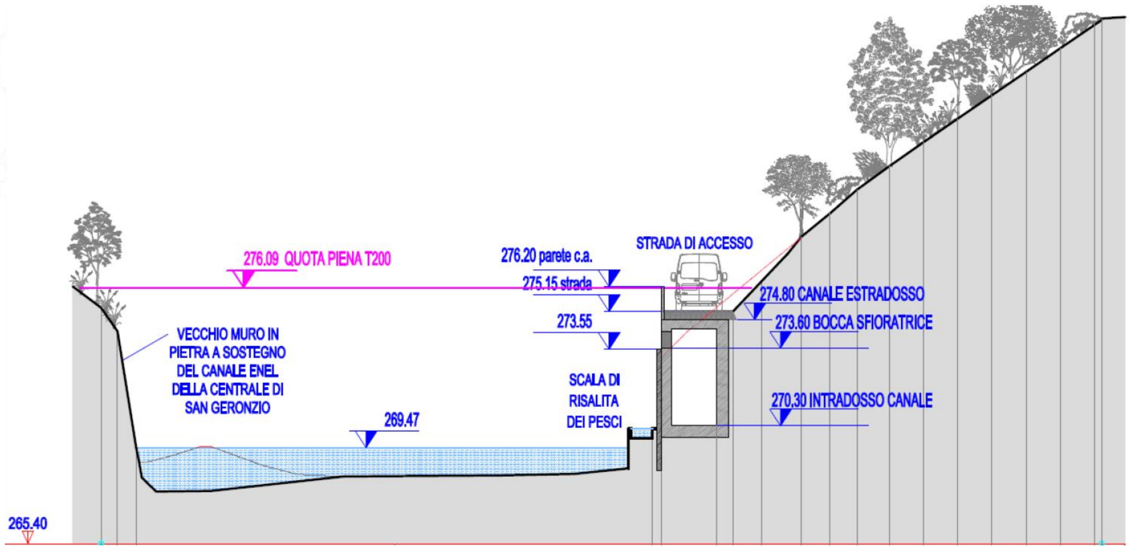


**FIGURE 32: RAINSING OF THE WALL**

The gross water available in the year 2020 resulted from the calculations as equal to 61.34 $\cdot 10^6$ $m^3$, this value was obtained based on the consideration of a derivation of a maximum of 4 $m^3/s$, which at that time was available for 78 days a year.

The gross water available must take into account the minimum vital flow (i.e., the *DMV*) and a flow rate required for the fish ladder, these rates must therefore be subtracted to the previous one. Hence, obtaining the net water available value, which was found as equal to 45.79 $\cdot 10^6$ $m^3$ a year, or an average net flow rate of 1,444 $m^3/s$.

The above-mentioned values had slightly increased with respect to the one selected in the year of 2012.

This project involved the use of a Kaplan turbine with vertical axis, described in the section 2.5.1.5, as it is the same turbine proposed for the current new project (2024).

## 2.5 New project (2024)

The new project places the micro hydroelectric power plant on the river's hydraulic right, near the downstream return point. This is achieved by modifying existing concrete walls of the fish-farming tanks to create a rectangular channel of approximately 2.5 m high, 1 m wide and 90 m long. Therefore, the existing tanks and canal are exploited as well as the natural hydraulic head of about 5.54 m.

### 2.5.1 Power plant components

#### *2.5.1.1 Weirs*

A weir is a small obstacle built across a riverbed in order to control the upstream water level. Over time, the term weir has taken on a more general definition in engineering to apply to any hydraulic control structure that allows water to flow over its crest. In fact, the spillways of many large dams use weirs as control structures.

From the basics of open channel hydraulics for a subcritical flow, that is a mainly slow and calm flow, the depth is controlled by downstream conditions, which means that the addition of a weir across a river will increase the water level upstream. The amount of flow that passes over the weir depends on the length of the weir, the height of the water level above the crest of the weir, and a coefficient that changes depending on the geometry of the weir.

The two most common types of weirs are the sharp-crested or thin plate weir, present in the river of concern, and broad-crested weir. More precisely, the sharp-crested weir is a vertical flat plate with a sharp edge at the top, over which the liquid must flow in order to drop into the area below the weir. If the downstream water rises above the weir crest elevation there is a so-called submerged flow or a submerged weir. The sharp-crested weir could be built in three different shapes: the V-notch, the contracted rectangular, and the one which is related to our case, the suppressed rectangular (Figure 33).

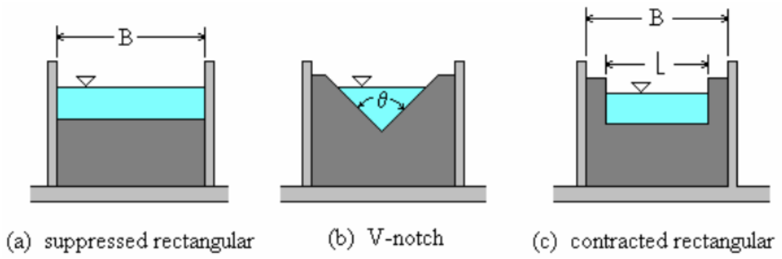


**FIGURE 33: SHARP-CRESTED WEIR SHAPES**

The suppressed rectangular sharp-crested weir is characterized by a weir length equal to the width of the channel, this type of weir is usually accompanied by vent pipes which are installed laterally in order to avoid strong pressures on the structure itself, therefore serving as a connection with the atmosphere. The contracted rectangular sharp-crested weir is characterized by a weir length smaller with respect to the width of the channel.

The broad-crested weir, on the other hand, is a hydraulic structure used to control the water flow in an open channel, it has a span that reaches the full width of the channel where it is located.

As the flow approaches the weir the velocity of the flow increases and the water level decreases, this leads to the transition to a critical flow regime over the hump where a critical depth is reached. As water approaches the weir the streamlines become not parallel between one another, creating therefore a non-uniform flow that can affect the accuracy of the measurements if not properly accounted for.

There is a direct relationship between the upstream water depth, $H_1$, and the discharge, *Q;* this means that the flow rate can be calculated measuring the upstream water level. The schematic representation shows in Figure 34 clearly illustrates the broad-crested weir and related basic parameters.

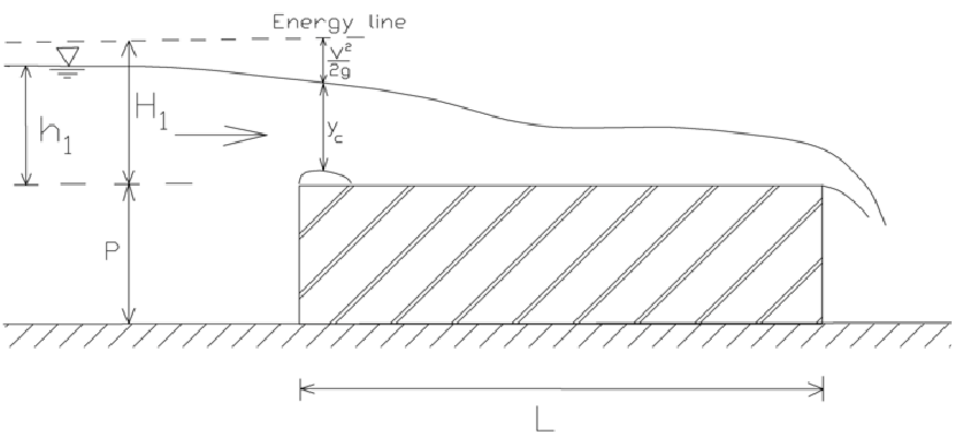


**FIGURE 34: SCHEMATIC REPRESENTATION OF A BROAD-CRESTED WEIR (FARZIN, 2011)**

Referring to the project, the first upstream concrete weir has a length of about 25.50 m and a height of 3.40 m, while the second downstream one, which is made of concrete and stone, is 21 m long and varies in height going from the right bank to the left one, from about 50 cm to 1 m.

Upstream of the first weir, which is rather flat and regular in nature, the free water surface is at about 272.90 m a.s.l., while downstream of the second weir, at the point of discharge, it is about 267.36 m a.s.l.

Despite the good state of preservation of the concrete weirs carrying out some modifications on them would be risky, being them old and irregular one would in fact risk weakening them. It was therefore decided to lay a bolted chestnut beam coinciding with the entire length of the existing upstream weir (which will reach 273.10 m a.s.l.), leaving a small section useful for the *DMV* release and another one for the entrance to the fish ladder.

Figure 35 shows the two involved broad-crested weirs, from which it is possible to understand their integration into the landscape of concern.

**FIGURE 35: INVOLVED TWO WEIRS**

### 2.5.1.2 *INTAKE STRUCTURE*

The design of an intake structure aimed at catching the flowing water for a hydropower plant is based on the purpose of delivering a required flow over a selected range of hydraulic elevations with a specific hydraulic efficiency.

Riverbanks projects typically provide lateral intakes which are designed to divert the water at a certain degree angle from the main stream flow, usually 90-degree angles are adopted. Lateral intakes must be located considering issues as clogging and instability during possible flood events.

Referring to the project, on the hydrographic right, a new intake structure for the water adduction will be created replacing the old one (Figure 36). The new structure will be optimized a value of the maximum flow rate equal to 4.0 $m^3/s$ (Section 3.1.3 - Flow rate analysis). The restitution will take place immediately downstream of the second weir, therefore, creating a section of subtraction of the natural riverbed of about 90 m.

**FIGURE 36: LATERAL VIEW OF THE OLD INTAKE STRUCTURE**

The intake work, illustrated in detail in the graphic elaboration represented in the following section (Section 2.5.1.2), consists of a loading basin equipped with a sluice gate with an automated up and down sluice gate and a grit removal sluice gate that allows for the removal of grit material before entering the channel.

In order to avoid an excessive accumulation of material at the base of the adduction channel, a sluice gate will be built in the terminal section, orthogonally to the stream flow, with a discharge which goes directly to the river.

### *2.5.1.3 TRASH RAKE CLEANING MACHINE*

The Renpower group has gained extensive expertise and numerous references in hydro-mechanical equipment. One of their main projects concerns is the Trash Rake Cleaning Machines, *TRCM*, an eco-friendly and oil free screening machine patented by the company itself.

These machines, designed for large plants, come in three different categories: the telescopic arms, the wire rope types and the articulated boom. These TRCMs are modular and can be customized in order to meet all the possible specific needs and characteristics of each plant.

The project of concern involves the implementation of an articulated boom TRCM, displayed in the next image (Figure 37), this system is designed to allow an efficient lifting and lowering of stop logs and screens, as well as a rotation movement and a cleaning process of the trash racks. The system is capable of handling both vertical and horizontal movements.

One of the key advantages of this design is that the arm movement is independent of the rack, allowing therefore the machine to adapt to any imperfections in civil works. The boom is engineered to deliver a controlled and strong downward thrust, effectively removing any sediment or solid debris.

This system can achieve a cleaning depth of up to 30 m and has a daily cleaning capacity of up to 900 tons, ensuring the efficient and uninterrupted operation of the hydropower plant where it is installed.

Both large aggregates and floating materials will be intercepted by the grit removal system, the small natural aggregates will then be returned to the riverbed during the plant operation, and from there resume their normal course.

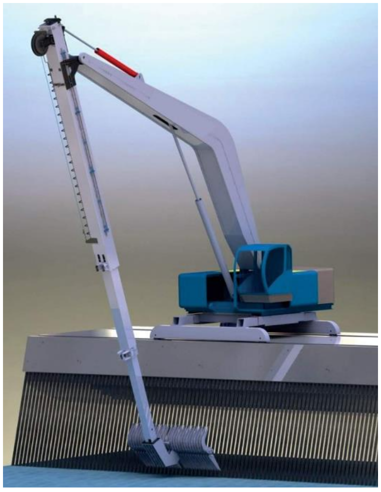

**FIGURE 37: ARTICULATED BOOM TRCM**

### 2.5.1.4 CHANNEL

The channel will be characterized by a rectangular geometry, it will be positioned parallel to the existing concrete retaining wall and sized in order to be able to derive the maximum flow rate, taken as 4.0 $m^3/s$ (Section 3.1.3 - Flow rate analysis).

The dimensions are 2.5 m of height and 1.00 m of width, for a length of about 90 m to the powerhouse, with a slight variation in slope to exploit.

The previously designed channel, related to the project presented in 2012, was a completely buried channel that would have required a much more expensive construction and material exploitation. In addition, the channel was designed in order to have a height of 2.00 m and a width of 3.5 m. Length and maximum flow rate have remained unchanged.

In order to decide the best configuration for the channel different calculations have been adopted.

In the first place, the option of adding two vertical PVC pipes was analysed. In this case the equation of Hazen-William has been applied. The Hazen-Williams equation is an empirical formula used to calculate the pressure drop or head loss due to friction in water pipes. It is particularly useful for designing water supply systems. The general form of the equation is expressed as follows:

$$h_f = 0.2083 \left(\frac{100}{C}\right)^{1.852} \frac{Q^{1.852}}{d^{4.8655}}$$

where:

- $h_f$ is the head loss (m),
- *C* is the Hazen-Williams roughness coefficient (dimensionless),
- *Q* is the flow rate (l/s),
- *D* is the inside diameter of the pipe (mm).

The Hazen-Williams equation is a valid formula for pipes less than 1.8 m in diameter (Casey, 1992) that convey water. The roughness coefficient, *C*, varies depending on the material of the pipe. For example, a new cast iron pipe might have a *C* value equal to 130, while a smooth plastic pipe could have a value of 150.

Therefore, applying the equation in case of two PVC pipes with a diameter of 1m each, the flow rate did not reach the target values.

The following Table 4 has been used to select the appropriate roughness coefficient of the pipes.

| Coefficient of roughness | |
|---|---|
| 100 | Concrete pipes |
| 120 | Steel pipes |
| 130 | Coated cast iron pipes |
| 140 | Stainless steel pipes |

| | |
|---|---|
| 150 | PE, PVC and GRP pipes |

**TABLE 4: ROUGHNESS COEFFICIENT FOR PIPES**

Secondly, the option of an open rectangular channel was considered. To calculate the flow rate of a rectangular open channel, the Manning equation was applied. This equation relates the flow rate to the channel width, depth of flow, slope, and the roughness coefficient.

$$Q = \frac{1}{n} A \ R^{\frac{2}{3}} \ S^{\frac{1}{2}}$$

where:

- $Q$ is the flow rate ($m^3/s$),
- $n$ is the Manning's roughness coefficient,
- $A$ is the cross-sectional area of flow ($m^2$), for a rectangular channel the area is equal to the product between the channel's width, $b$, and the depth of the flow, $h$

$$A = b \ h$$

- $R$ is the hydraulic radius (m), calculated dividing the area, $A$, by the wet perimeter, $P$, and the area, $A$

$$R = \frac{A}{P}$$

  In turn the wet perimeter, $P$, is the length of the boundary between the water in the channel and the channel itself, for a rectangular open channel, it includes the bottom width and the two sides of the channel that are in contact with the water. It is given by the following formula:

$$P = b + 2 \ h$$

- $S$ is the slope of the energy grade line (m/m), also referred to as $p$, as per in the next schematic representation (Figure 38).

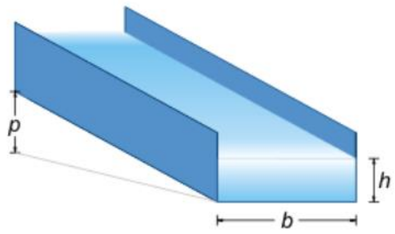


**FIGURE 38: RECTANGULAR CHANNEL PARAMETERS**

In conclusion the final flow rate obtained using the Manning's equation, considering a height of the channel of 2.5 m, a width of 1.00 m, a slope of 0.0013 m/m (1.3‰), and a roughness coefficient equal to 0.15 (coarse concrete, masonry), resulted as equal to 4.11 $m^3$/s.

The following Table 5 has been used to select an appropriate roughness coefficient, an intermediate value between the given roughness related to the coarse cement, regular masonry and the cement with embedded river pebbles.

| Roughness relative to the riverbed | |
|---|---|
| 0.05 | Plastic with well-fitted joints |
| 0.10 | Smooth or metallic concrete |
| 0.15 | Coarse cement, regular masonry |
| 0.30 | Cement with embedded river pebbles |
| 0.35 | Degraded cement, coarse masonry |

**TABLE 5: ROUGHNESS COEFFICIENT**

The maximum flow rate that can be derived from the river was crucial to design the rectangular channel of the plant. As a matter of fact, the channel has been engineered in order to handle effectively the maximum expected flow. Needless to say, that if the channel was designed for an occasional flow rate, it could lead to an oversized structure used at full capacity only for a few days a year.

It is also important to control the velocity of the water within the channel, as a matter of fact, it should be at least 1 m/s in order to prevent sediments to settle at the bottom of the channel, and to minimize the possible damages to the channel.

The analysis of the flow duration curve for the Burano River, explained in detail in Section 3.1.3, shows that the Burano River consistently provides a minimum flow rate of 4.0 $m^3/s$ for approximately 63 days per year. This flow rate represents the lower range of the river's capacity during those days and is considered sufficient for the project's design parameters.

However, the river also experiences higher flow rates during the remaining periods of the year. These flow rates, combined with the lower threshold of 4.0 $m^3/s$, provide a reliable operational range for the turbine, sluice gates, and channel section. In designing the system, both the periods of high flow and the need to maintain the minimum vital flow (*DMV*) to ensure that the river's ecological requirements are met, were considered.

Thus, while the turbine will indeed be operational during the period when flows exceed the 4.0 $m^3/s$ threshold, the system's design is robust enough to account for both the periods of lower and higher river flows, ensuring continuous operation throughout the year when feasible.

#### *2.5.1.5 TURBINE*

The building used to accommodate the turbine has been designed in order to have dimensions of 6.0 m x 4.0 m and height above ground of 3.1 m, the construction is intended to host the measurement and electrical panel room.

In order to respect the orography of the area and the environmental scenario, the works will be conducted trying to move as less soil and natural material as possible, without even disrupting or modifying the river runoff.

The central production manufacture, built partly above the ground and partly underground, has limited dimensions given the simplicity of the equipment which is planned to be installed.

An access point to this building will be located at an elevation of 273.00 m above sea level, a staircase will be built inside the above-ground compartment, therefore, giving the possibility to reach and easily perform maintenance operations in the underground part of the manufacture where the electromechanical components and the turbine-alternator units are hosted.

The extrados of the building will have an elevation of 276.10 m a.s.l., this specific elevation being defined after the estimate of the possible flooding heights via the HEC-RAS software.

The structure will be made of reinforced concrete by exploiting the already existing walls which were used with the purpose of fish farming. The power plant will be hidden as much as possible within the surrounding vegetation by covering the external concrete walls with the typical stone of the area, the “White Stone of Cagli”. The covering of the access point to the electromechanical equipment room will be flat and it will be coated with a fine gravel finish.

The electromechanical equipment hosted in the manufacture consists of a turbine-alternator and an electrical power organ for transforming the rotary motion of the shaft into electricity by means of an asynchronous generator will be inserted. The presence of a fully openable skylight in the machine room roofing slab will allow the assembly and eventual removal by crane truck for extraordinary maintenance of the turbine, without the need to install a fixed overhead crane.

The Kaplan Turbine, named after its inventor Viktor Kaplan, is an excellent solution aimed at using large volumes of water in case of low jumps. The impeller blades can be adjusted at any moment, this results in a very good efficiency of the partial loads. The Kaplan turbine is an axial flow turbine; therefore, the fluid enters and exits in an axial direction relatively to the impeller's rotation axis (Figure 39).

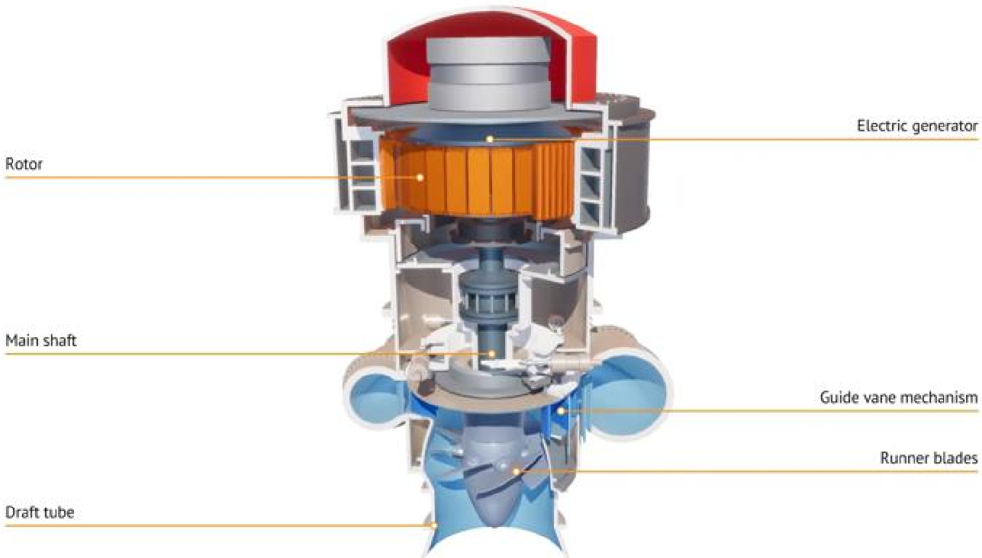


**FIGURE 39: SCHEMATIC DRAWING OF A KAPLAN TURBINE (SOURCE: ENERGY ENCYCLOPEDIA, KAPLAN TURBINE, SCHEMATIC DIAGRAM)**

Some useful definitions are listed below in order to be able to analyse the used turbomachine:

- *Geodetic height of the loading basin* ($H_g$) is defined as the elevation, in meters, between the free water surface of the inlet and the origin of our reference system.
- *Geodetic jump* ($\Delta H_g$) is the difference between the two free water surfaces of the inlet basin and the outlet basin, respectively.
- *Total motor jump* ($H_t$) is the difference between the free water surface of the upper (inlet) basin and the discharge section of the turbomachine.
- *Useful motor jump* ($H_u$) considers the pressure drop.

Fundamentally, the water arrives at the turbine through a spiral distributor, and it is subsequently pushed towards a steerable vane distributor. The water passes through a non-paddle toroidal channel in which the radial effect of the fluid motion is elided. Afterwards, the fluid affects the impeller blades, resulting in the transfer of its mechanical energy to the impeller itself and the rotation of the impeller around its own axis. The effect of the tangential component is cancelled, and the flow is free to be discharged in the diffuser in the axial direction.

Because of its specific characteristics of being able to work at very low available jumps (between 2 and 30 meters) and high discharge velocities, in order to be able to guarantee a correct functioning with respect to other similar hydraulic turbines, the diffuser will have an increasing section, technically called divergent, and will be “L” shaped. In addition, in order to contain fluid-dynamic losses due to the incident flow, the impeller blades are deflected.

The analysis of the performance of the turbine is done using the collinear diagrams and the characteristic curves, which represent a constant value of the geodetic height drop. For the Kaplan turbine, a more interesting observation is done based on the variation of the flow rate as a function of machine speed.

When the required usable drop is very low, as in the case of concern, the turbine is called a *bulb* turbine, it is characterized by an almost horizontal axis turbine operating with a drop value of about 6 metres. This kind of turbines are basically arranged axially in order to avoid trends being too tortuous.

The following Table 6 outlines all the specific characteristics of the Kaplan turbine, which, though not new, is intended to be reused by the Renpower Company for their project. The table provides detailed information on the turbine key parameters and operational features.

| KAPLAN TURBINE CHARACTHERISTICS | | |
|---|---|---|
| Maximum flow rate | l/s | 4000 |
| Minimum flow rate | l/s | 500 |
| Maximum power output of the prime mover | kW | 170 |
| Installed generator power | kW | 200 |
| Installed electric power | kW | 200 |
| Rated concession power | kW | 78.48 |
| Average concession flow rate | l/s | 1444 |
| Nominal head | m | 5.54 |

**TABLE 6: EXISTING KAPLAN TURBINE HIGHLIGHTED CHARACTERISTICS**

The Kaplan turbine (Figure 40) will be separated from the generator, which will remain isolated from the turbine water. The turbine will consist of:

- Propeller with blades made at machine tools from steel blocks.
- Propeller hub with outer profile hydraulically shaped in one piece at machine tools.
- Propeller blade adjustment levers located inside the hub.
- Turbine shaft drilled inside for passage of turbine blade control rod.
- Support with biodegradable grease lubricated guide bearing.
- Impeller shroud made of steelwork, complete with reinforcing ribs and anchor bolts in concrete.
- Hydraulically shaped suction elbow, constructed of electro-welded steel, complete with anchors to be embedded in concrete.

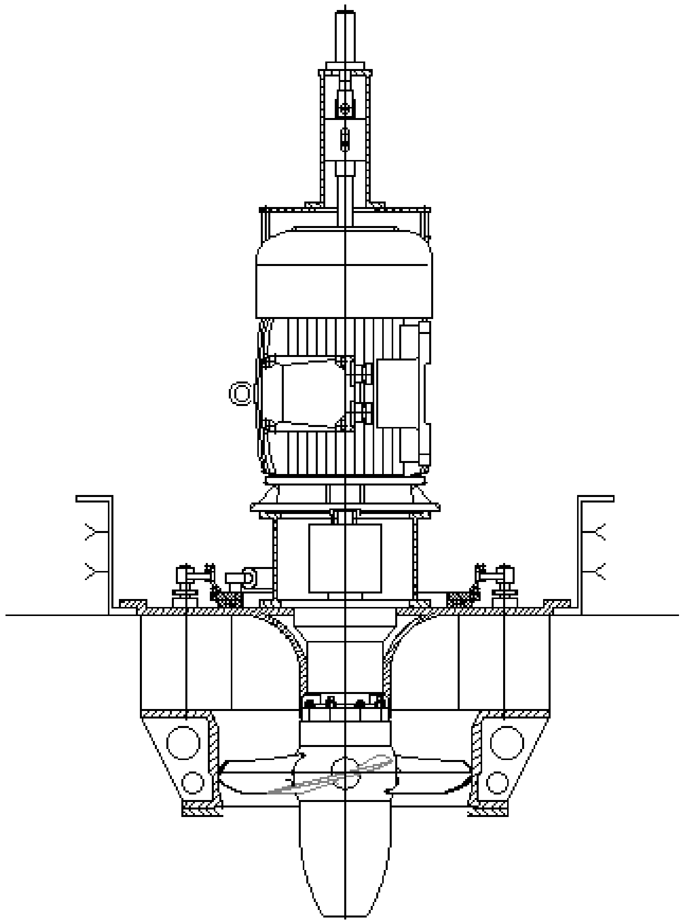

**FIGURE 40: DETAILED TECHNICAL DRAWING OF THE KAPLAN TURBINE OF CONCERN**

The control equipment, found inside the manufacture, will have the task of monitoring and managing the proper operation of all components and, at the same time, adjusting the operation of the machine by acting on special actuators to vary the flow rate worked by the turbine, and at the same time provide for adjusting the opening of the de-icer sluice gate in the intake work, when necessary.

In the next images (Figure 41 and Figure 42), there are the two main components related to the Kaplan turbine, the red cylindrical component in the foreground is the electric generator that converts mechanical energy from the turbine into electrical energy. The blue circular structure in the background is the draft tube, critical component that discharges water from the turbine after it has passed through the blades. It is designed to recover kinetic energy from the water exiting the turbine, improving efficiency.

The overall setup would involve the Kaplan turbine mounted inside the casing, with the shaft connecting the turbine to the generator.

**FIGURE 41: TURBINE COMPONENTS**

**FIGURE 42: TURBINE DRAFT TUBE**

### 2.5.1.6 *FISH LADDER*

The impact of hydropower structures and dams is a major worldwide issue for fish migrations, particularly for potadromous (freshwater) and anadromous species attempting to reach upstream spawning grounds or other habitats in a timely manner. Conventional fish ladders and lifts have provided passages for some fish at many hydropower projects, but it is crucial to meet a reasonable passage efficiency. (Al. M. S., 2023)

Fundamentally, these passage designs must provide a safe, timely, and effective passage for a wide range of species. The principle is that to alternate areas of fast current (jumps) with areas with limited speed (pools) where fishes are able to recover their energy and prepare for the next jump.

The fish ladder of concern will be built according to the *rustic ladder* scheme (Figure 43), it will be inserted in the riverbed and set along the hydraulic right. The ladder has been sized to allow the passage of all salmon species present along the studied river stretch. Such structure will be built resembling a natural stepped stream, it will be created using large natural aggregates, with the aim of minimizing, if not nullifying, the environmental impact and its maintenance operations. The ladder will have a width of 100 cm, with a maximum slope of 17% and a maximum hydraulic tailwater of about 40 cm to ensure practicability by as many species as possible, the expected flow rate is of 50 l/s.

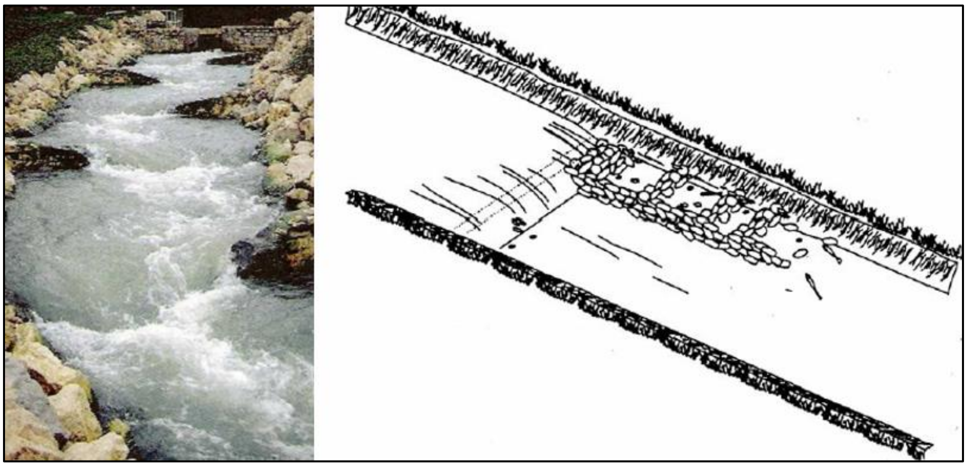

**FIGURE 43: EXAMPLE OF A RUSTIC FISH LADDER (SOURCE: MONTANARI, LE SCALE DI RISALITA DEI PESCI, UNIBO.IT)**

### 2.5.1.7 DISCHARGE

When discharging a flow into a natural stream it is important to consider the distance of the opposite riverbank, in order to take into account possible erosion due to the strength of the discharge flow.

In this case, the opposite riverbank with respect to the discharge area is about 7 m away and it is, therefore, not affected by the release. However, to prevent minor erosive phenomena from occurring on the opposite bank, the project plans to locate cyclopean rocks that can be found in the area and will result from the demolitions on rock planned for the construction of the plant.

Figure 44 shows the existing discharge which was used for the fish farming activity.

**FIGURE 44: VIEW OF THE EXISTING DISCHARGE**

### 2.5.1.8 ELECTRIC ROOM PANEL

The Renpower Group uses a Software to remotely control all their plants. The Ubiquiti Control Centre, often referred to as the UniFi Network Controller, is a centralized management platform which allows the management and configuration of various network devices such as Wi-Fi access points, switches, and security cameras, from a single interface.

Using the Ubiquiti Control Centre for monitoring hydropower plants can be quite effective, especially when integrated with other automation and monitoring systems. This remote-control system makes it possible to keep an eye on various parameters of the plant from anywhere, ensuring that everything is running smoothly. The system provides real-time data on water flow, turbine performance, and energy output. It also allows setting up alerts for any anomalies or issues, such as changes in water levels or equipment malfunctions, to address problems promptly.

The following screenshots (Figure 45 and Figure 46) show some examples of the possible interfaces that the remote-control centre of the hydropower plant of concern might show once concluded and in operation.

The example is taken from a plant located in the municipality of Palena in the Abruzzo Region. The first interface showed (Figure 45) provides a general visualization of the conduits and machinery of the plant, some fundamental parameters, such as the active power (kW), the current (A), the frequency (Hz), the voltage (V), the total energy produced (kWh) and the status of all the involved valves.

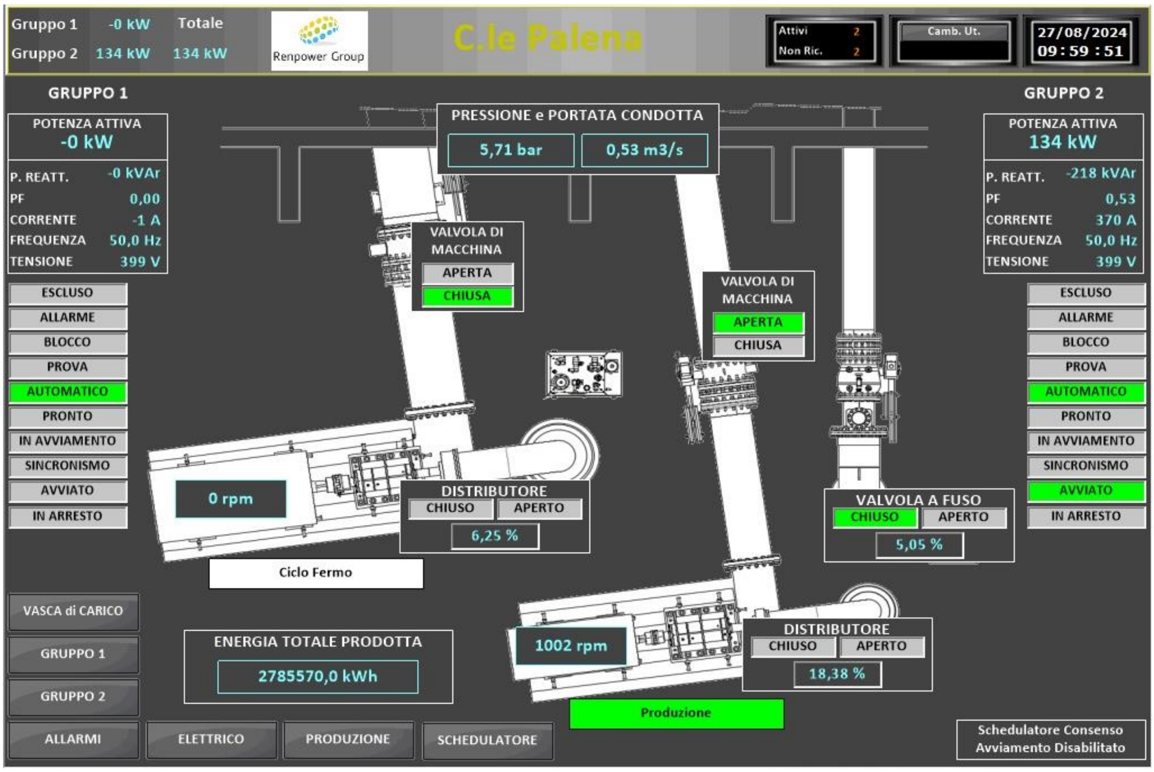


**FIGURE 45: EXAMPLE OF REMOTE-CONTROL PANELS FROM THE PALENA PLANT**

This next interface (Figure 46) focuses on the turbine of the plant; therefore, it displays information such as conduit vibration (mm/s), conduit flow rate ($m^3/s$), temperatures (°C), status of distributor and blades, as well as the generator speed (rpm). In addition, this interface also provides information about the intake structure, for instance the hydraulic head upstream and downstream, the status of the gates and the pressure (bar).

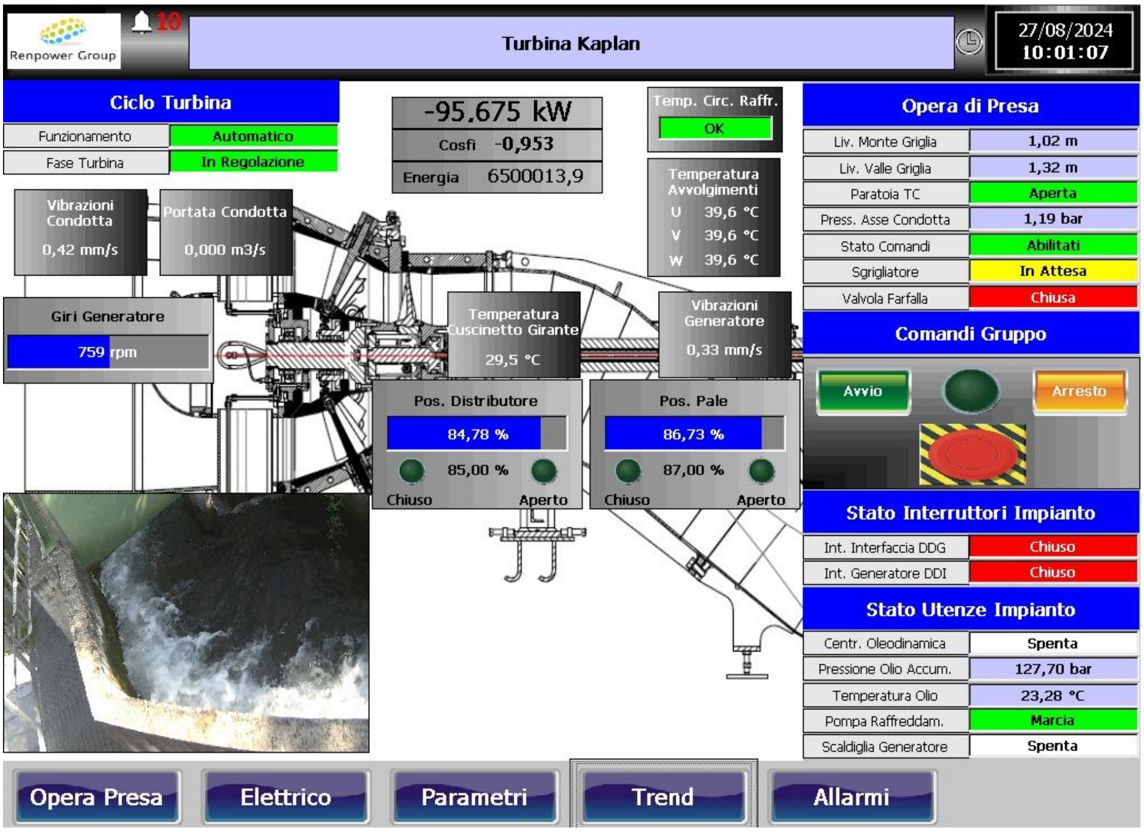


**FIGURE 46: EXAMPLE OF REMOTE-CONTROL PANEL FOR A KAPLAN TURBINE**

Basically, the display can be created based on the needs and the type of plant which is being monitored. To create such a premium Human-Machine Interface, *HMI*, for Ubiquiti systems, the advanced *HMI* software can be used to create a sophisticated and user-friendly interface for monitoring and managing each device. In substance, each interface can be customized with different options, buttons, parameters, technical drawings, real-time data access, and seamless integration capabilities.

### *2.5.1.9 ACCESS POINT*

The project involves the implementation of a small access road on a 5 m wide plateau which runs along the hydraulic right of the river. This narrow road will ensure the access to the turbine cabin and therefore allow for its maintenance. Its construction and management will require limited soil movements and excavations, basically it will have a base of geotextile material cover in stabilized material.

Figure 47 and Figure 48 show, respectively, the steep trail that allows for the access to the plant and the access point from the road.

**FIGURE 47: TRAIL FOR THE ACCESS POINT TO THE PLANT**

**FIGURE 48: ACCESS TRAIL FROM THE ROAD TO THE RIVER**

## 2.6 SOLIDWORKS SOFTWARE

The entire plant was modelled using the 2020's version of Software SolidWorks, a three-dimensional modelling software used for various field, including civil and mechanical engineering. This software provides the necessary tools to design and simulate the entire structure as well as all components. Its parametric modelling makes it possible to easily modify the dimensions of the drawings and when changing parameters an iterating process starts to redefine the whole designs. The use of this powerful tool also simplifies the final steps of rendering which are very useful when Environmental Authorization must be achieved.

Figure 49 provides a total view of the 3D model that recreates the whole structure of the hydroelectric plant, focusing on the structural alignment and the overall flow direction of the facility. This side perspective reveals its internal sections therefore provides for a clearer understanding of how the water actually moves through the system.

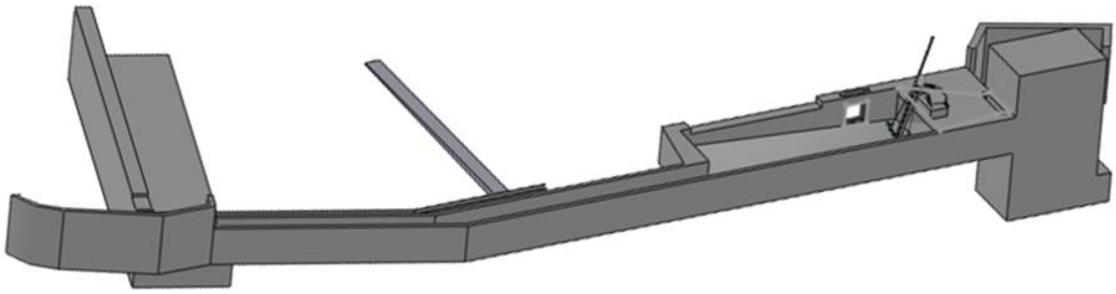

**FIGURE 49: SIDE VIEW OF THE 3D MODEL**

Figure 50 presents the 3D model of the hydroelectric plant, showcasing the integration of both the existing and the newly designed components. More in detail, the blue walls in the model represent the pre-existing structural elements which have been incorporated into the plant's design. The model also highlights the two perpendicular existing weirs serving as flow regulators and structural supports.

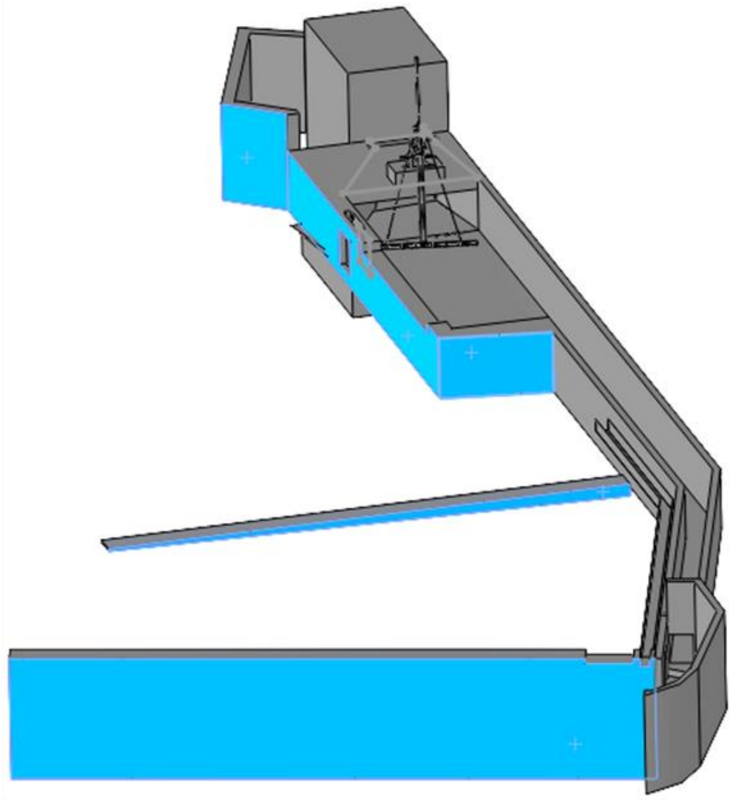

FIGURE 50: 3D VIEW OF THE PLANT VISUALIZED FROM THE UPSTRAM WEIR

The water enters the hydropower plant thanks to the first upstream weir (at the bottom of the Figure 50), which acts as a gentle waterfall. Positioned above this weir is the beam, an essential component that helps regulate the flow of water into the intake structure, it allows water to enter the plant while still ensuring that water can pass through for the *DMV* and the fish ladder flow, which are vital for maintaining the river ecological balance, particularly when the water levels are not very high. This guarantees that the plant is always able to operate and that the ecosystem downstream is always supported.

The next two images show a lateral section of the plant (Figure 51), a section which longitudinally cuts through the plant providing a cross-sectional profile of the structures as well as a visualization of the internal details such as the elevations and the interaction between the different components; and a plant view (Figure 52).

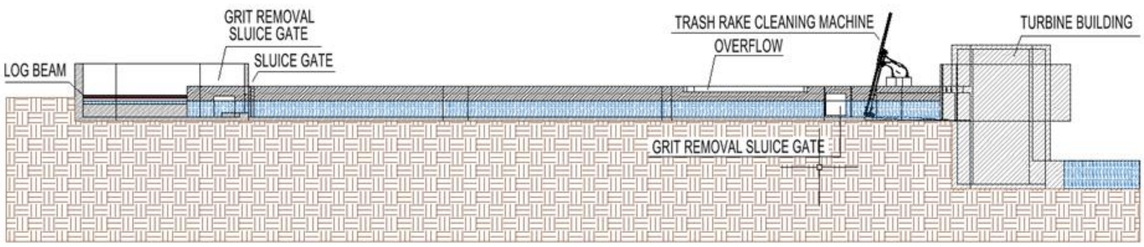


FIGURE 51: LATERAL SECTION OF THE PLANT

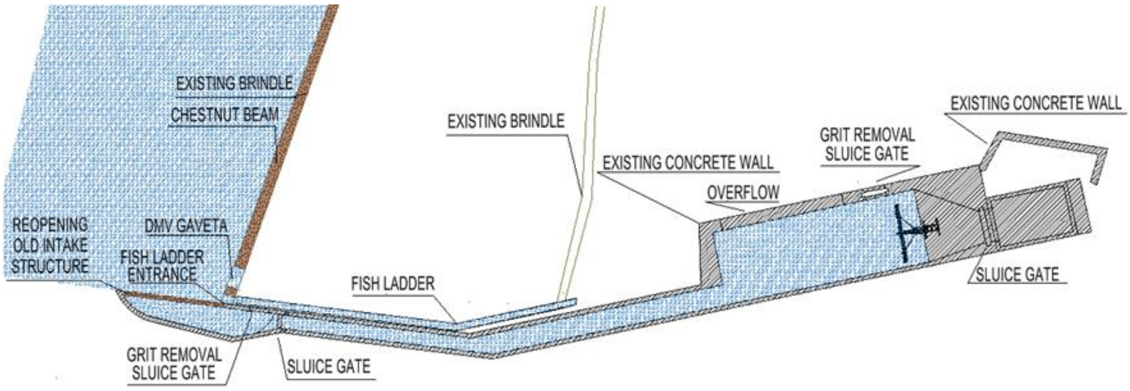


**FIGURE 52: TOP VIEW OF THE PLANT**

At the intake structure, the entrance is protected by a log beam (visible in Figure 53) which serves the crucial purpose of keeping debris and large objects out of the system, ensuring that only water flows into the plant.

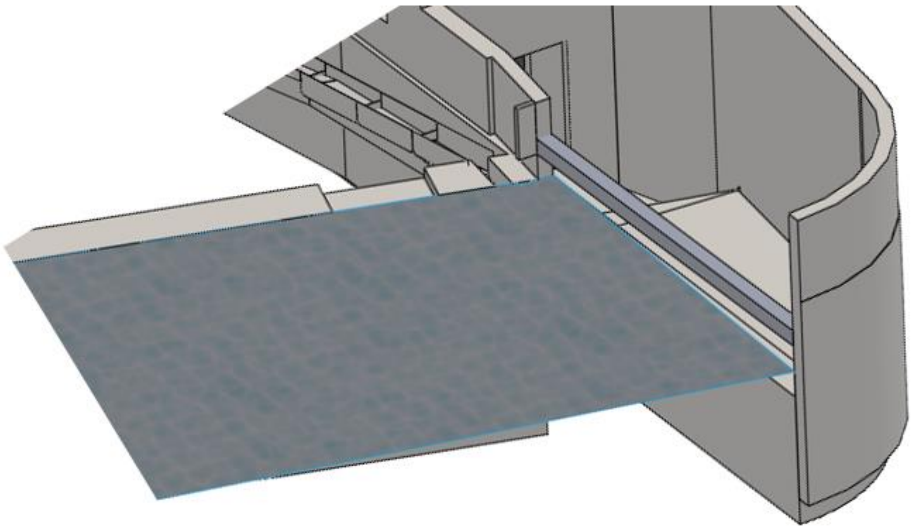

**FIGURE 53: ZOOMED-IN VIEW OF THE INTAKE STRUCTURE AND THE LOG BEAM**

As it can be seen from Figure 54, once inside, the water is initially managed by a sluice gate that has a dual function: it can either allow water to return to the river, bypassing the hydropower plant entirely, or it can direct water further into the plant for the final power generation. This feature provides flexibility in managing the entire water flow, especially during maintenance or when the water levels are too high or low for an optimal energy production. Before the water continues deeper into the plant, it passes through a grit removal system. This system plays an important role in filtering out all the sediments, sand, and other debris that could damage the plant's equipment or reduce its final efficiency.

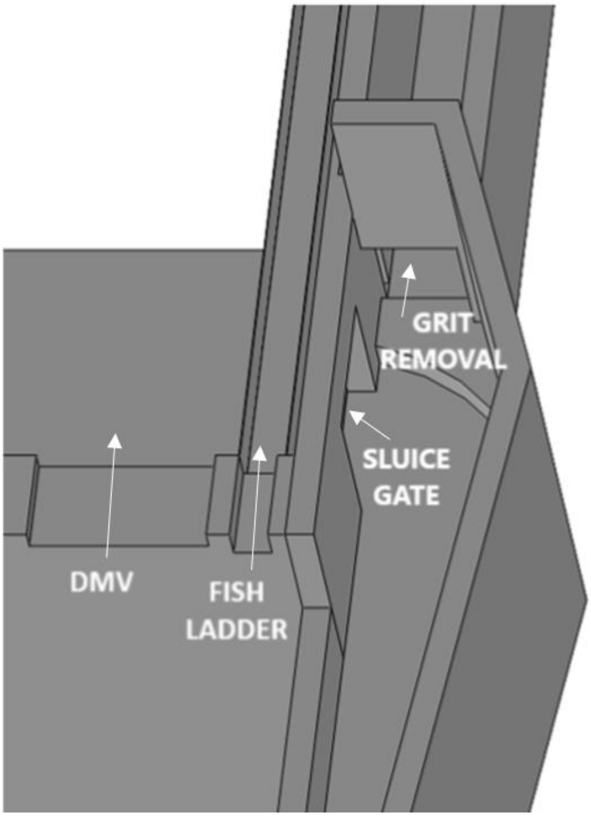


FIGURE 54: ZOOMED-IN VIEW OF THE INTAKE STRUCTURE WITH ALL ITS COMPONENTS

Once the grit is removed, the water flows into a rectangular channel which directs the water in a controlled manner towards the next stage, ensuring that the flow remains steady and without unnecessary turbulence, which could in turn affect the plant's performance.

The water then reaches the collection tank, clearly visible from Figure 55, a reservoir where it is temporarily held before entering the turbine. At the top of the collection tank an overflow system was designed in order to prevent the tank from overfilling. If the water level rises above that safe capacity level, the overflow system will release the excess, allowing it to spill safely back into the river, preventing, therefore, any potential flooding or pressure overload that could damage the plant's infrastructure as well as the turbine.

Before the water is allowed to enter the turbine, it passes through another sluice gate and a second grit removal system. This final grit removal system, visible from Figure 55 and Figure 56, ensures that any remaining fine debris is filtered out, leaving the water clean and suitable for entering the turbine. It's a fundamental step to protect the turbine from wear and tear caused by debris, to ensure the long-term efficiency and performance of the plant.

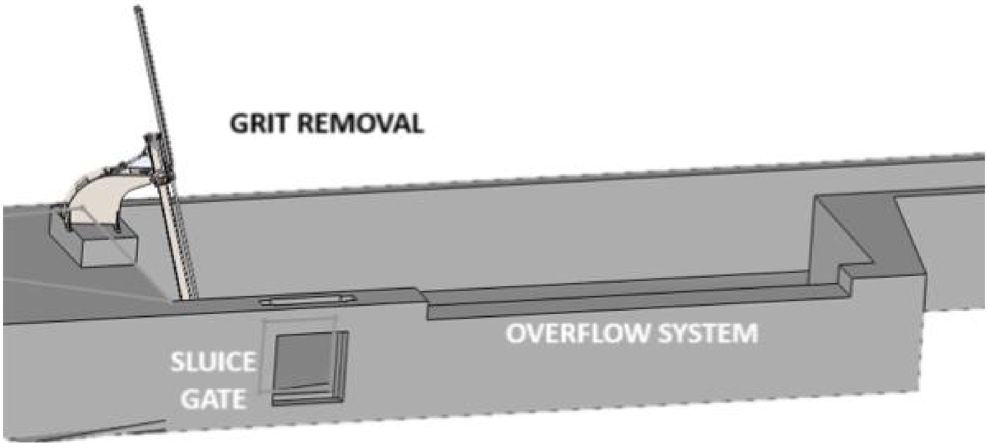


**FIGURE 55: ZOOMED-IN VIEW OF THE COLLECTION TANK AND ITS COMPONENTS**

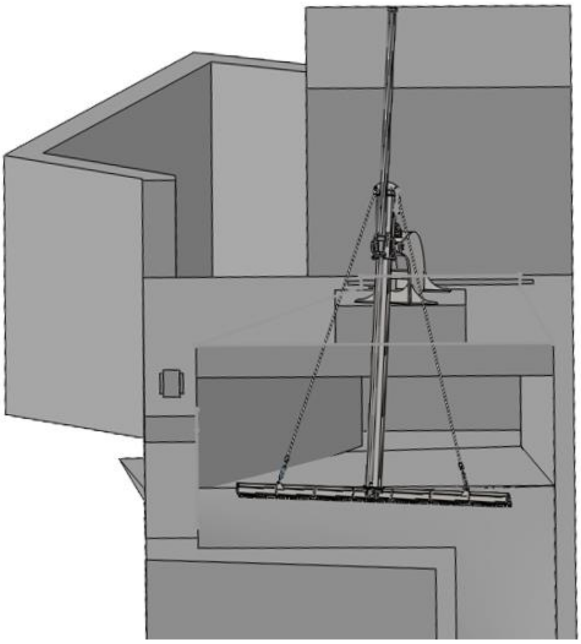

**FIGURE 56: ZOOMED-IN VIEW OF THE GRIT REMOVAL SYSTEM**

Finally, the water enters the turbine building (Figure 57), where the core of the hydropower process takes place. As the water flows through the turbine, it drives the turbine blades, converting the water kinetic energy into mechanical energy then into electrical energy, producing almost 100 kW of power. After the water has passed through the turbine, it is discharged back into the river, this discharge system ensures that the water re-enters the river in a controlled manner, preventing any disruption to the river's ecosystem while complying with environmental standards.

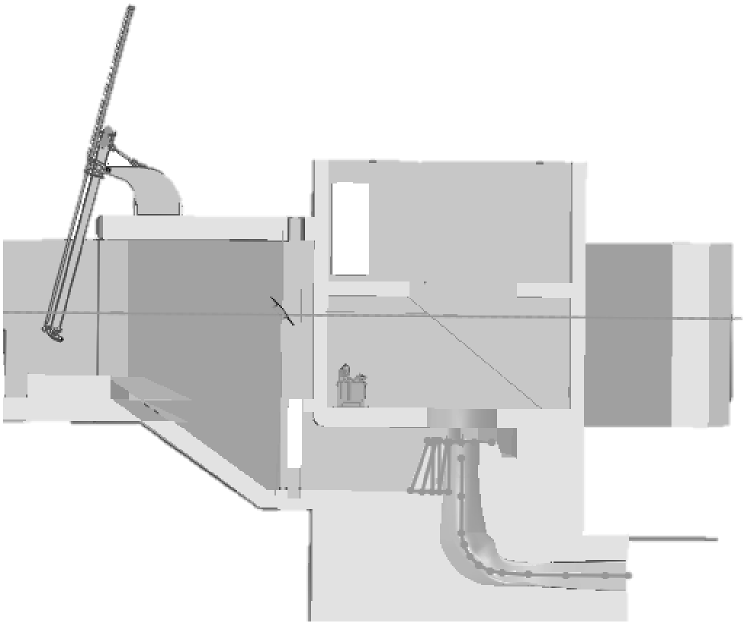

**FIGURE 57: ZOOMED-IN VIEW OF THE SECTIONS OF THE TURBINE BUILDING**

The sectioned view of the turbine building in Figure 57 was retrieved from the 3D model of the original project of 2020, as the same turbine model is planned for reuse in this project.

This entire process demonstrates how the plant carefully manages the water flow from entry to discharge, maximizing energy production while ensuring environmental protection and equipment safety.

# 3 RESULTS

This section presents the results of the comprehensive hydraulic analysis and power output calculations for the proposed hydropower plant. Key hydraulic parameters, such as flow rate, water surface level, minimum reservoir volume, and Minimum Vital Flow (*DMV*), were evaluated to ensure the plant efficient and sustainable operation. The analysis also explores the plant's performance under various scenarios, including peak flow conditions, to determine the optimal configuration and operational schedule for maximizing energy production while maintaining system stability. The findings provide crucial insights into the hydraulic conditions that will guide the successful operation of the micro-hydroelectric system.

## 3.1 HYDRAULIC ANALYSIS

Effective reservoir management is crucial to ensure a reliable water supply for the plant and to maintain high functionality levels of the hydraulic systems. Two key parameters in this context are the minimum reservoir volume and the Minimum Vital Flow, *DMV*.

While the *DMV* represents the volume of water required in a river to preserve its ecological balance and to sustain its aquatic life, the minimum reservoir volume refers to the smallest volume of water that must be maintained in a reservoir to ensure that the system can meet its operational requirements.

### 3.1.1 MINIMUM RESERVOIR VOLUME

This section is related to the hydraulic invariance analysis conducted in order to prove the necessity of including invariance elements to the plant, such as a storage tank to laminate the water.

The first step of the analysis includes the calculation of the minimum reservoir volume, which is fundamental when planning a hydroelectric power plant for several reasons. This volume ensures that there is a sufficient influent amount of water to generate electricity even during dry periods or low-flow periods. It also allows the most efficient functionality of the turbine, warranting the optimal energy production levels. In case of flooding events due to high water flows, the correct calculation of the above-mentioned volume will protect the whole infrastructure and the surroundings.

The size of the minimum reservoir volume to provide in case of areas that can be subjected to a share of transformation, namely rivers, is defined using the following equation. This equation accounts for the changes that there might be in a reservoir volume due to the transformation of a certain percentage of the area, *I*, while also considering an unchanged quota, *P*.

$$w = w^0 \left(\frac{\phi}{\phi^0}\right)^{\left(\frac{1}{1-n}\right)} - 15I - w^0 P$$

where:

- $w^0$ is the initial reservoir volume, which is equal to the value 50 $m^3$/ha,
- $\phi$ is the runoff coefficient after the area transformation, it represents the current transformation factor,
- $\phi^0$ is the runoff coefficient before the area transformation, it represents the initial transformation factor,

- *I* is the percentage of the area subjected to the transformation,
- *P* is the percentage of the area left unchanged; it is such that *I + P = 100%*,
- *n* is a constant related to the transformation process accounting for the non-linearity, it is equal to the value 0.48. This value is estimated under the assumption that the percentages of the hourly rainfall falling in the 5', 15' and 30' are 30%, 60%, and 75%, respectively. For the “significant” and “marked” imperviousness classes, it is permissible to use a different value of parameter *n* if appropriately justified by a specific hydrology contextualized to the site undergoing the transformation.

Thus, the final volume, *w*, is expressed in $m^3$/ha, has to be multiplied by the total area of intervention, *St*, regardless of the unchanged area, *P*.

To estimate the runoff coefficients, $\phi$ and $\phi^0$, fundamental to determine amount of rainfall that will become surface runoff, the two following standard relations were applied. These are based on the proportions of impermeable, *Imp*, and permeable, *Per*, areas.

$$\phi^0 = 0.9\, Imp^0 + 0.2\, Per^0$$

$$\phi = 0.9\, Imp + 0.2\, Per$$

where:

- $Imp^0$ is the initial percentage of the impermeable area,
- *Imp* is the present percentage of the impermeable area,
- $Per^0$ is the initial percentage of the permeable area,
- $Pe^0$ is the present percentage of the permeable area.

Hence, the calculation of the minimum reservoir volume requires the definition of the portion of area which is impacted by the transformation including paved and settled areas, the portion of area which remains unaffected by the transformation including only those sections that have not undergone significant changes. The portion of the area considered permeable is assessed both before and after the transformation, as well as the portion of the area considered impermeable.

The indices *Imp* and *I*, *Per* and *P* are conceptually different. On one hand, *Imp* and *Per* are used to evaluate the conventional runoff coefficient expressing the ability of the plot to accept the rainfall before generating surface runoff, on the other hand *I* and *P* represent the portions respectively of urbanized and unaffected, agricultural, portions.

In order to allow differential consideration based on the area of intervention and on the waterproofing potential, the classification of land transformation interventions according to the degree of urbanization is found in the “Guidelines on Hydraulic Invariance in Land Transformation”, was taken into consideration (Table 7). These guidelines govern the concept of hydraulic invariance, ensuring that any new land transformation does not increase the hydrogeological risk and maintains the hydraulic balance of the land.

| INTERVENTION CLASSES | SIZE THRESHOLDS |
|---|---|
| Negligible waterproofing potential | **Intervention on areas of less than 0.1 ha (1,000 m $^2$)** |
| Modest waterproofing potential | Intervention on areas larger than 0.1 ha (1,000 m $^2$) and less than 1 ha (10,000 m $^2$) |
| Significant waterproofing potential | Intervention on areas larger than 1 ha (10,000 m $^2$) and less than 10 ha (100,000 m $^2$); Intervention on areas larger than 10 ha (100,000 m $^2$) with *Imp* < 0.3 |
| Marked waterproofing potential | Interventions on areas larger than 10 ha (100,000 m $^2$) with *Imp* > 0.3 |

**TABLE 7: CLASSIFICATION OF LAND USE TRANSFORMATION INTERVENTIONS FOR THE PURPOSE OF HYDRAULIC INVARIANCE**

From the hydraulic point of view, the effectiveness of the lamination that can be obtained through the use of reservoir devices depends on two basic parameters: the size of the outlet spans of the reservoir, therefore conduits or weirs, and the maximum tailwater level allowed to form within the reservoir. In case of reservoirs with high water levels small spans in the outlet are necessary to maintain control of the flow, preventing therefore an excessive release of water that can cause erosion.

In this project the transformation is supposed to affect an area of less than 0.1 ha (which falls within the definition of “Negligible waterproofing potential” described in the previous Table 7), and the new waterproof area will have a total surface of 659 m $^2$. Hence, it is necessary to provide an invariance device.

The evaluation of the volume required for the lamination of the flows is based on the indications of the *DGR No. 53/2014*, which states that in the case of negligible potential waterproofing, it is sufficient that the volumes available for lamination meet the dimensional requirements of the formula for calculating the above-mentioned minimum storage volume w; obtained from the calculation shown below (Table 8). The minimum reservoir volume was calculated using an Excel file, which included built-in formulas and automated calculations for determining the values based on the input parameters.

| | |
|---|---|
| Total surface | 741 m² |

| ANTE OPERAM | |
|---|---|
| Impervious existing surface | 245 m² |
| $Imp^0$ | 0.33 |
| Permeable existing surface | 496 m² |
| $Per^0$ | 0.67 |
| $Imp^0+Per^0$ | 1.00 |

| POST OPERAM | |
|---|---|
| Impervious transformed surface | 659 m² |
| Imp | 0.89 |
| Permeable project surface | 82 m² |
| Per | 0.11 |
| Imp+Per | 1.00 |

| TRANSFORMATION INDEXES | |
|---|---|
| Transformed surface | 741 m² |
| I | 1 |
| Unaltered surface | 0 m² |
| P | 0 |
| I+P | 1 |

| RUNOFF COEFFICIENTS ANTE AND POST OPERAM | |
|---|---|
| $\phi^0$ | 0.43 |
| $\phi$ | 0.82 |
| W | 157.59 m³/ha |
| $W^0$ | 50 m³/ha |
| $\phi/\phi^0$ | 1.91 |
| 1/(1-n) | 1.92 |

| MINIMUM RESERVOIR VOLUME | |
|---|---|
| Q | 1.48 l/s |
| W | 11.7 m³ |

**TABLE 8: HYDRAULIC INVARIANCE CALCULATIONS SHEET (DGR NO.53/2014)**

Based on the above-mentioned calculations and analysis, it is necessary to create a storage volume for the water lamination of 11.7 m$^3$.

### 3.1.2 Minimum Vital Flow (*DMV*)

To determine how much water can be safely diverted from the Burano River at a specific location, it is essential to first assess the Minimum Vital Flow, *DMV*. This is essentially the smallest amount of water that must be maintained in a river to ensure its ecological health and function, thereby sustaining aquatic ecosystems and providing the necessary amount of water to support animals, plants, and other organisms. Practically, the DMV value must be subtracted from the derivable flow rate.

Data for this study has been obtained from two different rainfall stations located in proximity of the area of interest.

The Regional Basin Authority of Marche Region has proposed the following method of calculating the *DMV*:

$$DMV = [(q_{d.m.v.} \cdot G \cdot S \cdot P \cdot H \cdot B_{mon})(E \cdot max\,(N, P_{IFF}) \cdot G_m \cdot T)]$$

Each parameter will be described in detail.

The parameter $q_{DMV}$ represents the specific discharge, which is equal to 1.6 l/s·km$^2$, it defines a minimum reference flow rate proportional to the area of the basin. The value of 1.6 l/s·km$^2$ is region-specific, it's an empirical value set by the local the Regional Basin Authority of the Marche Region.

*G* is a tabulated geographic parameter; in this case it has been set as equal to 0.7 (in the following Table 9).

| River | G VALUE |
|---|---|
| Arzilla | / |
| Aso | 1.1 |
| Aspio | 0.2 |
| Bosso Burano | **0.7** |
| Candigliano Biscuvio | 0.5 |
| Cesano | 0.5 |
| Chienti | 0.7 |
| Esino | 0.7 |
| Etevivo | 0.2 |
| Fiastra | 0.3 |
| Fiastrone | 0.9 |
| Foglia | 0.4 |
| Metauro | 0.9 |
| Misa | 0.3 |
| Musone | 0.6 |
| Potenza | 0.8 |
| Scarzito | 1.1 |
| Tenna | 0.9 |
| Tesino | 0.3 |

**TABLE 9: G FACTOR FOR THE RIVERS IN THE MARCHE REGION (SOURCE: MARCHE, NORME TECNICHE DI ATTUAZIONE, SEZIONE D, 2010)**

*S* is the watershed surface, which is equal to 124.13 km$^2$.

*P* is the tabulated rainfall parameter; in this case it has been set as equal to 1.06 considering a mean annual precipitation over a 7-year period of 1066.6 mm (see Table 10 and

Table 11), data which has been retrieved from the available "Annali Idrologici" from the Sirmip page of the Marche Region. (Marche, Annali idrologici, parte prima)

| Mean annual precipitation (mm) | P VALUE |
|---|---|
| < 1.000 | 1 |

| | |
|---|---|
| ≤ 1.500 | $\frac{mm}{1.000}$ |
| > 1.500 | 1.5 |

**TABLE 10: P FACTOR FOR THE MEAN ANNUAL PRECIPITATION VALUES (SOURCE: MARCHE, NORME TECNICHE DI ATTUAZIONE, SEZIONE D, 2010)**

Table 11 shows the data retrieved from the "Annali Idrologici", more specifically Table II of Part I, that have been used in order to calculate the mean annual precipitation in mm in correspondence of two rainfall stations located near the site of concern.

Data from 2012 to 2014 have been retrieved from the rainfall station of Cagli, a few km downstream with respect to the site. Data from 2019 to 2022 have been retrieved from the station of Cagli Civita, which is in proximity of the previous station. The missing data from 2015 to 2018 have not been considered since there was no close enough rainfall station available for measurements. The two stations used to analyse the data are shown below in Figure 58, retrieved from Google Maps.

| Rainfall station | Years of measurements | Station location (m a.s.l.) | Year | Annual precipitation (mm) |
|---|---|---|---|---|
| Cagli | 1924-2015 | 276 | 2012 | 1180.6 |
| | | | 2013 | 1360.8 |
| | | | 2014 | 1447.8 |
| Cagli Civita | 2018-present | 251 | 2019 | 877.0 |
| | | | 2020 | 826.8 |
| | | | 2021 | 813.3 |
| | | | 2022 | 960.9 |

**TABLE 11: PRECIPITATION DATA RETRIEVED FROM THE "ANNALI IDROLOGICI" FROM THE MARCHE REGION**

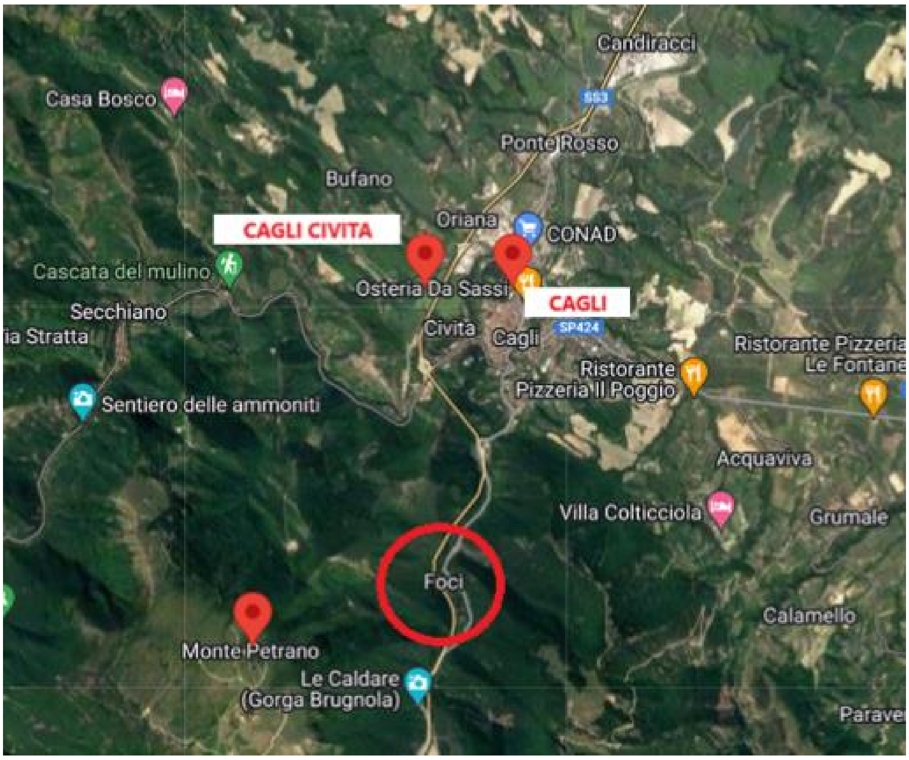


**FIGURE 58: LOCATION OF BOTH RAINFALL STATIONS WITH RESPECT TO THE AREA OF INTEREST, FROM GOOGLE MAPS**

Figure 59 shows an extract of the “Annali Idrologici” Table I of Part I, where the amount of daily rainfall, the monthly and annual total of precipitation and the number of rainy days, are reported per each station.

| Giorno | (PP) | | | | | Bacino: Metauro | **CAGLI CIVITA** | | | | | (251 m s.l.m.) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | G | F | M | A | M | G | L | A | S | O | N | D |
| 1 | - | - | - | **11.0** | - | - | - | - | 25.0 | 0.2 | 0.2 | 0.2 |
| 2 | - | - | - | 7.0 | 4.0 | - | - | - | « | - | - | - |
| 3 | - | - | - | - | - | - | - | - | - | - | - | 2.0 |
| 4 | - | - | 4.0 | - | **10.0** | - | - | - | - | - | 21.6 | 1.0 |
| 5 | 4.0 | 5.0 | - | - | « | - | - | - | - | 0.2 | 7.6 | 10.8 |
| 6 | **31.0** | - | - | « | « | - | - | - | - | 0.2 | - | 25.8 |
| 7 | 2.0 | - | - | - | 6.0 | - | 1.0 | - | - | 0.2 | 0.4 | 2.0 |
| 8 | - | - | - | - | - | - | - | 4.0 | 10.0 | - | 0.2 | - |
| 9 | 2.0 | - | - | 5.0 | - | **54.0** | - | - | - | 0.4 | - | 11.8 |
| 10 | 2.0 | - | « | - | - | - | - | - | - | **2.2** | - | **44.0** |
| 11 | - | - | - | - | - | - | - | - | - | - | - | 6.8 |
| 12 | - | - | - | - | - | - | - | - | - | - | 0.2 | 0.2 |
| 13 | - | - | - | - | - | - | - | - | - | - | 1.2 | 7.0 |
| 14 | - | 1.0 | - | - | - | - | - | - | - | 0.2 | 7.6 | 4.8 |
| 15 | - | 10.0 | - | - | - | - | - | 1.0 | **69.0** | 0.2 | 5.2 | 27.4 |
| 16 | - | 5.0 | - | - | - | - | - | 1.0 | - | 0.2 | 4.8 | 5.0 |
| 17 | - | - | - | - | - | - | - | - | 15.0 | 0.2 | - | 1.0 |
| 18 | - | - | - | - | - | - | - | 2.0 | - | 0.2 | 5.4 | - |
| 19 | - | - | - | - | - | - | - | 10.0 | 4.0 | 0.2 | **39.6** | - |
| 20 | 3.0 | - | - | - | - | - | - | - | - | 0.2 | 2.8 | - |
| 21 | - | 5.0 | - | 5.0 | - | - | - | - | 1.0 | 0.2 | 1.0 | - |
| 22 | - | - | - | 2.0 | - | - | - | - | - | « | 30.0 | - |
| 23 | - | - | - | - | - | - | - | - | - | - | 1.4 | - |
| 24 | - | - | - | 9.0 | - | - | - | - | 27.0 | - | - | - |
| 25 | - | 12.0 | - | - | - | - | - | - | 30.8 | - | 0.2 | - |
| 26 | - | **20.0** | - | - | - | - | - | - | 0.6 | - | 3.8 | - |
| 27 | - | « | - | - | - | - | - | **41.0** | 3.8 | 0.2 | 3.2 | - |
| 28 | - | - | - | - | 9.0 | - | - | 39.0 | - | 0.2 | 0.4 | - |
| 29 | - | | - | - | 7.0 | - | - | - | 17.2 | 0.2 | 4.0 | - |
| 30 | - | | 14.0 | - | 1.0 | - | **2.0** | - | 31.6 | - | 0.2 | - |
| 31 | - | | **35.0** | | - | | - | - | | 0.4 | | - |
| Totali mensili | 44.0 | 58.0 | 53.0 | 39.0 | « | 54.0 | 3.0 | 98.0 | 235.0 | 6.0 | 141.0 | 149.8 |
| N giorni piovosi | 6 | 7 | 3 | 6 | « | 1 | 2 | 7 | 11 | 1 | 15 | 13 |
| | Totale annuo: « | | | | | | | | | Giorni piovosi: « | | |

**FIGURE 59: "ANNALE IDROLOGICO" PART I TABLE I (CAGLI CIVITA)**

*H* is the tabulated altitude parameter; in this case it has been set as equal to 1.13 considering a mean altitude between the source and point of derivation of 663 m (in the following Table 12).

| Mean altitude of the basin (m a.s.l.) | H VALUE |
|---|---|
| < 400 | 1 |
| 400-1000 | $\mathbf{1+\left(\frac{H_m-400}{2000}\right)}$ |
| > 1.500 | 1.5 |

**TABLE 12: H FACTOR FOR THE MEAN ALTITUDE VALUE OF THE BASIN (SOURCE: MARCHE, NORME TECNICHE DI ATTUAZIONE, SEZIONE D, 2010)**

$B_{mon}$ is a constant discharge parameter (tabulated), it is assumed to be equal to 1.2 for stretches of watercourse with a sub watershed ≤ 100 km$^2$ and a mean elevation ≥ 750 m a.s.l., while for the remaining watercourses it is assumed equal to 1. In this case this parameter will be considered is equal to 1.

*E* is the tabulated ecological parameter; it is the value corresponding to the ecological status of the ARPAM station located immediately downstream of the diversion point. The monitoring station in the area of the basin of reference has been defined as equal to 1.1, (in the following Table 13).

| Ecological conditions | E VALUE |
|---|---|
| High | 1 |
| Good | **1.1** |
| Sufficient | 1.2 |
| Poor | 1.3 |
| Bad | 1.4 |

**TABLE 13: DETERMINATION OF THE E FACTOR (SOURCE: MARCHE, NORME TECNICHE DI ATTUAZIONE, SEZIONE D, 2010)**

*N* is the tabulated naturalistic parameter; in this case it has been set as equal to 1.1 (in the following Table 14).

| Naturalistic classes | N VALUE |
|---|---|
| Natural protected areas, areas of the Natura 2000 European ecological network, protected floristic areas, oases for wildlife protection | 1.3 |
| areas of exceptional value for the botanical vegetation subsystem, areas of outstanding value and widespread quality of the botanical vegetation subsystem | **1.1** |
| areas of agricultural and urbanizing interest | 1 |

**TABLE 14: DETERMINATION OF THE N FACTOR (SOURCE: MARCHE, NORME TECNICHE DI ATTUAZIONE, SEZIONE D, 2010)**

$P_{IFF}$ is the tabulated functioning parameter, in this case it has been set as equal to 1.1 (in the following Table 15), The IFF index has been identified by compiling an IFF form consisting of 14 questions covering the main ecological characteristics of a watercourse. The IFF score, obtained by summing the partial scores for each question, can take a minimum value of 14 and a maximum value of 300, staying therefore close to a mean value of 180.

| Mean IFF | Functionality | $P_{IFF}$ VALUE |
|---|---|---|
| 201-300 | High-good | 1 |
| 101-200 | Good-mediocre-poor | **1.1** |
| 14-100 | Poor-bad | 1.2 |

**TABLE 15: DETERMINATION OF THE $P_{IFF}$ FACTOR (SOURCE: MARCHE, NORME TECNICHE DI ATTUAZIONE, SEZIONE D, 2010)**

*Gm* is the geomorphological parameter (tabulated) established by the competent authority, it is assumed between the values 0.9 and 1.1. in this case it was set as equal to 1 for safety reasons.

*T* is the tabulated month parameter which describes the different riverbed runoff variations based on the month (in the following Table 16).

| | Basins | |
|---|---|---|
| | FOGLIA, ARZILLA, METAURO, CESANO, MISA, ESINO, MUSONE, ETE VIVO, TESINO | POTENZA, CHIANTI, TENNA, ASO, TRONTO |
| Month | **T VALUE** | |
| January | 3 | 1.3 |
| February | 3 | 1.5 |
| March | 3 | 1.5 |
| April | 2 | 1.31.2 |
| May | 2 | 1.3 |
| June | 1 | 1.3 |
| July | 1 | 1 |
| August | 1 | 1 |
| September | 1 | 1 |
| October | 1 | 1 |
| November | 2 | 1.3 |
| December | 3 | 1.3 |

**TABLE 16: DETERMINATION OF THE T FACTOR (SOURCE: MARCHE, NORME TECNICHE DI ATTUAZIONE, SEZIONE D, 2010)**

In conclusion, the following table (Table 17) includes all the selected parameters that have been used to find the three different monthly based *DMV* values.

| | $DMV_1$<br>June, July, August, September, October | $DMV_2$<br>April, May, November | $DMV_3$<br>January, February, March, December |
|---|---|---|---|
| $q_{d.m.v.}$ | 1.6 | 1.6 | 1.6 |
| $G$ | 0.7 | 0.7 | 0.7 |
| $S$ | 124.13 | 124.13 | 124.13 |
| $P$ | 1.06 | 1.06 | 1.06 |
| $H$ | 1.13 | 1.13 | 1.13 |
| $B_{MON}$ | 1 | 1 | 1 |
| $E$ | 1.1 | 1.1 | 1.1 |
| $P_{IFF}$ | 1.1 | 1.1 | 1.1 |
| $G_M$ | 1 | 1 | 1 |
| $T$ | 1 | 2 | 3 |
| l/s | **201.5** | **402.9** | **604.5** |
| $m^3/s$ | 0.2 | 0.4 | 0.6 |

**TABLE 17: DMV CALCULATION**

This means that 200 l/s represent the minimum release that must be always guaranteed with continuity during the months of June, July, August, September and October, during the other months the plant must guarantee higher values, namely 400 l/s during April, May, November, and 600 l/s during January, February, March and December.

In conclusion, the *DMV* will be released continuously throughout the year via an *outlet* placed on the existing crossbeam on top of the weir, which is clearly visible from Figure 60. Additionally, during certain months, it will be released through a sluice gate canal. The entrance dimensions for both the upstream fish ladder and $DMV_1$ release were designed to have the same height of 20 cm to simplify construction and avoid errors.

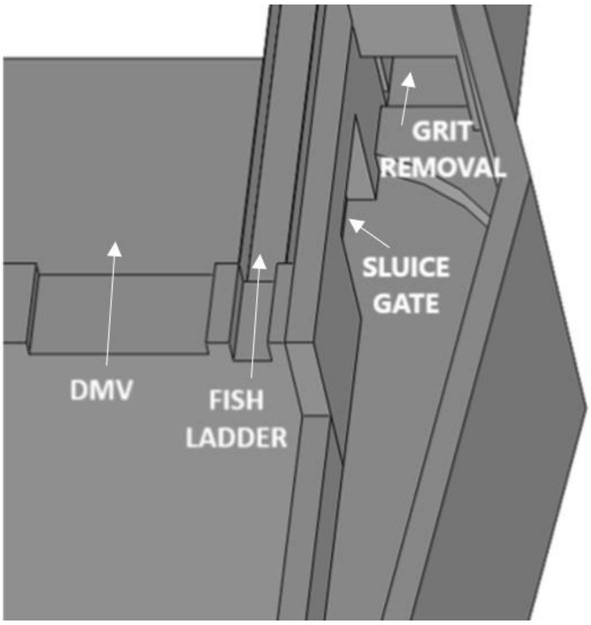


**FIGURE 60: ZOOMED-IN VIEW ON THE DMV OUTLET AND ON THE FISH LADDER OUTLET**

To prevent structural damage to the existing bridleway, a chestnut beam will be bolted along the entire length of the existing crossbeam, except in the sections needed for $DMV_1$ release and the fish ladder entrance.

Based on the $DMV_1$ release flow rate of 200 l/s and a height of 20 cm, the width of the *outlet* was calculated to be equal to 115 cm by using the following formula, whose parameters have been represented in the next image (Figure 61):

$$Q = \mu \, b \sqrt{2 \, g} \, h^{\frac{3}{2}}$$

where:

- $Q$ is the flow rate over the weir ($m^3/s$), equal to 0.2 $m^3/s$,
- $b$ is the width of the *outlet* (m),
- $p$ is the height of the *outlet* (m), equal to 0.5 m,
- $H$ is the total height of the water above the *outlet* (m),
- $h$ is the height of the water over the *outlet* (m), equal to 0.2 m,
- μ is the outflow coefficient

$$\mu = \left(0.405 + \frac{0.003}{h}\right)\left(1 + 0.55\frac{h^2}{H^2}\right)$$

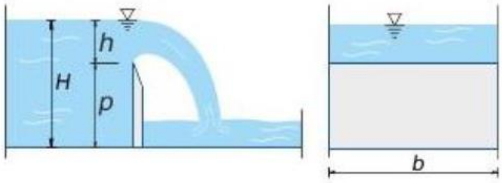


**FIGURE 61: FLOW RATE OVER A WEIR**

Using the same formula, the dimensions for the passage of the fish has been calculated with a width of 30 cm and a height of 20 cm.

Instead, the release of *$DMV_2$* and *$DMV_3$* will be ensured through the use of the sluice gate and will therefore have an opening degree according to the time of year.

During the months of April, May, and November, the *$DMV_2$* needs to release approximately 400 l/s. Given that 200 l/s is already being released continuously from the *outlet* placed on top of the weir, then the 1.17 m wide sluice gate will need to release an additional 200 l/s. To achieve this, the sluice gate will need to provide a height of 4 cm. The dimensions of the sluice gate have been calculated using the following formula, whose parameters have been represented in the next image (Figure 62):

$$Q = \frac{2}{3} \mu \, b \, \sqrt{2\,g} \, (h_2^{\frac{3}{2}} - h_1^{\frac{3}{2}})$$

where:

- $Q$ is the flow rate through the gate ($m^3/s$),
- $b$ is the width of the gate (m),
- $h_1$ is the head over the gate (m),
- $h_2$ is the head plus the height of the gate (m),

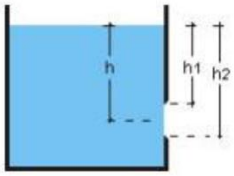


**FIGURE 62: FLOW RATE THROUGH A GATE**

During the months of January, February, March, and December, the *$DMV_3$* will have to release about 600 l/s. Since 200 l/s is already being continuously released from the *outlet* in the weir, then the 1.17 m wide sluice gate will need to release an additional 400 l/s. To achieve this, the sluice gate will need to be opened at a height of 8 cm.

### 3.1.3 Flow rate analysis

To work out the flow rates in correspondence of the area of interest, an analysis of both hydrographs and duration curves has been conducted.

Again, data was retrieved from the "Annali Idrologici", more specifically Section C of Part II, that provided the flow rate values in $m^3/s$ in correspondence of the hydrometric station of Cagli Ponte Cavour (Figure 63), which is located a few km downstream with respect to the site of concern. (Marche, ANNALI IDROLOGICI parte seconda)

A 4-year period was used to conduct the flow rate analysis, more specifically the years from 2019 to 2022 have been implemented. The 2022 was the most recent available data that could be retrieved from the Marche Region data.

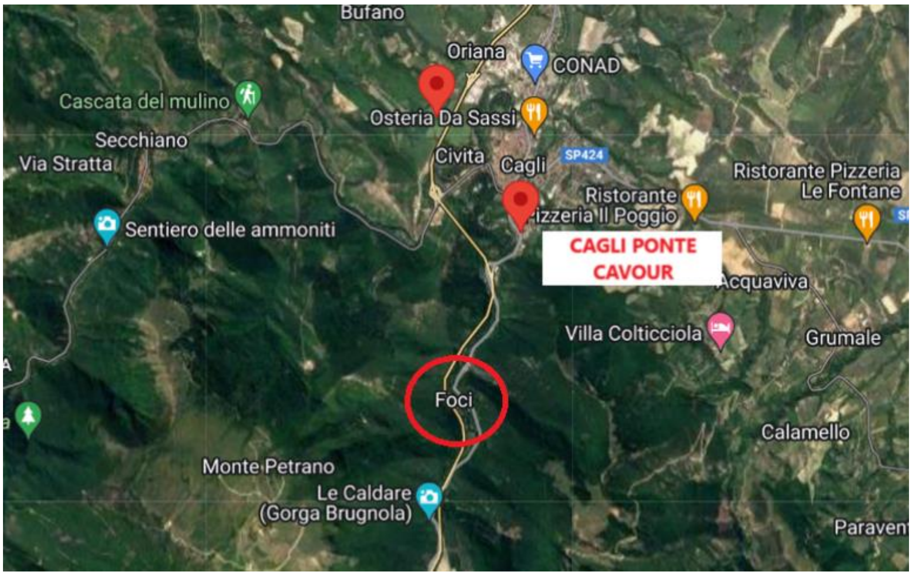


**FIGURE 63: LOCATION OF CAGLI PONTE CAVOUR HYDROMETRIC STATION WITH RESPECT TO THE AREA OF INTEREST, FROM GOOGLE MAPS**

The following extracted tables show an example of what is visible from the "Annali Idrologici" from 2022. Figure 64 shows the flow rates values per each day of each month, Figure 65 shows some key elements relevant to the hydraulic analysis and Figure 66 shows the duration of the most relevant flow rates values in days.

PORTATE MEDIE GIORNALIERE in $m^3s^{-1}$

| Giorno | Gennaio | Febbraio | Marzo | Aprile | Maggio | Giugno | Luglio | Agosto | Settembre | Ottobre | Novembre | Dicembre |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **1** | 4.03 | 1.37 | 5.16 | **12.66** | 2.12 | 0.72 | 0.42 | 0.58 | 0.70 | **14.73** | 0.59 | 2.39 |
| **2** | 3.49 | 1.33 | 4.24 | 9.62 | 2.07 | 0.67 | 0.41 | 0.59 | 0.65 | 7.30 | 0.59 | 2.19 |
| **3** | 3.23 | 1.25 | 3.94 | 8.16 | 1.93 | 0.63 | 0.41 | 0.56 | 0.60 | 4.97 | 0.59 | 1.97 |
| **4** | 2.90 | 1.27 | 3.64 | 6.36 | 1.83 | 0.61 | 0.40 | 0.56 | 0.62 | 3.91 | 1.99 | 1.93 |
| **5** | 2.57 | 1.30 | 3.50 | 4.96 | 1.63 | 0.62 | 0.39 | 0.57 | 0.52 | 3.26 | 1.23 | 3.29 |
| **6** | 4.10 | 1.27 | 3.25 | 4.14 | 1.63 | 0.59 | 0.41 | 0.57 | 0.34 | 2.71 | 1.09 | 4.75 |
| **7** | **6.41** | 1.19 | 3.00 | 3.98 | 1.57 | 0.56 | 0.39 | *0.56* | 0.35 | 2.32 | 0.96 | 4.67 |
| **8** | 5.13 | 1.10 | 2.58 | 3.74 | 1.65 | 0.53 | 0.38 | **0.90** | 0.39 | 2.07 | 0.83 | 4.12 |
| **9** | 4.47 | 1.07 | 2.21 | 3.49 | 1.54 | 0.79 | 0.38 | 0.68 | 0.38 | 1.84 | 0.78 | 4.29 |
| **10** | 4.87 | 1.01 | 2.05 | 3.28 | 1.45 | 0.74 | 0.40 | 0.60 | 0.32 | 1.69 | 0.73 | 17.39 |
| **11** | 5.90 | 0.98 | 2.14 | 3.17 | 1.43 | 0.61 | 0.40 | 0.58 | 0.34 | 1.50 | 0.62 | 13.52 |
| **12** | 5.01 | 0.95 | 1.94 | 3.02 | 1.36 | 0.55 | 0.39 | 0.57 | 0.35 | 1.40 | 0.58 | 8.29 |
| **13** | 4.13 | *0.92* | 1.81 | 2.78 | 1.26 | » | 0.39 | 0.57 | 0.33 | 1.29 | 0.52 | 6.33 |
| **14** | 3.79 | 0.94 | 1.73 | 2.56 | 1.21 | » | 0.39 | 0.58 | 0.30 | 1.21 | *0.48* | 5.57 |
| **15** | 3.96 | 2.16 | 1.76 | 2.42 | 1.15 | » | 0.38 | 0.57 | 61.11 | 1.18 | 0.58 | 11.87 |
| **16** | 4.28 | **8.95** | 1.99 | 2.25 | 1.11 | » | 0.36 | 0.57 | 29.80 | 1.09 | 5.64 | **23.40** |
| **17** | 4.15 | 5.88 | 1.90 | 2.03 | 1.12 | » | 0.35 | 0.56 | 8.04 | 1.03 | 5.97 | 12.13 |
| **18** | 3.66 | 4.21 | 1.74 | 1.96 | 1.11 | » | *0.33* | 0.59 | 5.16 | 0.98 | 3.76 | 8.53 |
| **19** | 3.28 | 3.52 | 1.52 | 1.95 | 1.04 | » | 0.36 | 0.80 | 3.56 | 0.93 | 3.61 | 6.71 |
| **20** | 3.55 | 3.07 | 1.39 | 1.81 | 0.95 | » | 0.33 | 0.74 | 2.75 | 0.90 | 12.43 | 5.28 |
| **21** | 3.53 | 2.62 | 1.31 | *1.77* | 0.93 | » | 0.33 | 0.71 | 2.12 | 0.85 | 6.37 | 4.59 |
| **22** | 3.16 | 2.39 | 1.25 | 2.10 | 0.90 | 0.49 | 0.34 | 0.71 | 1.76 | 0.82 | 11.57 | 4.06 |
| **23** | 2.89 | 1.87 | 1.21 | 2.19 | 0.88 | 0.49 | 0.34 | 0.72 | 1.52 | 0.83 | **13.63** | 3.76 |
| **24** | 2.42 | 1.64 | 1.18 | 2.51 | 0.88 | 0.46 | 0.35 | 0.72 | 1.57 | 0.78 | 8.44 | 3.41 |
| **25** | 2.06 | 1.60 | 1.18 | 3.59 | 0.82 | 0.46 | 0.35 | 0.71 | » | 0.76 | 6.03 | 2.99 |
| **26** | 1.91 | 3.43 | 1.15 | 3.23 | 0.79 | 0.45 | 0.45 | 0.70 | 10.85 | 0.76 | 4.47 | 2.74 |
| **27** | 1.65 | 3.99 | 1.09 | 2.93 | » | 0.46 | **0.63** | 0.76 | 5.47 | 0.66 | 4.12 | 2.55 |
| **28** | 1.61 | 4.97 | 1.05 | 2.54 | 0.83 | 0.43 | 0.58 | 0.83 | 4.26 | 0.63 | 3.67 | 2.31 |
| **29** | 1.51 | | *1.03* | 2.33 | 0.97 | 0.42 | 0.58 | 0.75 | 3.81 | 0.61 | 2.95 | 2.15 |
| **30** | 1.48 | | 1.07 | 2.26 | 0.82 | 0.41 | 0.59 | 0.70 | 9.08 | *0.58* | 2.62 | 2.02 |
| **31** | *1.45* | | **10.60** | | 0.77 | | 0.59 | 0.59 | | 0.59 | | *1.86* |

**FIGURE 64: "ANNALE IDROLOGICO" PART II SECTION C (CAGLI PONTE CAVOUR)**

ELEMENTI CARATTERISTICI PER L'ANNO 2022

| | ANNO | Gen | Feb | Mar | Apr | Mag | Giu | Lug | Ago | Set | Ott | Nov | Dic |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Q max ($m^3s^{-1}$) | » | 6.41 | 8.95 | 10.60 | 12.66 | » | » | 0.63 | 0.90 | » | 14.73 | 13.63 | 23.40 |
| Q media ($m^3s^{-1}$) | » | 3.44 | 2.37 | 2.37 | 3.66 | » | » | 0.41 | 0.65 | » | 2.07 | 3.58 | 5.84 |
| Q min ($m^3s^{-1}$) | » | 1.45 | 0.92 | 1.03 | 1.77 | » | » | 0.33 | 0.56 | » | 0.58 | 0.48 | 1.86 |
| Q media ($ls^{-1}km^{-2}$) | » | 26.68 | 18.36 | 18.42 | 28.40 | » | » | 3.20 | 5.05 | » | 16.06 | 27.79 | 45.31 |
| Deflusso ($mm$) | » | 71.45 | 44.40 | 49.34 | 73.60 | » | » | 8.58 | 13.53 | » | 43.02 | 72.02 | 121.37 |
| Affl. meteorico ($mm$) | 1219.50 | 60.30 | 86.90 | 69.90 | 71.10 | 45.10 | 39.00 | 10.80 | 112.20 | 407.90 | 7.40 | 172.10 | 136.80 |
| Coeff. deflusso | » | 1.18 | 0.51 | 0.71 | 1.04 | » | » | 0.79 | 0.12 | » | 5.81 | 0.42 | 0.89 |

**FIGURE 65: "ANNALE IDROLOGICO" PART II SECTION C – KEY ELEMENTS OF 2022**

| Durata delle portate | |
|---|---|
| Giorni utili: 354 | |
| Portate | 2022 |
| Giorni | $m^3s^{-1}$ |
| **10** | 12.13 |
| **30** | 5.97 |
| **60** | 4.10 |
| **91** | 3.25 |
| **135** | 2.07 |
| **182** | 1.37 |
| **274** | 0.61 |
| **355** | » |

**FIGURE 66: "ANNALE IDROLOGICO" PART II SECTION C – FLOW RATES DURATION (DAYS)**

The following hydrograph (Figure 67) shows the results obtained from computing the flow rates values given by the Marche Region, it illustrates the variation in the flow rate over the 4-year period at the study site.

The flow-rate series reveals a significant peak flow of 74.25 $m^3/s$ during the month of May of 2019 coinciding with a recorded rainfall event of 31 mm. This indicates a direct relationship between the precipitation event and the flow response, emphasizing therefore the importance of understanding the dynamics of storm events in order to have a reliable flood risk management.

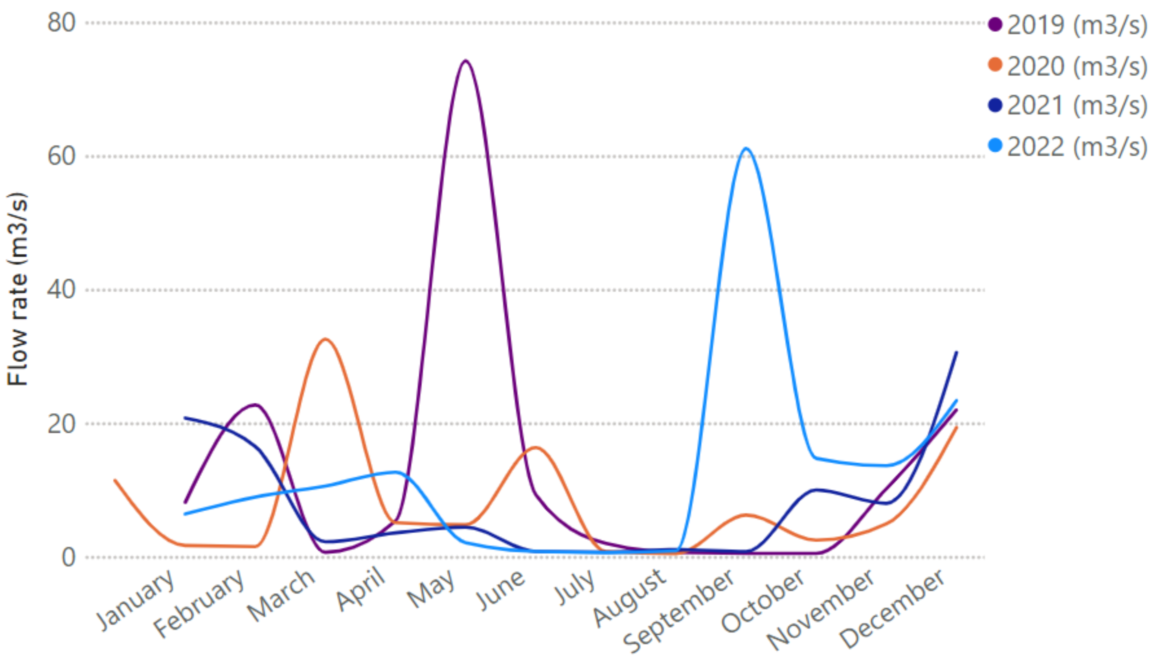


**FIGURE 67: HYDROGRAPH OF THE BURANO RIVER IN THE CAGLI PONTE CAVOUR STATION FOR THE YEARS 2019, 2020, 2021 AND 2022**

To further analyse the flow rates observed in the hydrograph (Figure 67), also a duration curve was developed for the same 4-year period (Figure 68). This duration curve provides an additional perspective that illustrates the frequency and the duration of various flow rates over the timeframe. This graphical representation ranks the flow rates from the highest to the lowest values, hence, displaying the percentage of time each flow rate is being equalled or exceeded over the period. This visualisation allows for the identification of the most critical flow rates value that the plant of concern will have to undergo.

The duration curve also displays an average flow rate across these years of analysis, this plot was computed by calculating the arithmetic mean of the flow rates for each exceedance probability value across the individual years data. By analysing the average flow rate and calculating the standard deviation of each year's flow rate relative to the average flow rate values, it is possible to identify a representative (typical) year.

For each year, the deviation from the average flow rate was computed at each exceedance probability point using the following formula:

$$\sigma = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(Q_{year,i} - Q_{average,i}\right)^2}$$

where:

- $Q_{year,i}$ is the flow rate for the specific year with the exceedance probability *i*,
- $Q_{average,i}$ is the average flow rate with the exceedance probability *i*,
- *n* is the total number of exceedance probability points.

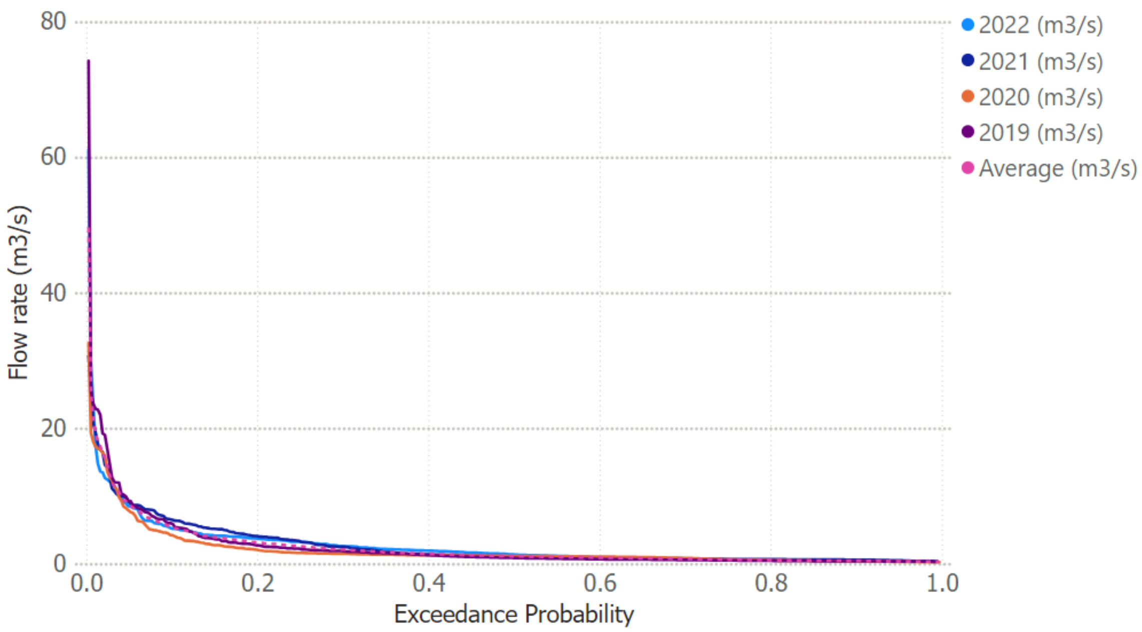


**FIGURE 68: DURATION CURVE DISPLAYING THE EXCEEDANCE PROBABILITY AND THE FLOW RATES RELATIVE TO THE YEARS 2019, 2020, 2021 AND 2022, ALONG WITH AN AVERAGE FLOW RATE**

The

Table 18 show the values of the standard deviation calculated per each year, based on this, the year 2022 was considered as the typical year.

| Year | Standard deviation |
|---|---|
| 2019 | 1.41 |
| 2020 | 1.13 |
| 2021 | 1.12 |
| 2022 | 0.81 |

**TABLE 18: STANDARD DEVIATION VALUES PER EACH YEAR**

As a consequence of this analysis, both hydrograph and duration curves related to the year 2022 are provided in Figure 69 and Figure 70.

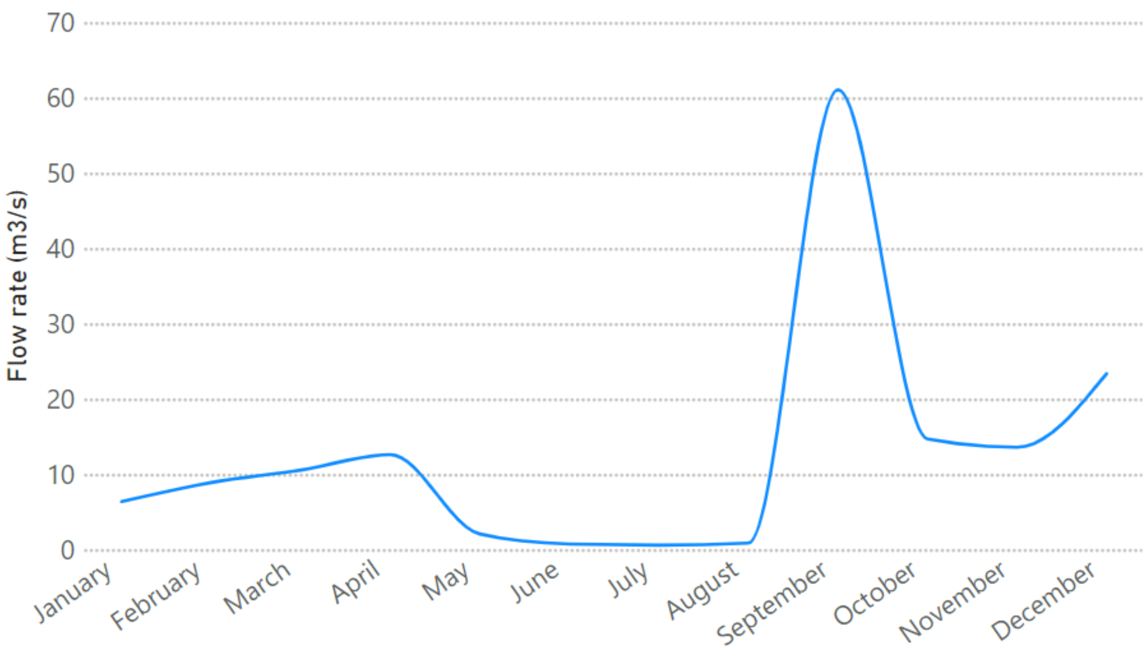


**FIGURE 69: HYDROGRAPH OF THE TYPICAL YEAR (2022)**

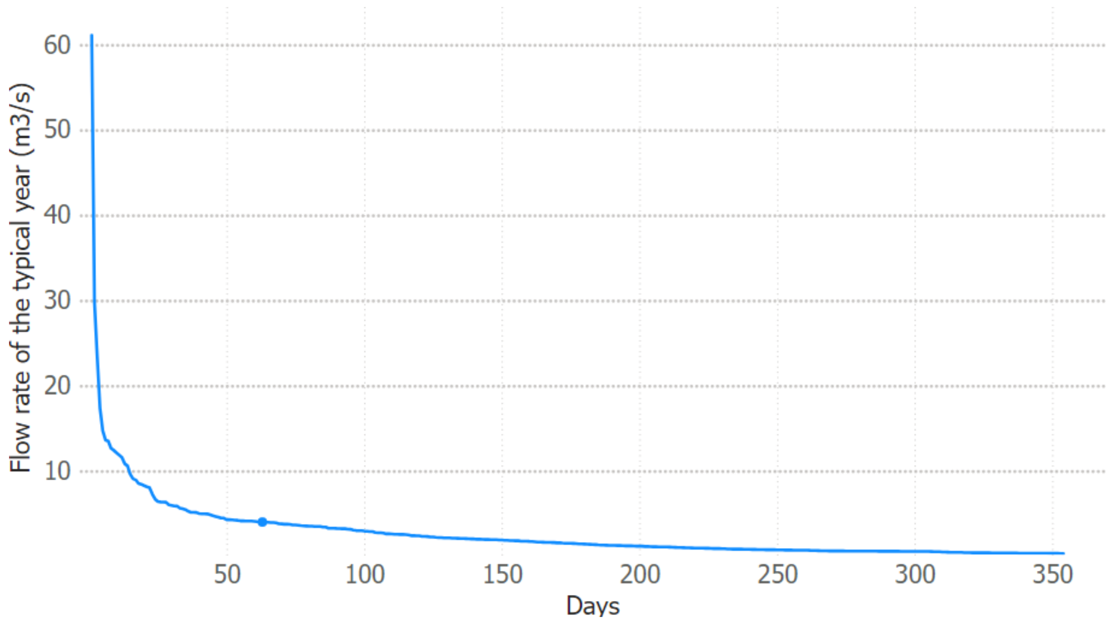


**FIGURE 70: DURATION CURVE OF THE TYPICAL YEAR (2022)**

By analysing the duration curve of the typical year more in detail, it is clear that the upper portion (5 - 61.11 $m^3/s$) indicates flow rates that are only exceeded for a short duration, therefore representing peak flows only associated with flood events. On the other hand, the lower section of the curve illustrates values that are sustained over much longer periods, these flow rates are vital for maintaining aquatic ecosystems and supporting the minimum water supply to the plant during dry seasons.

The maximum flow rate that can be derived from the river was crucial to design the rectangular channel of the plant. As a matter of fact, the channel has been engineered in order to handle effectively the maximum expected flow. Needless to say, that if the channel was designed for an occasional flow rate, it could lead to an oversized structure used at full capacity only for a few days a year.

The flow duration curve analysis for the Burano River at the Cagli Ponte Cavour hydrographic station indicates that the river consistently delivers a flow rate of 4.0 $m^3/s$ for approximately 63 days per year. This flow rate has been deemed appropriate for the project's objectives and is the basis for the design of the channel section, including the sluice gates and turbine.

While 4.0 $m^3/s$ represents the lower limit of the river's capacity during those days, the river experiences higher flow rates throughout the remaining of the year. These additional flows, together with the 4.0 $m^3/s$ baseline, offer a reliable operational range for the system. The design accounts for both high and low flow periods while maintaining the minimum vital flow (*DMV*) to meet ecological requirements.

Therefore, although the turbine will operate during periods when flows exceed 4.0 $m^3/s$, the system is designed to ensure reliable operation across varying flow conditions throughout the year.

Hence, by considering deriving a maximum of 4 $m^3$/s, available for 63 days per year, and assuming the operating period of 365 days, the $m^3$ of gross water available in one year is calculated as shown in Table 19.

| FLOW RATE ($m^3$/s) | DAYS | VOLUME OF WATER ($m^3$) |
| --- | --- | --- |
| 4.00 | 63 | $21.77 \cdot 10^6\ m^3$ |
| 3.85 | 91.25-63 | $9.39 \cdot 10^6\ m^3$ |
| 3.25 | 109.5-91.25 | $5.12 \cdot 10^6\ m^3$ |
| 2.75 | 127.75-109.5 | $4.34 \cdot 10^6\ m^3$ |
| 2.30 | 146-127.75 | $3.63 \cdot 10^6\ m^3$ |
| 1.95 | 164.25-146 | $3.07 \cdot 10^6\ m^3$ |
| 1.70 | 182.5-164.25 | $2.68 \cdot 10^6\ m^3$ |
| 1.45 | 200.75-182.5 | $2.29 \cdot 10^6\ m^3$ |
| 1.15 | 219-200.75 | $1.81 \cdot 10^6\ m^3$ |
| 0.90 | 237.25-219 | $1.42 \cdot 10^6\ m^3$ |
| 0.75 | 255.5-237.25 | $1.18 \cdot 10^6\ m^3$ |
| 0.60 | 292-255.5 | $1.89 \cdot 10^6\ m^3$ |
| 0.50 | 328.5-292 | $1.58 \cdot 10^6\ m^3$ |
| 0.40 | 365-328.5 | $1.26 \cdot 10^6\ m^3$ |

**TABLE 19: SUMMARY OF THE CALCULATIONS FOR THE TOTAL VOLUME OF WATER**

The decreasing flow rates going from 4 $m^3$/s to 0.4 $m^3$/s likely represent different periods within one year where the water availability varies due to several factors such as seasonal changes, varying rainfall, or different water usage patterns. Figure 71 shows all the flow rate values listed in the above Table in a semi logarithmic graph, therefore allowing for a better visualization of alle the values going from 4 $m^3$/s to 0.4 $m^3$/s.

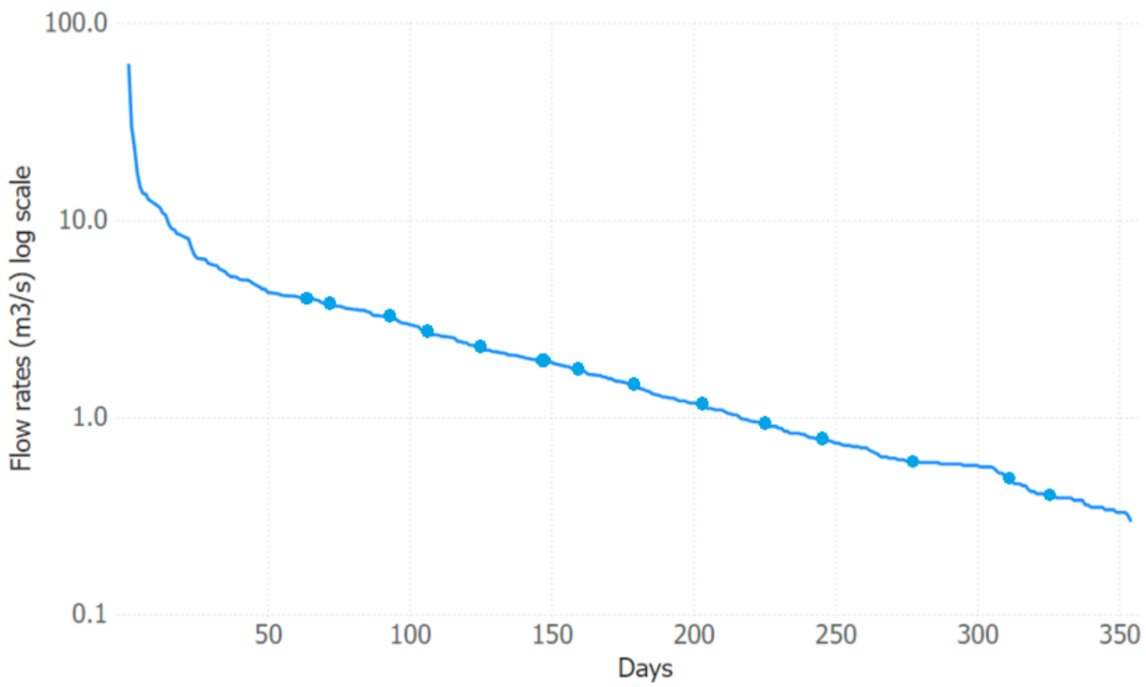


**FIGURE 71: SEMILOGARITHMIC GRAPH DURATION CURVE OF THE TYPICAL YEAR (2022), SEMI-LOGARITHMIC GRAPH**

These above set of calculations provide a value of gross water that is equal to $61.43 \cdot 10^6$ $m^3$ (61 million of $m^3$). The gross flow rate represents the total volume of water which is available throughout the year. However, this volume cannot be used entirely, this is why two components must be subtracted to calculate the net flow rate, these are the *DMV*, or the minimum vital flow, and the flow required for the fish ladder. Flows that must be maintained to be able to support the ecological health of the river and the fish migration.

The volume of water needed for the *DMV* in one year is equal to:

$$(0.6\frac{m^3}{s} \cdot 60s \cdot 60min \cdot 24h \cdot 121d) + (0.4\frac{m^3}{s} 60s \cdot 60min \cdot 24h \cdot 91d) +$$

$$(0.24\frac{m^3}{s} \cdot 60s \cdot 60min \cdot 24h \cdot 153d) = 12.06 \cdot 10^6\ m^3$$

The $DMV_3$ covers 121 days since it is related to the months of January, February March and December; the $DMV_2$ covers 91 days since it is related to the months of April, May and November; $DMV_1$ covers 153 days since it is related to the months of June, July, August, September and October.

The volume of water needed for the fish ladder in one year is equal to:

$$0.05\frac{m^3}{s}\cdot 60s\cdot 60min\cdot 24h\cdot 365d \ = \ 1.58\cdot 10^6\ m^3$$

Subtracting to the gross flow rate, the required flow rate for the *DMV* of the river and the required flow rate for the fish ladder, it is possible to obtain the water volume available in one year, which is fairly similar to the value used in the design, i.e. $47.51 \cdot 10^6$ m$^3$. It is calculated as follows:

$$WV_{net} = (61.43 \ \cdot \ 10^6\ m^3) - (12.06 \ \cdot \ 10^6\ m^3) - (1.58 \ \cdot \ 10^6\ m^3) \ = \ 47.79\cdot 10^6\ m^3$$

The net flow rate is then calculated as:

$$Q_{av} = \frac{47.79 \ \cdot \ 10^6\ m^3}{60s\cdot 60min\cdot 24h\cdot 365d} \ = \ 1.5\ m^3/s$$

The net flow rate is a fundamental design parameter for the project, as it represents the actual water that is available for the operational use of the plant itself after satisfying both environmental and legal requirements. This value ($Q_{av}$=1.5 m$^3$/s) determines the sizing of the infrastructure components such as the turbine and the sluice gates.

## 3.2 POWER OUTPUT

In this section, the concept of power output is introduced as a critical parameter in evaluating the performance of the hydropower plant. After a comprehensive analysis of the hydraulic aspects, including flow dynamics, head variations, and volumes, it is essential to translate these findings into the power output that the plant can reliably generate.

The gross power output of a hydropower plant is determined by the flow rate of the water, the available hydraulic head, and the efficiency of the conversion processes from hydraulic to mechanical energy. The gross power output can vary significantly over time due to fluctuations in the water availability, operational adjustments, and other environmental factors. Therefore, understanding the gross average power, which is indeed averaged over a specified period, provides a more stable and realistic estimate of the plant energy production capacity.

This section presents the methodology used to calculate the output power, taking into account the analysed hydraulic factors. By integrating the results from the hydraulic analysis with the power calculations, it is possible to provide a clear picture of the plant potential performance under various operating conditions. This analysis will be crucial in ensuring that the plant meets its design objectives and operates optimally within its intended environmental and economic constraints.

The power generation capability of a hydropower plant is fundamentally based on the conversion of potential energy stored in water into electrical energy. The potential energy, $E$, of water at a specific height is given by the formula:

$$E = mgH$$

where:

- $m$ is the mass flow rate of water,
- $g$ is the acceleration due to gravity (9.81 m/s$^2$),
- $H$ is the water head.

Starting from this formula, it is possible to calculate the gross average power output of the system using the average flow rate and the head. Given an average flow rate $Q_{av}$=1.5 m$^3$/s and a head of 5.54 m, the gross average power, $P_{gross}$, is calculated as:

$$P_{gross} = Q_{av}gH = 1.5\frac{m^3}{s} \cdot 9.81\frac{m}{s^2} \cdot 5.54\, m = 81.52\, kW$$

This result, 81.52 kW, represents the gross average power output, assuming ideal conditions without any losses.

However, in a real-world scenario, there are inefficiencies in the system, such as electromechanical losses and hydraulic losses. Assuming an overall efficiency of 80% ($\eta$ = 0.80, this assumption of an overall efficiency of 80% derives from the previous project conducted by the Renpower Group), the net power output, $P_{net}$, which represents what can actually be harnessed as electricity, is calculated as:

$$P_{net} = \eta P_{gross} = 0.80 \cdot 81.52\, kW = 65.22\, kW$$

This 65.22 kW represents the average net power output after accounting for the efficiency of the system.

To estimate the maximum power output of the system, $P_{max}$, the scenario where the maximum flow rate and head are utilized must be considered. Assuming a maximum flow rate of 4 $m^3/s$ and the same head of 5.54 m, the maximum power output, without considering efficiency, is:

$$P_{max} = Q_{max} g H = 4 \frac{m^3}{s} \cdot 9.81 \frac{m}{s^2} \cdot 5.54\, m = 217.39\, kW$$

This value, 217.39 kW, represents the maximum potential power output under ideal conditions.

The following visualization (Figure 72) aims to highlight the differences between the theoretical gross power output, the net power output after accounting for system inefficiencies, and the maximum potential output achievable under ideal conditions:

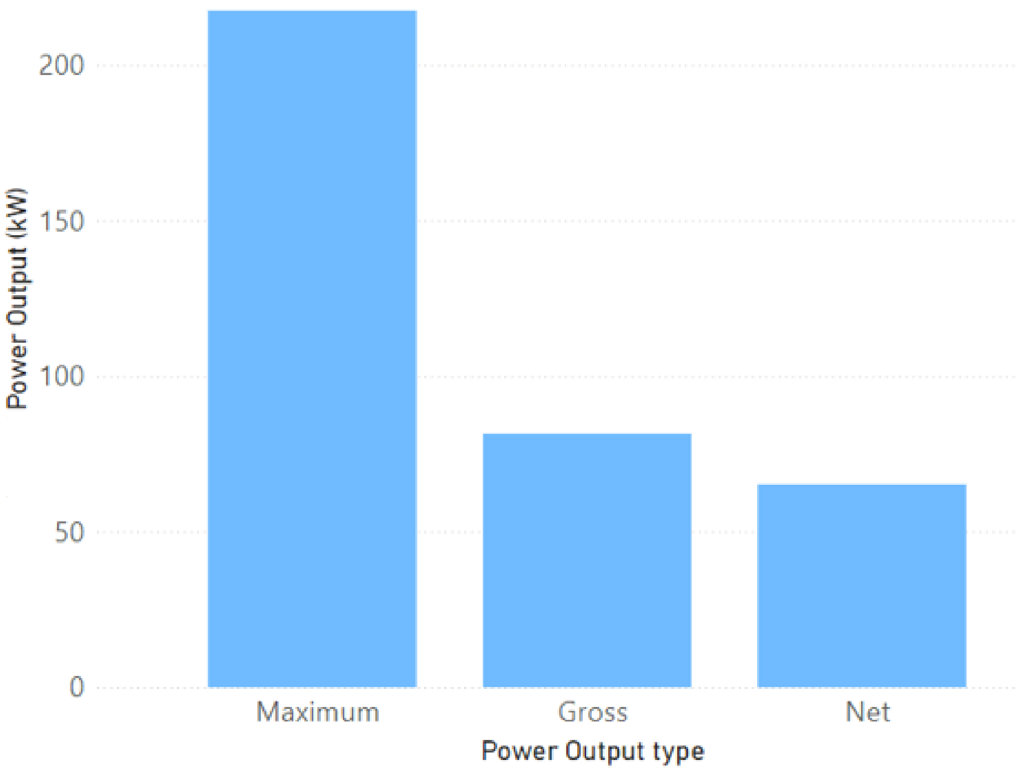


**FIGURE 72: COMPARISON OF POWER OUTPUTS**

To understand the energy production over a year, the average gross power and the net power outputs are multiplied by the total number of hours in a year, obtaining 714,115 kWh/y for the gross annual energy output and 571,327 kWh/y for the net annual energy output. These values have been calculated as shown below:

$$E_{gross} = P_{gross}\frac{hours}{year} = 81.52\ kW\ \cdot 24h\ \cdot 365\ d = \ 714{,}115\ \frac{kWh}{y}$$

$$E_{net} = P_{net}\frac{hours}{year} = 65.22\ kW\ \cdot 24h\ \cdot 365\ d = 571{,}327\ \frac{kWh}{y}$$

The following visualization (Figure 73) aims to highlight the differences between the gross annual energy output and the net annual energy output:

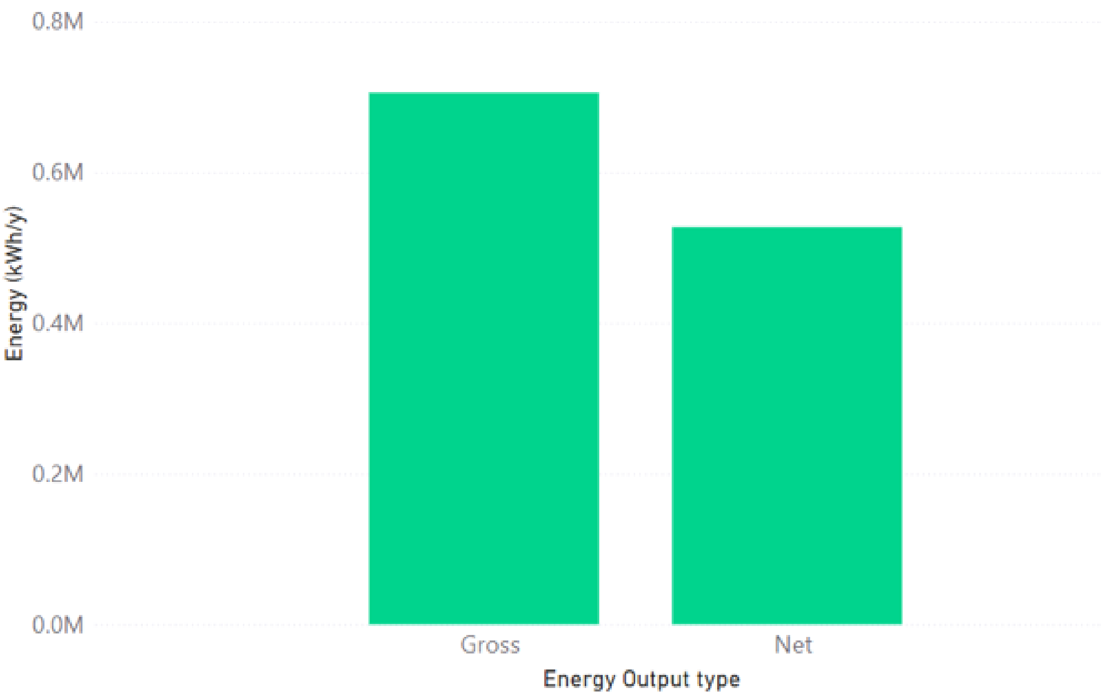


**FIGURE 73: COMPARISON OF ENERGY OUTPUTS**

In conclusion, the plant is expected to produce approximately 714,115 kWh of gross energy per year, with a net energy output, after accounting for system efficiencies, of about 571,327 kWh per year.

# CONCLUSIONS

This thesis demonstrates the feasibility of designing a 100kW micro-hydropower plant along the Burano River in Cagli, in the Marche Region, emphasizing the importance of small-scale renewable energy solutions in today's evolving energy landscape. The main goal of the project was to rehabilitate an existing weir system and to repurpose a disused fish farming structure for hydroelectric power generation. This involved modifying an existing water channel and installing essential components such as sluice gates, a turbine, a grit removal system, and a delivery substation.

The motivation for this project arises from both global and local trends. On a global scale, the urgent need for clean energy to meet $CO_2$ reduction targets has led to a push for more renewable energy production. Locally, the liberalization of the energy market has incentivized the development of small-scale, distributed power generation plants across all Europe, including Italy.

The project builds on previous designs, incorporating improvements over the years, actually, the original project presented in 2012 was redesigned in 2020 and further refined in 2024. The design takes advantage of the natural hydraulic head of 5.54 m and adapts the old fish farming infrastructure, ensuring minimal environmental impact on the river while achieving the target power generation. The Renpower Group has chosen to reutilize an existing Kaplan-type turbine, and the plant's design has been carefully optimized to accommodate the turbine's specifications, aligning with the available flow rate, the available head, and the specific spatial constraints of the site.

A comprehensive hydraulic analysis, including flow rate evaluations through hydrographs and duration curves, demonstrated that the Burano River consistently delivers a flow rate of at least 4.0 $m^3/s$ for 63 days per year. The system was designed to handle both low and peak flow conditions while maintaining the minimum vital flow (*DMV*) required to preserve the river's ecological health. While 4.0 $m^3/s$ represents the lower limit of the river's capacity during those 63 days, the river can experience higher flow rates throughout the remaining days of the year. These additional flows, together with the 4.0 $m^3/s$ baseline, offer a reliable operational range for the system.

The power output calculations yielded an estimated average gross power of 81.52 kW, with a net power output of 65.22 kW after accounting for an overall system efficiency of 80%. Over the course of a year, the system is expected to generate approximately 714,115 kWh of gross energy and 571,327 kWh of net energy, contributing to the renewable energy production of the small community of Foci, and supporting its commitment to sustainable energy solutions.

This project not only demonstrates the technical feasibility of repurposing an existing infrastructure for modern renewable energy applications, but it also highlights the potential of these micro-hydropower plants to contribute to the local energy grids.

Looking ahead, future work could focus on optimizing long-term monitoring of the environmental impact on the river’s ecosystem, which will be essential to ensure that the plant operates sustainably over its lifetime. This monitoring should encompass both the hydrological and ecological parameters, assessing how the plant's operations influence the water quality, the aquatic life, and the sediment transport. Additionally, continuous assessment of the turbine's performance, as well as advancements in hydropower technology, could also offer opportunities for future upgrades and improvements to the system's efficiency and environmental compatibility.

In conclusion, this project successfully addresses the need for small-scale, distributed renewable energy generation while making an efficient use of the existing infrastructure. By contributing clean energy to the local grid and aligning with global $CO_2$ reduction goals, this micro-hydropower plant offers a blueprint for similar initiatives in the future.

# **ANNEX I** - REGULATION

*The Regional Law 7/2004, Marche Region, regards the discipline of environmental impact assessment and it includes general guidelines for the implementation of the regional EIA.* (Marche, LEGGE REGIONALE 14 APRILE 2004, N. 7)

*The Legislative Decree 152/2006 approves the Code on the Environment, which sets out the legislative framework applicable to all matters concerning environmental protection. The Code is composed of six Parts. Part I (arts. 1-3) defines the application scope and lays down general provisions applicable to all areas covered by the Code. Part II (arts. 4-52) defines and regulates the procedures related to the Strategic Environmental Assessment (VAS), Environmental Impact Assessment (VIA) and Integrated Environmental Authorization (IPPC). Part III (arts. 53-176) is devoted to soil protection (particular regard is given to the need to combat desertification), protection of waters against pollution and management of water resources. As regards water policy and management, the national territory is divided into hydrographical districts upon which basin plans shall be implemented. Part IV (arts. 177-266) deals with waste management and rehabilitation of polluted sites. It provides for the arrangement of the Integrated Waste Management Service. Part V (arts. 267-298) deals with air quality and aims at reducing emissions into the atmosphere. Part VI (arts. 299-318) implements the precautionary principle and lays down the liability regime.* (Legislative Decree No. 152/2006 approving the Code on the Environment., 2024)

*The Legislative Decree No. 42/2004, also known as the Italian Cultural Heritage Code, pertains to the control and management of protected landscape assets. It includes the control and management of Protected Landscape Assets by outlining provisions related to the control and management of landscape assets that fall under protection. Specifically, Article 146 sets out restrictions on the use and disposal of these protected landscape assets by owners or possessors. These restrictions aim to safeguard the cultural and natural value of the landscape.* (Legislative Decree No. 42 laying down the Code on Cultural Heritage and Landscape., 2004)

*The Single Photovoltaic Authorization (AU) is a measure introduced by the Legislative Decree 387/2003 Article No. 12 and is a specific form of approval to be applied for photovoltaic installations above prefixed power thresholds that exploit Renewable Energy Sources (RES). It is a simplified procedure for the installation of a photovoltaic system with a maximum capacity of 200 kW. This authorization is issued by SUAP - One-Stop Shop for Productive Activities and it is valid for 15 years. Its main objective is to ensure that the PV system does not have a negative impact on the surrounding environment. With the publication of the Decree No. 13 of February 24, 2023, in the Official Gazette, simplifications and more* *streamlined procedures were introduced for the installation of photovoltaic systems, making it easier to switch to photovoltaics. Thanks to this decree, it will be enough for anyone who wants to have a photovoltaic system in their home to fill out the Simplified Single Form. (Autorizzazione unica fotovoltaico: quando serve, come si richiede, 2023)*

[*]*The Kyoto Protocol is an international treaty adopted in 1997 aimed at reducing the emission of gases contributing to global warming. It called for reducing the emissions of six greenhouse gases in 41 countries plus the European Union to 5.2% below 1990 levels during the commitment period from 2008 to 2012.* (Britannica, 2024)

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