Identifying an opportunity to develop a water reclamation system for the Estarreja Chemical Complex

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The Antuã river is one of the largest suppliers of fresh water to the Aveiro lagoon and estuary, a special protection zone, in the north of Portugal, that encompasses a high variety of aquatic ecosystems, with great importance at both national and European levels. At the same time, the river represents an important water source, for industrial use, by the Estarreja Chemical Complex, which can interfere in the natural flow of the river, especially in drier seasons.

This dissertation aims to assess the feasibility and design of a water reclamation system, from the Cacia wastewater treatment station to the Estarreja Chemical Complex, while evaluating the possibility of wastewater reuse as a water source, considering the associated costs and environmental benefits that come with this reuse.

The design of the transportation infrastructure was made in AutoCad and Microsoft Excel. Data from the military geographical charts, made available by the Centro de Informação Geoespacial do Exército, plus a legal framework for the construction and implementation plan for the system, the Regulatory Decree 23/95, of the 23rd of August, were followed.

The results show the possibility of implementation of a water reclamation system, composed of a piping system 15.7 km long, with two pumping stations and four reservoirs. Two different investment scenarios were considered, corresponding to a direct cost of equipment of 13 865 k€ or 18 697 k€, with an added operational cost that corresponds to the energy consumption of the pumps that is equal to 0.504 kWh/m3.

The externalities of such an implementation would be in alignment, thematically and objective-wise, with national (considering the Water Law and the Water Basin Management Plan, of the rivers Vouga, Mondego and Lis) and global contexts, as the UN Sustainable Development Goals. The plans for funding environmentally sensitive actions in the EU, such as the Cohesion Fund and the European Regional Development Fund, complemented the viability assessment, resulting in a positive impact by contributing to preserving the hydric domain, and thus, the region’s ecosystem.

Keywords: Reclamation; Wastewater; Estarreja Industrial Complex; Cacia Wastewater Treatment Plant; Preservation of the hydric domain; Resource sustainability

1. Introduction

It is commonly well known that water is an essential element of life, biologically, and for the functioning of human society and its activities.

There are currently several factors that threaten freshwater quality and availability, varying geographically and according to human practices and policies implemented (Fig. 1). Examples of such threats can go from meteorological events, such as droughts and floods (IPMA, 2022), freshwater contamination and pollution, due to unproper discharges and other human activities (Iberdrola, 2022), and other hydromorphological pressures, also caused by anthropogenic factors (EEA, 2020b).

Therefore, and given both its scarcity, in the form of fresh water (USBR, 2020), and the existing threats, caused by anthropogenic factors (EEA, 2020b), it is imperative that the global water resources are protected and sustainably maintained, in order to assure the continuity of its use, throughout generations. This can be accomplished through encompassing political directives, such as the Water Law (Parlamento Europeu, 2000) and the United Nations' Sustainable Development Goals (UN, 2015), that aim to guide actions towards water use sustainability, as well as national policies, plans and programs, that map and organize action towards responsible use of countries' hydric domains.

It is also important to consider the protection, preservation and maintenance of ecosystems that are dependent on water resources. As such, defining special protections zones can help reduce threats in impacted environmentally sensitive areas. Networks such as Natura 2000 (ICNF, 2019) and the Ramsar Convention (Secretariado da Convenção de Ramsar, 2015), help distinguish special interest areas, limiting human activities and impacts, in order to assure the conservation of that region's biodiversity and habitats.

One way to attempt to preserve water resources is through the implementation of water reclamation systems. These can take many forms, from water desalination (Wang & Wang, 2018), to the treatment and reclamation of wastewater (Sanz et al., 2015), being the latter, the focus of this project.

Considering wastewater treatment an essential practice implemented globally, the possibility of wastewater reclamation is increasingly greater and the proof of that is the current growth of post treatment, wastewater applications (APA, 2019). These can go from its use in agriculture and industry, to urban uses, varying from car and street cleaning, to firefighting, and even supporting endangered ecosystems that are also threatened due to the existence of water shortages.

As such, it is the purpose of this project to assess the possibility of implementation of a wastewater reclamation system, from the wastewater treatment plant in Cacia, to the Estarreja Industrial Complex (both inserted in a special protected zone, under the Natura 2000 network), as well as evaluate the positive impact, that such program can have regarding conservation and sustainability, of both water resources and the environment.

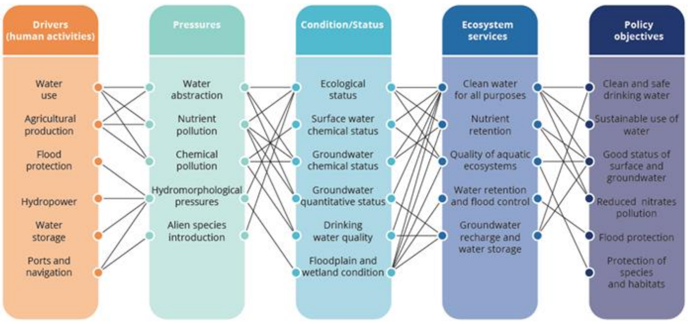

Fig. 1 – Links between drivers, pressures, ecosystem services and policy objectives, regarding the current state of EU's water resources (EEA, 2020b).

2. Methodology

2.1. Site Description

The totality of the system is situated between the municipalities of Aveiro and Estarreja. The wastewater treatment plant is situated in Cacia, a parish of Aveiro, about 9 km from the city center, and Estarreja Industrial Complex, is situated in the north of the municipality of Estarreja. This region is also considered to be a special protection zone, under the Natura 2000 network, for preservation and conservation of endangered areas, and as such it is necessary to consider the limitations imposed in these areas, while assessing the implementation of this project.

The wastewater treatment station, as well as the industrial complex, can also be considered risk zones, due to the presence of volatile, inflammable and/or explosive material, involved in their processes. This fact was taken into account when considering the construction of infrastructure.

2.2. Sizing of the water supply system

The dimensioning of the piping system was done by reverse calculating the minimum and maximum diameters, given the minimum and maximum velocities allowed by the legislation (Ministério das Obras Públicas Transportes e Comunicações, 1995), for both pumped and gravitic flow, as well as the desired water flow (12 000 m^3/day).

Once a spectrum of allowed diameters was obtained, the associated head losses, given the considered water flow, were calculated, using the Manning-Strickler equation (Quintela, 2014), allowing the drawing of the energy line and therefore the spatial identification of the need for pressure class changes, along with the existence of pumping stations.

Finally, considering the obtained head losses, associated with each diameter, for both pumped and gravitic flow, the used diameter was chosen, to accommodate the existing terrain. The compatible pressure classes were also taken into consideration, given the correspondent height of the water column.

2.3. Design of the water supply system

The first step in designing the water supply system was obtaining a longitudinal profile of the terrain, allowing the analysis of the need for reservoirs, pumping stations, as well as the determination of the adequate type of water flow. To obtain the longitudinal profile, in AutoCad, a polyline was made, following national roads (to facilitate construction permits), from the wastewater treatment plant to the industrial complex. Each polyline node contains coordinates and is associated to an elevation value. The first was used to calculate the distance between nodes, and when associated with the elevation (through the "*concatenate*" function, in Microsoft Excel), in a separate polyline, it originated the terrain profile of the area, that the piping system will follow (Galvão et al., 2020).

After obtaining the longitudinal profile, the values of head loss calculated previously were used in an iterative process, for the construction of the energy line of the system. This consisted in several attempts to utilize different values of head loss, corresponding to different diameters, for both pumped and gravitic flow, as the slope of the energy line that illustrates the water column height and determines whether the piping is adequate or not. An intersection between the energy line and the terrain would signify a stagnation of the flow (Galvão et al., 2020; Matos et al., 2020), and therefore cannot happen, without the existence of a pumping station. As such, the height of the water column determines the need for the construction of water pumping stations, which have the function of elevating said height and allowing for the continuation of the flow.

Once the piping and pressure classes were determined, as well as the existing reservoirs and water pumping stations, the final procedure was the identification of the system accessories that need to be inserted, in order to make it compliant with the current legislations that guide water supply systems (Ministério das Obras Públicas Transportes e Comunicações, 1995).

2.4. Calculation of the financial investment of the system's infrastructure

The estimation of the cost of infrastructure of the water supply system was divided in 3 parts: piping, pumping stations and reservoirs.

Regarding piping, their cost is equal to the length of each section of piping (considering its nominal diameter and pressure), multiplied by its cost. The costs vary, depending on the diameter and pressure class, and as such, each section was calculated individually and then added together.

The investment associated with pumping stations, was calculated through two equations, provided in (Galvão, 2020; Galvão et al., 2020; Matos et al., 2020), corresponding to the cost of the equipment (C_{eq}) and of the labor (C_{cc}), where Q_{dim} is the flow, and H is the elevation height of each pump (Fig. 2).

$$C_{cc}(€) = 39904 + 374 \times Q_{dim}(l/s) + 0.15 \times Q_{dim}(l/s) \times H\ (m)$$

$$C_{eq}(€) = 1317 \times Q_{dim}{}^{0.769}(l/s) \times H^{0.184}(m) + 2092 \times (Q_{dim}(l/s) \times H(m))^{0.486}$$

Fig. 2 – Equations for the calculation of the construction costs of labor (above) and equipment (below), for water pumping stations

Finally, the cost associated with reservoirs was calculated by multiplying their volumetric capacity, by the corresponding cost. The methodology to determine the volumes of the necessary reservoirs is indicated under regulatory decree (Galvão et al., 2020; Matos et al., 2020; Ministério das Obras Públicas Transportes e Comunicações, 1995).

2.5. Calculation of the operational costs, of the pumping stations

The operational costs of the water pumping stations were calculated by determining the power of each pump, and the energy they consume, as well as the cost associated with that energy consumption.

As such, the power of each pump was calculated using the following equation (Fig. 3), where P is power, Q_{dim} is the flow, ρ is the density, g is the acceleration of gravity, H is the elevation height of each pump, and η is their efficiency:

$$P\ (kW) = \frac{Q_{dim}(m^3/s) \times\ \rho(kg/m^3) \times g(m^2/s) \times H(m)}{1000\ \times\ \eta}$$

Fig. 3 – Equation for the calculation of a water pump's power, in kW

2.6. Amortization of the investment

The investment amortization was calculated using the Price method that corresponds to Fig. 3, where Parc is the parcel to be paid, on the specific period, Inv is the investment to be paid, i is the interest rate, and n is the period of payment. The parcel to be paid is a constant value, equal to the sum of the amortization and interest, for that period, and the use of this model results in an increasing amortization value and decreasing interest.

$$Parc\ (€) = \frac{Inv\ (€) * i}{1 - \frac{1}{(1+i)^n}}$$

Fig. 4 – Equation for the investment amortization, using the Price method

3. Results and discussion

3.1. Sizing of the water supply system

Considering a desired flow of 12 000 m^3/day, a maximum velocity of 1.5 m/s, and a minimum velocity of 0.3 m/s (for gravitic flow) and 0.6 m/s (for pumped flow), the pipe diameters range from 0.616 – 0.275 m, and 0.754 – 0.477 m, respectively. Thus, considering the available pipe diameters (Henan Bingo Pinpeline, 2015), for the pressure classes of PN2.5, PN3.2, PN4, PN5, PN6, PN10, PN12.5 and PN16, the corresponding hydraulic radius and section area were calculated, to obtain the necessary data to compute the associated head losses (Quintela, 2014).

Considering the obtained head loss values, an analysis was made, that took into consideration the value of the head losses (and consequently, the slope of the energy line), as well as the prices associated with each diameter and pressure class. The diameter chosen, taking both the energy line and associated costs into consideration, was 0.63 m, since the value of the head losses is low, while maintaining a reasonably affordable cost, being this the sole diameter of the system. The pressure class varies, depending on the height of the water column (Fig. 5).

3.2. Design of the water supply system

The piping system, consists of 15 767.56 m of piping, with a single diameter (0.63 m), divided into 3 sections: section B1 is a 6 093.87 m long pumped section, that uses the pressure classes PN10, PN6 and PN5, in that order; section B2 is a 4 525.92 m long pumped section, that uses pressure classes PN12.5, PN10, PN6 and PN5, in that order; and section G1 is a 5 147.77 m long gravitic section, that uses pressure classes PN6 and PN5. The first two sections are pumped, due to the low elevation of the terrain, disabling the possibility of gravitic flow of the

Fig. 5 – Longitudinal profile of the terrain, complemented with the energy line, that represents the height of the water column, the used diameter and pressure classes (PN12.5 – Yellow; PN10 – White; PN6 – Orange; PN5 – Red)

water, whereas section G1 initiates at the maximum height of the system, and the gravitic flow is therefore possible (Fig. 8).

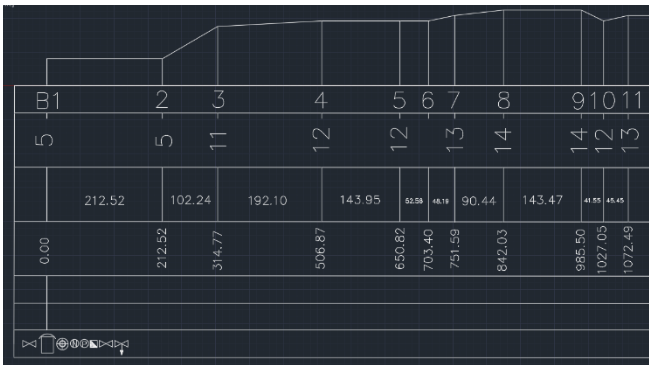

Fig. 6 – Initial section of the system, that contemplates the first pumping station (B1) and its accessories (from left to right, sectioning valve, reservoir (R1), pump, flow meter, pressure meter, retention valve, sectioning valve and bottom discharge valve)

Regarding the pumping stations, two of them are needed, given the terrain profile. One is at the beginning of the system, to initiate the water flow (Fig. 6), and one at the end of section B1, to elevate the water column and allow for the continuation of the flow (Fig. 7). These have elevation heights of 95 m and 113.05 m, respectively.

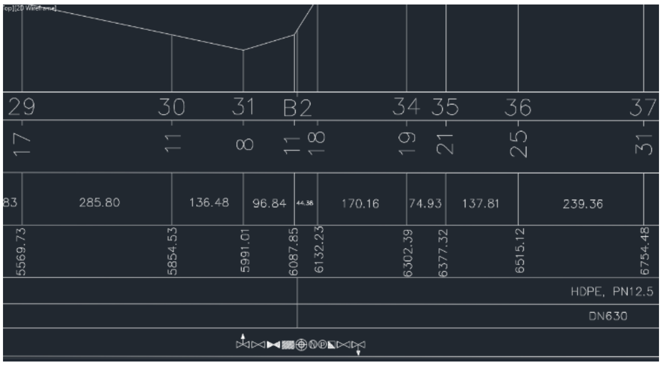

Fig. 7 – End of the first pumped section of the system, that contemplates the second pumping station (B2) and its accessories (from left to right, air relief valve, sectioning valve, flow regulation valve, transition reservoir (R2), pump, flow meter, pressure meter, retention valve, sectioning valve and bottom discharge valve)

Finally, the system requires four reservoirs: at the beginning and end of the system (R1 and R4) (Fig.6 and Fig. 9), that mainly serve as storage; a transition reservoir to balance the pressure differences, before a pumping station (R2) (Fig. 6); and another reservoir that, depending on the desired function, can be another transition reservoir (R3.1), or a larger, storage reservoir (R3.2) (Fig. 7).

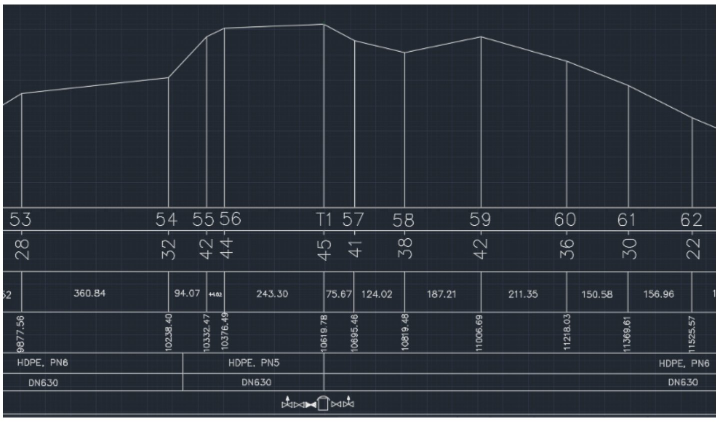

Fig. 8 – End of pumped section B2, and start of gravitic section G1, presenting reservoir R3 and its accessories (from left to right, air relief valve, sectioning vale, reservoir (R3), sectioning valve and air relief valve)

The system also contains a variety of valves and meters that were placed, according to legislation (Ministério das Obras Públicas Transportes e Comunicações, 1995).

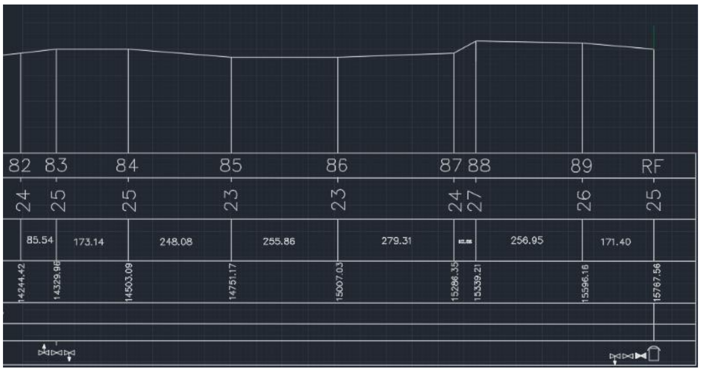

Fig. 9 – End section of the system, that contemplates the final reservoir (R4) and its accessories (from left to right, bottom discharge valve, sectioning valve, flow regulation valve, reservoir (R4))

3.3. *Financial investment of the infrastructure*

As indicated previously, the estimation of the costs associated with infrastructure, was divided into piping, pumping stations and reservoirs.

Considering the piping system, the costs of each section were as follows: B1 – 1 091 812 €, B2 – 1 154 137 €, G1 – 691 916 €. It can be observed that pumped sections originate a higher cost, due to the higher pressure class piping. These costs were calculated using the piping prices of Matrix Piping Systems (Matrix Piping, 2017).

Regarding the pumping stations, considering the calculated flow of 0.298 m^3/s, and the elevation heights of 95 m and 113.05 m, for B1 and B2, respectively, the costs associated with the construction of the pumping stations is, respectively, 647 203 € and 676 894 €.

The final volumes considered for the reservoirs are: R1 - 36 000 m^3, R2 - 1200 m^3, R3.1 - 1200 m^3, R3.2 - 36 000 m^3 and R4 – 24 400 m^3. For the storage reservoirs, due to their increased size, the cost used for calculation was 127 €/ m^3, while for the transition reservoir, the price corresponded to 225 €/ m^3.

As such, the final costs associated with the system's infrastructure are presented in Table 1 (Galvão, 2020):

Table 1 – Infrastructure costs, for the proposed water supply system, where PP stand for piping, P.S. stands for pumping stations and R stands for reservoirs

Infrastructure	Cost (€)
PP	2 937 866
P.S.	1 324 097
R (w/R3.1)	8 083 800
R (w/R3.2)	12 385 800
Total (w/R3.1)	12 345 763
Total (w/R3.2)	16 647 763

3.4. *Operational costs of pumping stations*

Considering the power obtained, for each pump, the value for the energy consumption of the transport system was determined to be 0.504 kWh/m^3 and with the data obtained from REN (REN, 2022), values for the operational costs were calculated. There were 3 scenarios considered for the price of electric energy. One considering the average annual price of electricity – 184 €/MWh (C1); the second considering the monthly average price of electricity – 143 €/MWh (C2); and the third considering the daily price of electricity – 103.97 €/MWh (C3, all obtained on the 16th of October 2020. Table 2 presents the annual costs of operation of the pumping stations, associated with the mentioned scenarios.

Table 2 – Energy costs/m^3, for the 3 price scenarios of the system's pumping stations

	P(kW)	C1 (€/m^3)	C2 (€/m^3)	C3 (€/m^3)
B1	172.71	0,043	0,033	0,024
B2	205.52	0,050	0,039	0,029
Total	378.23	0,093	0,072	0,053

3.5. *Amortization of the investment*

Considering a common interest rate of 4%, and a period of five years for the amortization of the investment, with annual payments, Table 3 presents the total investment, considering interest (I), as well the yearly amortization values (A).

Table 3 – Final values for infrastructure investment, with annual interest and amortization values

Year	I(€) (w/R3.1)	A(€) (w/R3.1)	I(€) (w/R3.2)	A(€) (w/R3.2)
1	493 831	2 279 363	665 911	3 073 629
2	402 656	2 370 537	542 965	3 196 574
3	307 835	2 465 359	415 102	3 324 437
4	209 220	2 563 973	282 125	3 457 414
5	106 661	2 666 532	143 828	3 595 711
Total (w/R3.1) (€)		13 865 966		
Total (w/R3.2) (€)		18 697 695		

3.6. *Compatibility with national and international goals*

The main goals of the implementation of the presented project are the circular use of the wastewater treated in Cacia, to promote sustainable water use practices, as well as the preservation of the natural ecosystems of the Aveiro lagoon region.

These objectives are directly aligned with the Water Law and Sustainable Development Goal 6 – Clean Water and Sanitation, as well as the Water Basin Management Plan, of the considered region. Given the variety of approaches that can be taken, to address the existing water stresses, nationally and in the EU, the introduction of a system that at the same time saves water by decreasing extractions, and enforces resource circularity, in the form of water reclamation and environmental reinsertion, can help tackle different water scarcity issues and promote a more integrated and responsible water governance.

As such, water reclamation systems, based on wastewater treatment plans, can be implemented as an integrated part of a plan or program that aims to achieve those national and international goals.

3.7. Environmental protection

When analyzing the impacts of a water reclamation project on the environment, it is possible to highlight positive impacts on two main fronts.

The first being the conservation of the natural flux of the river that feeds environmentally sensitive habitats, assuring the continuing availability of water to accommodate the ecosystems needs. This is done by reducing the water extractions, from the Antuã river, and utilizing reclaimed water for the necessary industrial processes (EEA, 2020b). Also, given the sensitive nature of region (Fig. 10), the conservation of the existing ecosystems is of even greater importance, not only nationally, but also regarding the EU.

The second benefit of implementation is the possibility to reinsert reclaimed water in environmentally sensitive areas. Given the compatibility with the defined quality norms for environmental support (under urban uses), part of the reclaimed water produced can be reintroduced back into the natural ecosystems, functioning as a preservation and conservation tool (APA, 2019). That reinsertion can be done both seasonally, to satisfy water needs, for example, in the summer, where instances of extreme drought and water scarcity are more common and relevant; or regularly, given the condition of the existence of storage reservoirs.

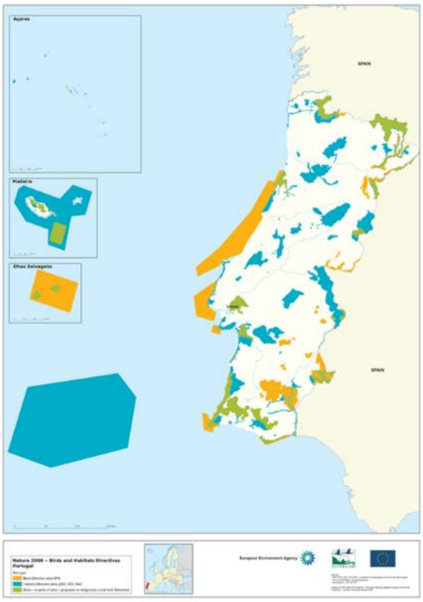

Fig. 10 – Regions that fall under the environmental protection of the Bird's Directive (Orange), Habitats Directive (Blue), and both (Green) (EEA, 2020a)

3.8. Uses of reclaimed water

In light of the national legislation, that dictates water quality norms, and types of treatment, related to specific uses of reclaimed water (DRE, 2019), it can be assumed that the water obtained post treatment, from the Cacia wastewater treatment plant, does not have the necessary quality for all the available uses, defined by the legislation.

Due to inexistence of any complements to the secondary treatment, available at the wastewater treatment plant, the treated water can only be used for the irrigation (with limitations) of certain areas (agricultural uses) and for the support of ecosystems (urban uses). All other uses that fall under agricultural or urban uses, see the need for a membrane filtration and/or disinfection of the water. If the wastewater treatment plant sees these improvements, the post treatment water is adequate for all agricultural and urban uses, and a bifurcation in the presented system, can serve as a distribution system for those specific uses.

On the other, the quality norms for industrial use only consider human safety. As such, even though the current quality is compatible with legislation, it is advised that an additional layer of treatment is implemented, either in the wastewater treatment plant, or at the entrance of the industrial complex, to assure the necessary quality for industrial use. This can be achieved by adding nanofiltration (NF) and/or reverse osmosis (RO) processes, as well as the necessary pre-treatments that these might require, that will guarantee the necessary water quality, for regular industrial processes (EMIS, 2010; Membracon, 2022; Safe Drinking Water Foundation, 2010). These processes, however, will limit the possible water uses of the treated water, given that post RO water is completely striped of its minerals and ions, becoming a very hypotonic medium, and potentially harmful to crops, gardens, and even improper for human consumption. As such, the alternatives must be considered, given the specific water uses that are to be deemed relevant.

4. Conclusion

The presented study wanted to demonstrate the possibility of implementation of water reclamation system, in a special protection zone, originating a 15 767.56 m long, water supply system, composed of HDPE piping, with 0.63 m of diameter, and varying nominal pressures; two water pumping stations to enable and facilitate the transport of water; four reservoirs with functions such as storage and leveling the water pressure; as well as other piping accessories, such as valves, and flow and pressure meters.

The overall financial investment needed, equals 13 866 k€ or 18 698 k€, depending on the chosen scenario, being most of that investment applied to the construction of reservoirs, with the addition of the energy consumption of the operation of the pumping stations, equal to 0.504 kWh/m^3, and its associated costs.

It was then concluded that this project is in thematic and objective accordance with both national and European plans and directives, with emphasis on the Water Basin Management Plan (Ribeiro, 2012) and the Water Law (Parlamento Europeu, 2000). On the other hand, given the environmentally sensitive nature of the region, the conservation of the river's natural flow, accompanied by the possibility of water reinsertion, in the habitats, can be considered positive impacts of the implementation of such a project.

It was also observed that, given the present water treatment capabilities, the post treatment water uses are limited to some irrigation and ecosystem support. Given the implementation of additional layers of treatment, the potential for a larger variety of water uses grows exponentially.

Finally, future work opportunities, associated with this project, were identified: first, a study involving the analysis of the quality needs and current capabilities of both the wastewater treatment plant and the industrial complex, in order to determine the exact quality needed for industrial use, and the required treatment to accommodate it; secondly, communication and open dialogue with the involved municipalities, in order to facility the implementation of the project, as well as the discussions and negotiation of similar interests and goals; and thirdly, the application towards several national and European funding opportunities, in order to alleviate the financial burden, associated with a project of this magnitude.

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