Agricultural Water Management 263 (2022) 107435

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

A method for the prioritization of water reuse projects in agriculture irrigation

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ARTICLE INFO

Handling editor - J.E. Fernández

Keywords:
Wastewater treatment
Reclaimed water
Optimization
Irrigation network
Cost Benefit Analysis
Spain

ABSTRACT

Water reuse is a strategic priority for Water Authorities in Europe to reduce the pressure on water resources, although implementation is lagging behind expectations due to financial, administrative and social acceptance concerns. In this context, there is a special interest to identify in which specific Wastewater Treatment Plants it would be interesting to add a Water Regeneration Plant, taking account of potential existing clients in the vicinity and the implied costs and benefits. This paper proposes a method to quantify the infrastructure and operation costs of project implementation and the benefits of the additional water offer. An algorithm designs the distribution network, allowing for a quick cost analysis. The method is applied in the Upper Guadiana in Central Spain, where irrigation led to the overexploitation of the local aquifers and the subsequent restrictions on water use. Taking account of the existing Wastewater Treatment Plants, candidate reuse projects are classified according to their benefit/cost ratio, showing large differences according to the location and potential use of the regenerated water. The analysis allows for a quick assessment of the costs and benefits implied in different reuse projects and scenarios, providing science-based evidence to support water policy decisions.

1. Introduction

The growing competition on water abstraction for urban, industrial, agricultural, and other uses, and the perspective of diminishing availability due to climate change are pushing the agenda for the quest of alternative water sources (UN-Water, 2020). One of these sources is urban wastewater (Qadir et al., 2003), which is normally discharged to rivers and seas after a convenient treatment. An additional treatment of regeneration/recycling/reuse (different terms are used in the literature) can make these waters available for further use (Voulvoulis, 2018). Regenerated treated wastewater use is increasing; it is recognized as a promising and necessary solution to alleviate water stress, especially in areas where the shortages of conventional water resources is a structural problem (European Parliament and Council, 2020).

In the European Union (EU), numerous initiatives have been recently put in place to foster wastewater reuse, promoting a more resource-efficient circular economy. The maximization of treated wastewater reuse for irrigation has been underlined as a specific objective in several Communications by the Commission ('A Blueprint to Safeguard Europe's Water Resources' (2012), and 'Closing the loop – An EU action plan for the circular economy' (2015)), and identified as a top priority in the Strategic Implementation Plan of the European Innovation Partnership

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https://doi.org/10.1016/j.agwat.2021.107435
Received 11 April 2021; Received in revised form 8 November 2021; Accepted 23 December 2021
Available online 4 January 2022

on Water.

Recently, a new Regulation (EU) 2020/741 has been set to facilitate the use of urban wastewater for agricultural purposes, by providing harmonized minimum water quality requirements (European Parliament and Council, 2020). The Regulation defines four different classes (Class A being the strictest) of water quality, depending on the contact level between the reused water and the edible part of the crop. A maximum level of microbial pollution is set for each class, in order to prevent the spread of waterborne diseases. The Regulation also requires that the input of Water Regeneration Plants (i.e., the output of Urban Wastewater Treatment Plants) is compliant with the wastewater directive (Council of the European Communities, 1991). In sum, it completes the existing EU legal framework on water: the Water Framework Directive (WFD), 2000/60/EC (European Parliament and Council, 2000), and The Urban Waste Water Treatment Directive (UWWTD) (Council of the European Communities, 1991).,

Although major regulatory strides have been made to boost water reuse in the EU, only a small part of treated wastewater is currently reused (BIO Deloitte, 2015). The widespread implementation of water reuse projects appears to be limited due to several technical and non-technical barriers (Alcalde Sanza and Gawlik, 2014; Licciardello et al., 2018; Ricart and Rico, 2019; van Rensburg, 2016). Recent research on the subject claims that, while technical barriers related to water reuse could largely be resolved (e.g., through adapted irrigation systems, improved storage, and treatment methods) (Xylem, 2020), social and economic issues (e.g., public acceptance and the cost of reclamation) may seriously condition the success of water reuse projects, and yet they are poorly investigated (Saliba et al., 2018; Smith et al., 2018). Economic analyses related to wastewater reuse have primarily focused on the evaluation of water reuse practices in comparison with other non-conventional sources, mainly desalinization (Lapuente, 2012). Much less efforts have been spent on the study of the financial and economical sustainability of wastewater reuse investments, and on the prioritization of water reuse projects (Arborea et al., 2017; Arena et al., 2020).

Although new decision support tools, such as the Poseidon software (Oertlé et al., 2019), are currently being developed to support pre-feasibility studies on water reuse projects, Cost-Benefit Analysis (CBA), remains the major appraisal method to assess water-related investments (Molinos-Senante et al., 2010). This method enables a direct comparison of the total costs and benefits of a project, using a common metric (monetary units). In the case of wastewater treatment reuse projects, its application is not straightforward. One of the major difficulties in assessing the costs consists of the determination of the distribution network that connects the regenerated water plant to the final users. Other issues, such as on-site versus at source, and the short-term and long-term nature of the cost and benefits attained (e.g., the discount rate) are also commonly discussed (Giannoccaro et al., 2019).

The paper aims to provide a method to quantify the costs and benefits of water reuse projects for irrigation, identifying potential projects with higher net benefits and hence contributing to the development of CBA in water reuse. The work provides a method for prioritizing wastewater reuse projects in agriculture irrigation. We use the Upper Guadiana (in central Spain) as a case study to arrange candidate reuse projects according to their cost and benefit ratio. The proposed method streamlines the process through the minimization of input data (Wastewater treatment plant location and capacity, potential clients' location and water use). As a novelty, the definition of the pipe distribution network is automated through the design of an algorithm based on Minimum Span Trees (Jarník, 1930; Prim, 1957). The benefits of agricultural uses are also calculated, and the methodology allows for other potential uses (industrial, urban) of regenerated water, given their water consumption and monetarized benefits. The flexibility facilitates the definition of alternative scenarios and provides solid scientific evidence to support water policy decisions.

1.1. Study area

The methodology is applied in the Upper Guadiana area, in Spain, where overexploited aquifers can no longer provide for the water volumes required by agricultural users. The regeneration of a portion of the wastewater generated by the urban agglomerations may alleviate the pressure on water resources.

The area of study comprises the groundwater bodies “Mancha Occidental I” and “Mancha Occidental II” (Fig. 1) in Central Spain.

The implementation of irrigation projects in the 20th century has led to the overexploitation of the groundwater bodies (Table 1). This has implied a drawdown of the local water level (IGME, 2020).

Currently, the River Basin Authority has restricted water abstractions to match the available renewable resources. Therefore, permitted irrigation for herbaceous crops ranges between 2000 and 2200 m3/ha/year; in the case of permanent crops, it is restricted to 1500 m3/ha/year. These figures have been further reduced to 1800m3/ha/year (herbaceous crops) and 1350 m3/ha/year (permanent) in 2021 due to drought conditions.

The Guadiana River Basin Management Plan “Non-conventional resources” section (CHG, 2016) declares that “in the deficit areas, and especially in the Upper Guadiana Subsystem, water reuse will exclusively be allowed to substitute irrigation or industrial water rights”. That is, that water reuse should be a relief to the existing abstraction, and not a net increase in the water offer. Current water reuse in the area is marginal, with 4.75 and 1.27 hm^3/year being produced at the Alcazar and Tomelloso Wastewater Treatment Plants (WWTP) (CHG, 2016).

Fig. 2 shows the location and relative size of the larger WWTPs in the area, and Table 2 lists their size in population-equivalent (European Commission, 2019).

2. Materials and methods

We propose a CBA method to systematically quantify all the costs and benefits of the water reuse projects, in order to assess its economic feasibility. First, we estimate the costs of implementing a water reuse project (initial investment in the reuse plant and distribution network, operation, and maintenance costs) using secondary data from official sources, then we calculate the benefits of the additional productivity of the agricultural fields irrigated with the reused waters. The methodology is summarized in Fig. 3.

Given a WWTP capacity, the costs (both initial investment and operation) of regenerating the water to reuse standards are assessed. If water uses are not simultaneous to regenerated water production, a storage tank can be envisaged, and its costs assessed. For a geographical setup of potential users, a distribution network is automatically generated through a purpose-developed algorithm.

Once the length and diameter of connection pipes is known, their supply and installation cost is assessed. Given the relative elevation of WWTP and water users, the friction head losses through the distribution network and the required water pressure at each distribution point, a pumping unit is sized, and the investment and operation costs are assessed. The initial investment costs are then annualized using a financial function in order to perform the analysis in monetary units per year (European Commission, 2003).

On the benefit side, each user is characterized by the annual volume of water required and the monetarized benefit generated by the use of the water. The methodology allows for any kind of user (urban, industrial, agriculture). In the application shown in this paper (a rural area in the Upper Guadiana in Central Spain) the potential use is irrigation agriculture, so the required annual volume and the potential benefit assessment is based on local crop data.

Once the total costs and benefits are assessed for each candidate project, the potential net benefit can be calculated, and projects can be prioritized according to their investment returns. The flexibility of the methodology allows for the creation of different scenarios that facilitate

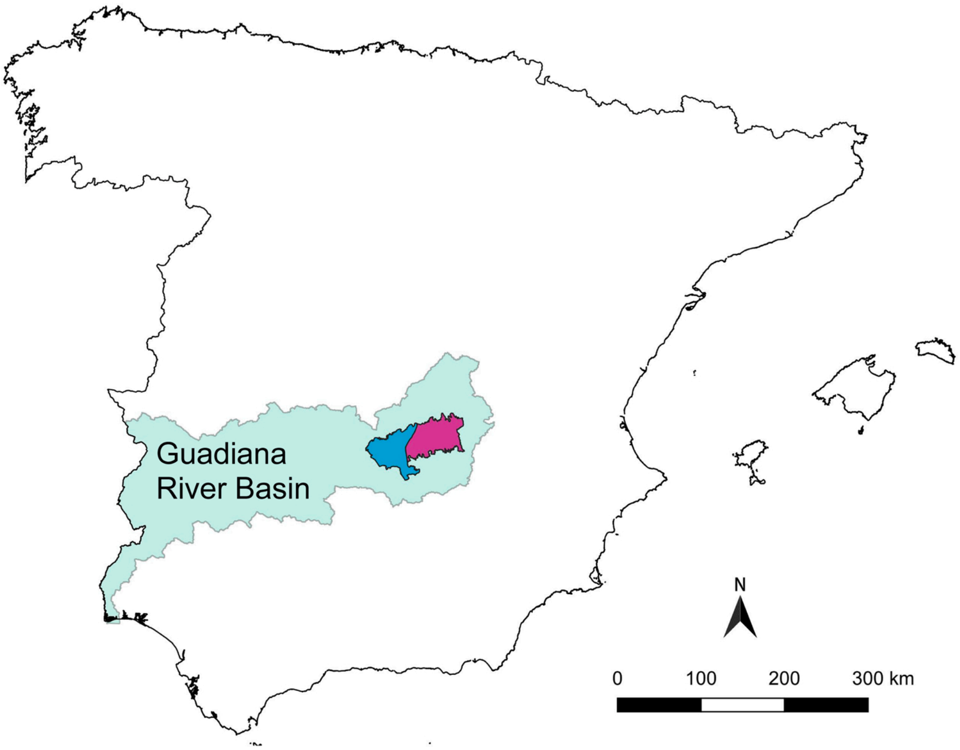


Fig. 1. Location of the study area in Central Spain: Mancha Occidental I (blue) and Mancha Occidental II (red) groundwater bodies.

Table 1
Water balance in the Guadiana River basin groundwater bodies.

Groundwater body	Available renewable resource (hm3/ year)	Water extraction permits (hm3/ year)	Exploi-tation index (Ie)	Balance (hm3/ year)
Mancha Occidental I	91.2	327.39	3.59	-236.19
Mancha Occidental II	106.2	337.53	3.18	-231.33

Source: Guadiana River Basin Authority.

the optimization of the process.

In particular, the methodology allows for the quantification of the effects of the yearly regeneration period (whether the water regeneration plant works all year long or only in the irrigation months) and the choice of output water quality and process technologies.

2.1. Data

The methodology has been designed to exploit existing secondary data in order to minimize the cost of the analysis. The data used in this paper has been extracted from the following databases:

- Groundwater bodies extension (CHG, 2020), to delimitate the study area.
- Digital Elevation Model (Instituto Geográfico Nacional, 2020) in order to calculate the elevation of each WWTP and agricultural land plot.
- WWTPs location and capacity (European Commission, 2019), and list of authorized wastewater discharges in the study area (CHG, 2013).
- Local Wastewater production per inhabitant (INE, 2020).
- griculture land plots. Shapefile with the location, and surface and crop type of the agriculture land plots in the vicinity of each WWTP in order to identify the potential water users of each reuse project candidate (MAPA, 2010). Years 2000–2010.
- Weather data and crop parameters (MAPA, 2020).
- The additional gains in terms of gross margin for each crop have been calculated based on (MAPA, 2018, 2019) and fieldwork developed in the study area.
- Initial investment (CAPEX) and operation and maintenance cost (OPEX) of a water regeneration plant, according to its capacity and actual production (Simón, 2018).
- Water storing costs (Joint Research Centre, 2017) and pumping station initial investment cost (Grundfos, 2021).
- Pipe supply and installation costs (Canal, 2018; Joint Research Centre, 2017; OECD, 2000).

2.2. Method: cost-benefit analysis

2.2.1. Distribution network definition algorithm

For each water reuse infrastructure project, the distribution network must connect the water source (the Water Regeneration Plant) to the water users (irrigated plots, industrial or urban users) with a minimum cost. While the detailed design of a distribution network requires a dedicated effort of a design team, this network can be approximated through Minimum Span Tree algorithms (Jarník, 1930; Prim, 1957). The algorithm proposed in this paper (Bolinches et al., 2021) exploits the initial data (Water Regeneration Plant position, elevation and water availability; water clients position, elevation and water needs) to design a distribution network (set of pipes with initial and final positions, length and diameter) that connects all users to the water source minimizing the cost, through the following steps:

- The water source is defined by the coordinates, elevation, and annual volume of produced water of the Water Regeneration Plant.
- The water users are defined by the coordinates and elevation of the center point, crop type and annual water demand of the land plots potentially irrigated with regenerated water.

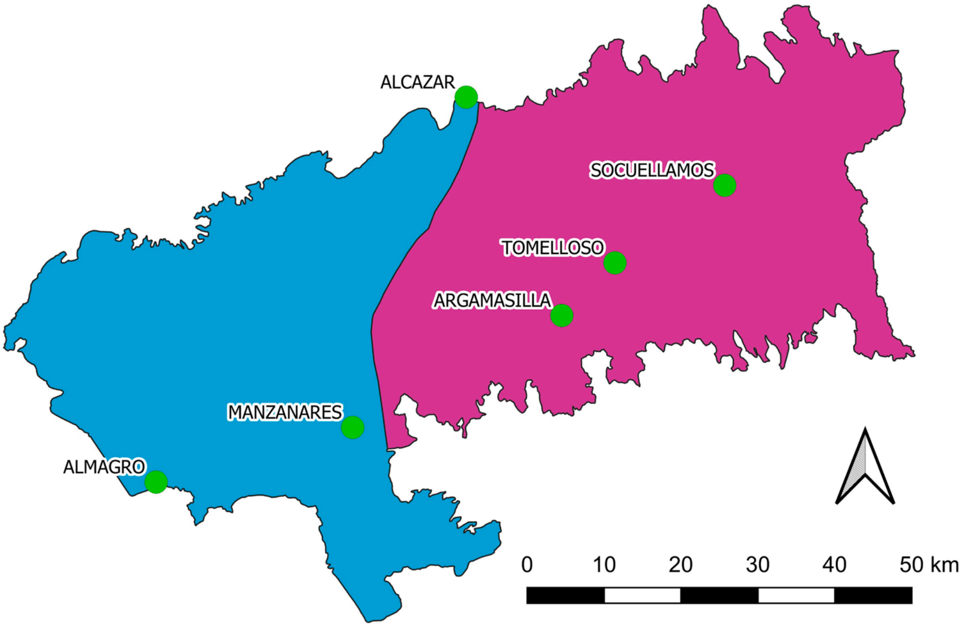


Fig. 2. Major Wastewater Treatment Plants in Mancha Occidental I and Mancha Occidental II groundwater bodies.

Table 2
Population-equivalent of Wastewater Treatment Plants (WWTP) in the study area (European Commission, 2019).

WWTP	Alcazar	Manzanares	Almagro	Tomelloso	Socuellamos	Argamasilla
Population-equivalent	322,400	73,200	43,858	40,627	28,700	13,759

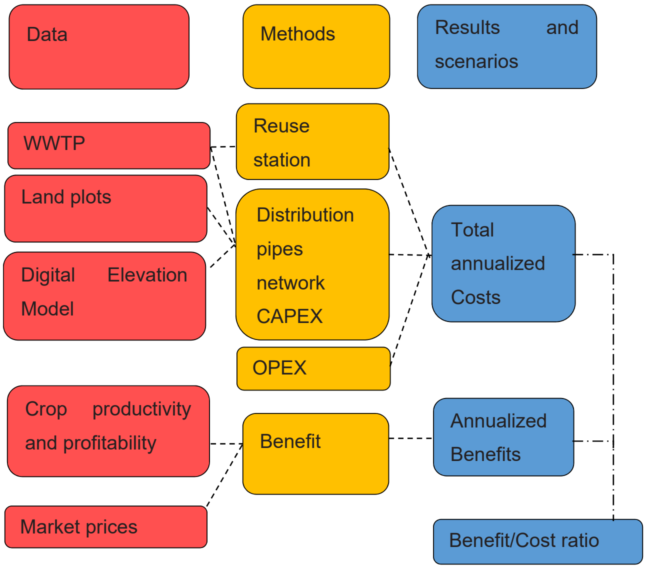


Fig. 3. Proposed methodology. WWTP: Wastewater Treatment Plant. CAPEX: Initial investments. OPEX: Operation and maintenance costs.

- The points are divided in two subsets: subset A (plots connected to the distribution tree) and subset B (plots not yet connected to the distribution tree). Initially, subset A only contains the Water Regeneration Plant, and subset B contains all the land plots.
- Elements in subset B are arranged according to their distance to the Water Regeneration Plant, and at each step the algorithm grows the distribution tree (i.e., adds elements from subset B to subset A) by choosing the pair of elements (one in subset A and another in subset B) for which the connection presents the minimum cost. This is done through the calculation of the cost of each candidate connection pipe, from the first element in the arranged B subset (i.e., the closest plot to the Water Regeneration Plant which is still unconnected to the tree) to each of the elements in subset A, then choosing the candidate with minimum cost.
- At each step, the algorithm identifies the parent (element in subset A from which the connection pipe departs), child (element in subset B to which the connection pipe arrives) and the hydraulic parameters (geometric head, water consumption of child element).
- The tree is grown sequentially until the cumulative water consumption of the land plots matches the capacity of the Water Regeneration Plant. Once all pipes initial and final positions are defined, the diameter of each pipe stretch is set according to the circulating flow.

2.2.2. *Clients of water reuse: volume requirements and benefits*

A selection of the most relevant crop types in the area was used for the analysis, namely vineyard, olives, fruit crops (almond), horticulture (particularly melon and onion), and cereals. Water requirements have been calculated based on a daily water balance set for each crop using weather data and crop parameters gathered from local weather stations (MAPA, 2020). Irrigation water requirements have been estimated in 1310 m^3/ha/year for vineyard, 2566 m^3/ha/year for olives, 4059 m^3/ha/year for almond, 5355 m^3/ha/year for horticulture, and 3556 for cereals.

With regard to the benefits associated to crop irrigation, the increase of crop gross margin per hectare is calculated comparing rain fed and irrigated cropping systems. Gross margin per hectare for each cropping system is obtained by subtracting production costs (costs of inputs, machinery, and labor costs) from revenues (value of production, estimated by multiplying average crop yields by crop prices, and subsidies) (see Table 3). The study assumes that irrigating with reclaimed wastewater would allow for changing from rain fed to irrigated crop production. Thus, the benefits associated to reclaimed wastewater use are

Table 3

Increase in annual gross margin due to irrigation per crop type. Own calculation based on (MAPA, 2018, 2019, 2020).

Crop type	*System*	*Revenue (€/ha/year)*	*Cost (€/ha/year)*	*Gross margin (€/ha/year)*	*Gross margin increase (€/ha/year)*
Vineyard	rain fed	2140	778	1363	1194
	irrigated	3649	1093	2557	
Olive	rain fed	1196	410	787	688
	irrigated	2429	955	1475	
Almond	rain fed	2075	762	1313	951
	irrigated	3665	1401	2264	
Horticulture[a]	irrigated	7520	4295	3226	3225
Cereals	rain fed	441	256	185	228
	irrigated	969	556	413	

a. For horticulture, the gross margin increase equals the gross margin of irrigated horticulture.

calculated as the difference between irrigated and rain fed crop gross margins per hectare (gross margin increase in Table 3).

2.2.3. *Water Regeneration Plant costs*

The treatment of WWTP effluents to reach the reuse grade requires the implementation of infrastructure (the Water Regeneration Plant) with initial investment (CAPEX) and operation and maintenance (OPEX) costs. These costs will depend on the technology used and the water quality required (Iglesias, 2016; Joint Research Centre, 2017). An estimation of these costs based on the experience of previous projects (Simón, 2018) is shown in Table 4.

Table 4

Cost of different reuse treatments (Simón, 2018).

Quality class and technology	CAPEX EUR/ (m3/day)		OPEX EUR/m3	
	min	max	min	max
Class A (Filtration)	200	–	0.16	0.20
Class A (Ultrafiltration)	480	480	0.07	0.09
Class B	150	170	0.08	0.08

The regenerated water quality classes are defined according to the European Regulation 2020/741 (European Parliament and Council, 2020), where the most strict class A is required for “All food crops consumed raw where the edible part is in direct contact with reclaimed water and root crops consumed raw”, and class B is required for “Food crops consumed raw where the edible part is produced above ground and is not in direct contact with reclaimed water, processed food crops and non-food crops including crops used to feed milk- or meat-producing animals”. The maximum allowed pollution for each class is defined accordingly, limiting for example the Escherichia coli bacterial presence to 10 units per 100 ml for class A, and 100 units per 100 ml for class B. The required regeneration process is then defined to guarantee these requirements.

In the case of class A, the regeneration process can be chosen between a traditional filtration followed by ultraviolet and chemical disinfection, with relatively low initial investment costs but higher operational costs, or an initial ultrafiltration process with higher investment costs but relatively lower operational costs.

The annual equivalent investment costs in EUR/year (Eq. 1) can be assessed through the annualization of initial costs throughout the infrastructure lifespan (European Commission, 2003):

$$AEC = \frac{NPV\cdot r}{1-(1+r)^{t}} \tag{1}$$

AEC: Annual equivalent cost (EUR per year).
NPV: Net present value of investment (EUR).
r: chosen discount rate (dimensionless).
t: lifetime of the capital equipment (years).

Where the lifetime of the Water Regeneration Plant may range between 15 and 25 years, and the discount rate depends on the economic conditions. A 3% discount rate has been used in the baseline scenario.

2.2.4. *Water storage costs*

Since the water reuse time patterns may differ from the water production, it is advisable to provide the system with some water storage capability. It is estimated that the cost of a water storage tank ranges between 2 and 8 EUR/m3 (Joint Research Centre, 2017). It must be noted that particular precautions must be taken to monitor the evolution of the quality of the water upon storage.

2.2.5. *Water pipes infrastructure cost*

Given a pipe length and diameter, the supply and installation cost will depend on the material of the pipes. Eq. 2 shows the averaged cost estimation of Madrid Water Utility company Canal Isabel II (CYII) and OECD for different materials (Canal de Isabel II, 2018; OECD, 2000).

$$Pipe\quad cost\quad (EUR/m) = 0.019\cdot Diameter\quad (mm)^{1.8819} \tag{2}$$

The lifetime of the distribution network is taken as 50 years.

2.2.6. *Water pumping costs*

Given a distribution network, a pumping station is needed to provide the necessary energy to the water to reach the land plots. The required pumping power is assessed through the flow and head of each water client (Eq. 3).

$$Power\quad (W) = \frac{1}{efficiency}\cdot density\left(\frac{kg}{m^3}\right)\cdot gravity\left(\frac{m}{s^2}\right)\cdot\sum Head(m)\cdot Flow\quad\left(\frac{m^3}{s}\right) \tag{3}$$

The total head for each water client is the addition of three factors: the geometric head (elevation of water point above water station), which is calculated by the network algorithm from the initial data (Instituto Geográfico Nacional, 2020); the water friction losses, taken as a fraction (which ranges from 1% to 5%) of the total pipe length; and water pressure required at the final point, taken as 10–50 m of water column. The pump efficiency can be approximated to 75% (Joint Research Centre, 2017).

Once the required power is known, the implementation cost of the pumping station can be approximated from previous literature (Joint Research Centre, 2017; OECD, 2000) and taking into account current prices (Grundfos, 2021). A trend line is calculated (Eq. 4).

$$Pump\quad cost(EUR) = 1178.8\quad Pump\quad power\quad (kW)^{0.6816} \tag{4}$$

To annualize the pump Capex, a lifetime cycle of 15–25 years can be considered.

The energy consumption of water is then calculated with the total head and the pumped volume. The operational cost (Eq. 5) is calculated multiplying the energy consumption and the energy cost, that may range between of 0.1 and 0.3 EUR/kW.

$$OPEX\quad\left(\frac{EUR}{year}\right) = \frac{\mathrm{Cost}\left(\frac{EUR}{kWh}\right)}{efficiency}\cdot density\left(\frac{kg}{m^3}\right)\cdot gravity\left(\frac{m}{s^2}\right)\cdot\sum Head(m)\cdot Volume\quad\left(\frac{m^3}{year}\right)\cdot\frac{1kWh}{3.6\cdot 10^{6}Ws} \tag{5}$$

2.3. Scenarios

The methodology allows for the definition of case scenarios where the consequences of different techniques and policy choices can be compared. The benefits and costs of each candidate project can be analized for the different envisaged scenarios.

A baseline scenario is proposed with the following parameters:

- Plots are chosen according to their proximity to the WWTP regardless of their current crop type.
- The quality of regenerated water is defined to its highest standard (Class A), with filtration technologies that minimize initial investments.
- Taking into account that water use is concentrated in the summer months, only water produced along 5 months (may-september) is reused to avoid high storage costs. The storage infrastructure is designed to contain one month of water production.
- The following values are used: Regeneration Capex = 200 EUR/(m3/day), Regeneration Opex = 0.18 EUR/m3, Storage Capex = 5 EUR/m3, friction head losses = 0.01 m head per linear m, user pressure = 30 m of water column, interest rate = 3%, regeneration and pumping station lifetime = 20 years, distribution pipes lifetime = 50 years.

A second scenario (all year reuse scenario) analyzes the expected costs and benefits when the Water Regeneration Plant treats the output of the WWTP all year long. Since the water consumption is concentrated on Spring and Summer months, the additional water regenerated throughout the Autumn and Winter months has to be stored, implying an increase in storage costs. The additional water supply allows tor the irrigation of supplementary water plots, with additional benefits but also additional distribution and pumping costs. The method quantifies these costs and benefits allowing to compare the potential benefits with respect to the baseline scenario.

An externality of water reuse that cannot be ignored in inland projects is the effect on surface water flows. An abuse of water reuse may result in diminishing flows in surface waters, and water authorities may impose minimum effluent restrictions to guarantee the sustainability of water environments downstream of the WWTP. A particular scenario is built to quantify the effect of these restrictions.

Another scenario (reused water quality and technology) is also proposed to assess the implications of implementing different Water Regeneration Plant technologies, achieving different output water quality. Among the water quality classes defined by the European Regulation (European Parliament and Council, 2020) regeneration cost structures are available for class B and two different technologies achieving class A (filtration and ultrafiltration). The scenario compares the cost structures for each choice, thus providing quantitative information for infrastructure choices.

2.4. Sensitivity analysis

The values of the inputs chosen in the baseline scenario are estimates that may change in real life scenarios. In order to assess the effect of input changes, two scenarios, labeled as 'more favorable' and 'less favorable', have been considered. In the former, parameters change from the baseline scenario to values which reduce costs and increase benefits; in the latter, parameters take values that increase costs and reduce benefits. Table 5 shows the values of the baseline scenario and the range of the variables. Cost values have been obtained from Joint Research Center (2017). Benefit values (increase in annual gross margin due to irrigation per crop type) have been calculated based on MAPA (2018, 2019, 2020).

Table 5
Range of input values in the sensitivity analysis (Joint Research Centre, 2017; MAPA, 2018, 2019, 2020).

Input	Units	Baseline scenario	More Favorable	Less Favorable
Costs:				
- Price of electricity	EUR/kWh	0.1	0.05	0.15
- Discount rate	%	3	1	6
- Pipe Lifetime	years	50	75	25
- Cost of storage	EUR/m3	5	2	8
Storage lifetime	years	50	75	25
Stations lifetime	years	20	25	15
Benefits (increase in annual gross margin):				
- Vineyard	EUR/ha/year	1194	1493	896
- Olive	EUR/ha/year	688	963	413
- Almond	EUR/ha/year	951	3187	1062
- Horticulture	EUR/ha/year	3225	4193	2258
- Cereals	EUR/ha/year	228	342	114

The model is run iteratively. In each iteration the inputs take a random value in a uniform distribution within the shown range in order to assess the robustness of the results shown for the baseline scenario.

3. Results

3.1. Baseline scenario

3.1.1. Pipe network definition

This section shows the developed piping network that connects the Water Regeneration Station to the agricultural land plots. Water Regeneration Station capacity can be calculated from WWTP discharge data or, as it was the case for this implementation, inferred from the population equivalent per WWTP and the local wastewater production per inhabitant.

Fig. 4 shows the networks generated by the algorithm for the considered project. The detailed view of the Almagro area shows how the pipes supply all the plots in the vicinity of the Water Regeneration Station.

In the implementation, it is assumed that the Water Regeneration Plant and the pipe network are fully operational from the first year of implementation, which is consistent with the relatively small sizes of the WWTPs under study. In the implementation of larger schemes, a phased implementation can be considered.

3.1.2. Cost and benefit structure

Once the distribution network is defined (length, size and elevation), the model can assess the initial investments and operational costs for each of the candidate projects. Fig. 5 shows the results for the six main wastewater treatment plants in the study area, baseline scenario. The cost of regenerated water varies between 34 and 39 Euro cents per cubic meter. The difference among projects corresponds to the distribution network (a larger dispersion of irrigated crops in the Alcazar project implies longer distribution pipes), and topography considerations (larger pumping costs to elevated land plots).

It must be noted that the 3.9 Euro cents per cubic meter storing costs correspond to the decision of storing the equivalent of one month

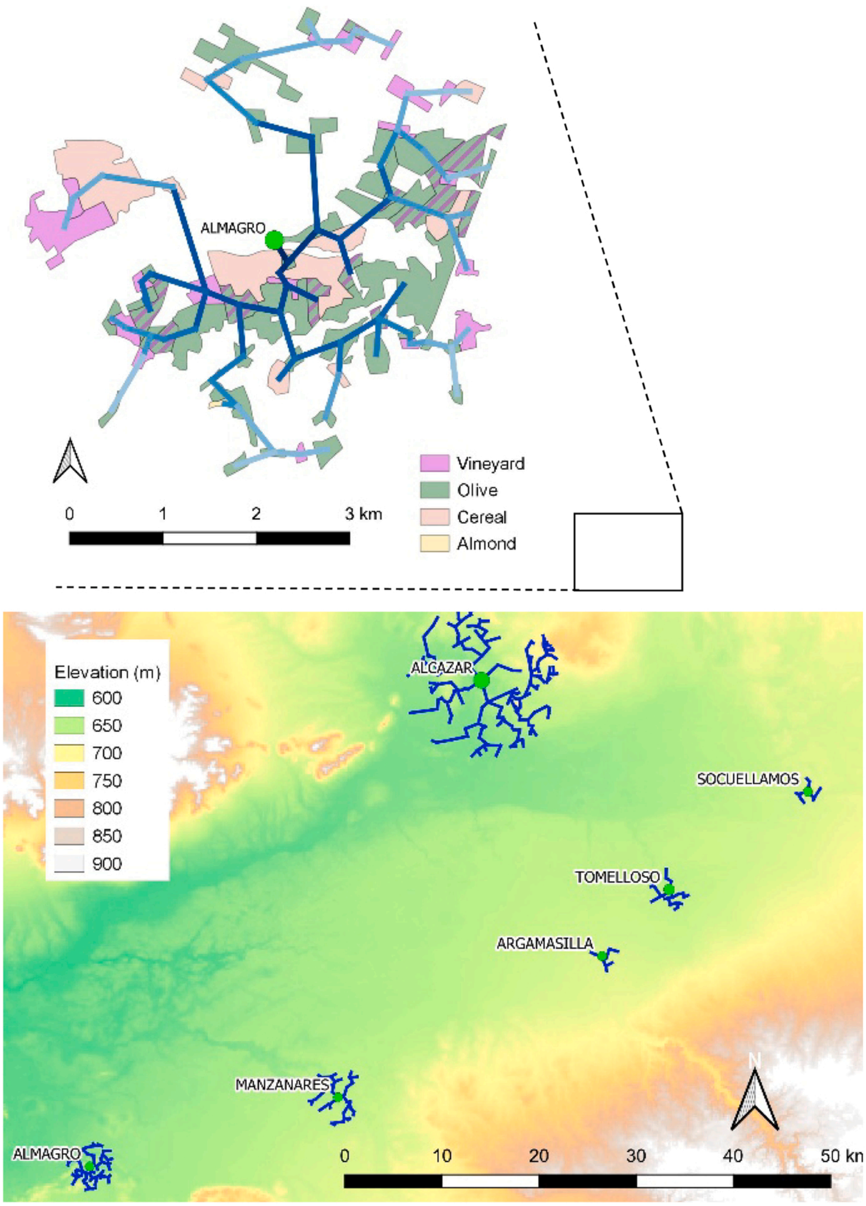


Fig. 4. Distribution networks with detail view on Almagro area. Pipe color in the detailed view shows the order of definition of distribution pipes by the algorithm (darker for initial pipes).

regenerated water production, and are subject to further optimization (see paragraph ↱3.2).

Adding the benefits to the analysis allows to compare if these outweigh the costs and provide a net benefit to the project. Fig. 6 shows the cost and benefit structure of the Tomelloso project. The inner ring shows the percentage of irrigated area covered by each crop type. The middle ring displays the annual benefit generated by the transition from rainfed to irrigated crops, showing the larger benefit potential of the vineyard crops. Finally, the outer ring shows the annual operation cost breakdown.

The analysis shows that most of the benefit is generated through the irrigation of vineyard crops. The higher annual cost is represented by the operation and maintenance of the water regeneration station, followed by the annualized costs of the initial investment of the station. These are followed by other initial costs (storage and distribution infrastructure), while the pumping costs are comparingly smaller. This cost structure is similar in the other candidate projects.

Since the cumulative benefits are larger than the cumulative costs, the project generates a net benefit of 162 433 EUR/year. The detailed results for each project are presented in the Appendix.

Considering the variety of assumptions, the net benefit should not be taken as an absolute result but rather as a tool of comparison. Under the baseline assumptions, candidate projects can be organized according to their return of investment. Fig. 7 shows a wide range of results, depending on the local geometry and the crop types. Projects with a high percentage of high value crops in the proximity of the WWTP are likely to produce net benefits, while candidate projects with a bigger share of low value crops in the vicinity may present losses. The methodology is able to quantify these values and provide alternative scenarios.

3.2. *All year reuse scenario*

The presence of net benefits of water reuse in some potential projects opens the question if expanding the water regeneration to all year (storing the water in the winter months for a larger availability in the summer months) would generate additional benefits.

Fig. 8 shows the cost and benefit structure of the reuse project if the regeneration station is exploited all year long. Since water use is

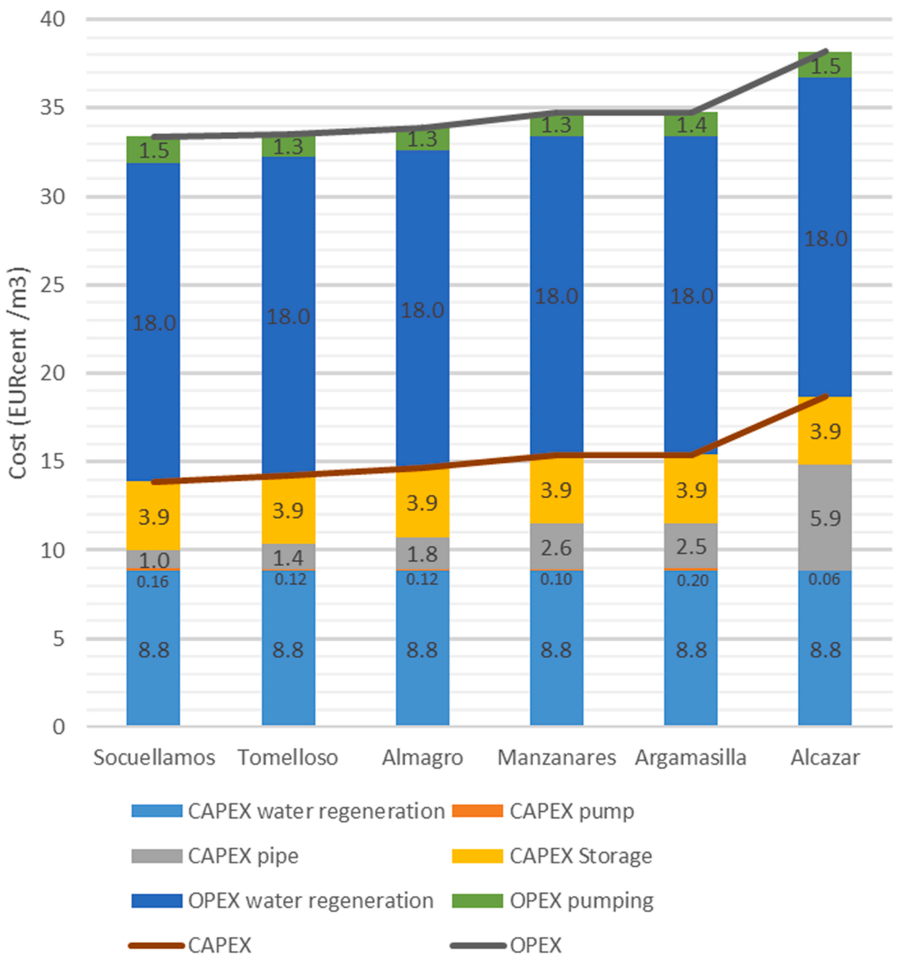


Fig. 5. Cost structure per candidate project.

concentrated in the summer months, the storage capacity has to be resized to accommodate the additional needs (here assessed to six months capacity).

The analysis quantifies the increase of storage costs (larger tanks or ponds to accumulate the water in non-irrigation periods) and distribution network costs (longer and bigger pipes to reach additional water users). Although the benefit also increases due to the additional irrigated land plots, the net benefit/cost ratio falls from a 31% to a 25%.

3.3. *Minimum effluent restriction scenario*

The minimum effluent restriction scenario described in section ↱2.3 is studied for the case of Tomelloso WWTP, where a minimum 10% effluent is considered according to the Guadiana River Basin Management Plan (CHG, 2016). Fig. 9 shows the changes in total costs and benefits after the restriction is applied.

The minimum effluent restriction implies a limitation on the irrigated area, and the crop benefit will be affected. Also, the total cost of the project will be affected since less infrastructure is needed. In this instance the minimum effluent restriction implies a reduction of 30% of the expected net benefits (from 331,160 to 230,982 euros). It must be noted that the effect on net benefit depends on the particular plot distribution of each project, and the dependence of net benefit on available water may not be monotonically increasing and present local maxima. The model allows to quantify the costs and benefits for each case.

3.4. *Water reuse quality and technology choices*

The choice of the technology used to regenerate the treated wastewater has a major effect on the structure of the project costs, and on the expected net benefit.

Compared to the baseline case (Class A, filtration), the choice of ultrafiltration technology to achieve Class A water quality implies a sharp increase in the initial investment of the regeneration plant, although the operation and maintenance costs are reduced significantly (Fig. 10). In this example the net benefit is reduced, although the actual result will depend on each case.

Fig. 10 shows the cost structure if the Water Authorities considered that the irrigated crops allow for a Class B regenerated water quality. The lower regeneration costs would imply an increase of the expected benefits.

3.5. *Sensitivity analysis results*

A sensitivity analysis is conducted through the calculation of costs and benefits for 100 instances where the input values are allowed to change within the ranges exposed in Table 5. Fig. 11 shows the net benefit / cost ratio when inputs are allowed to change within value range (more favorable to less favorable).

The results indicate that the net benefit / cost ratio relative positions are consistent with the baseline scenario prioritization. The relative ranking of net benefit / cost shown in Fig. 7 (Socuellamos, Alcazar, Tomelloso, Almagro, Manzanares and Argamasilla) stays true in all the iterations except a 5% where Almagro and Manzanares swap positions. A closer study of the exceptions shows that this happens in iterations where the increase in annual gross margin of olive crops is particularly small, penalizing the olive-rich Almagro area. The analysis demonstrates the robustness of the model and its utility for policy assessment.

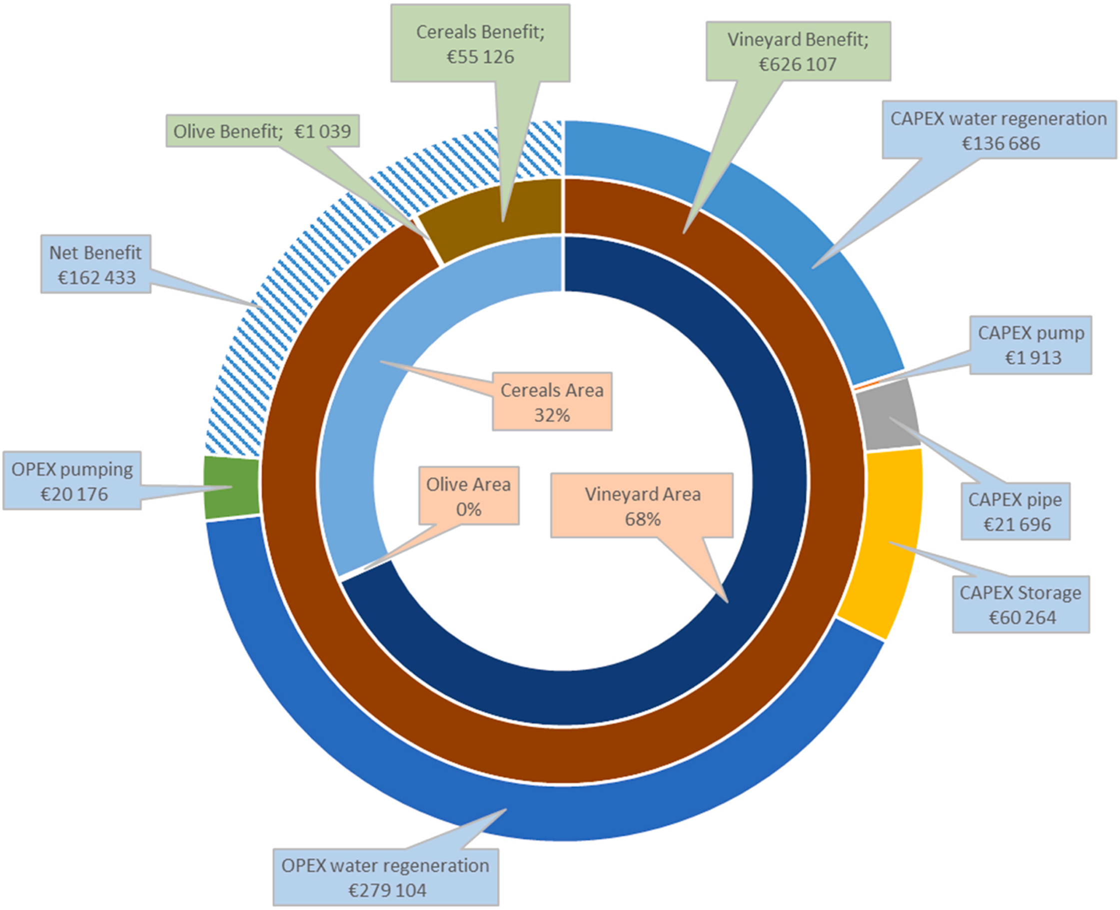


Fig. 6. Cost and benefit structure of Tomelloso reuse project. Reuse of wastewater in the may-september period.

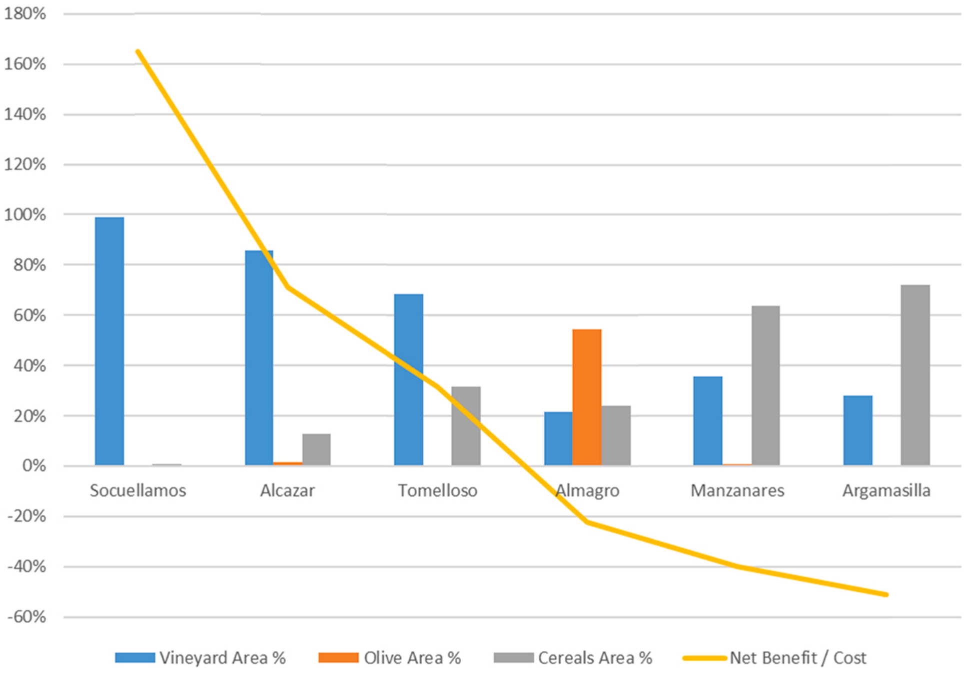


Fig. 7. Prioritization of projects according to expected net benefit ratio.

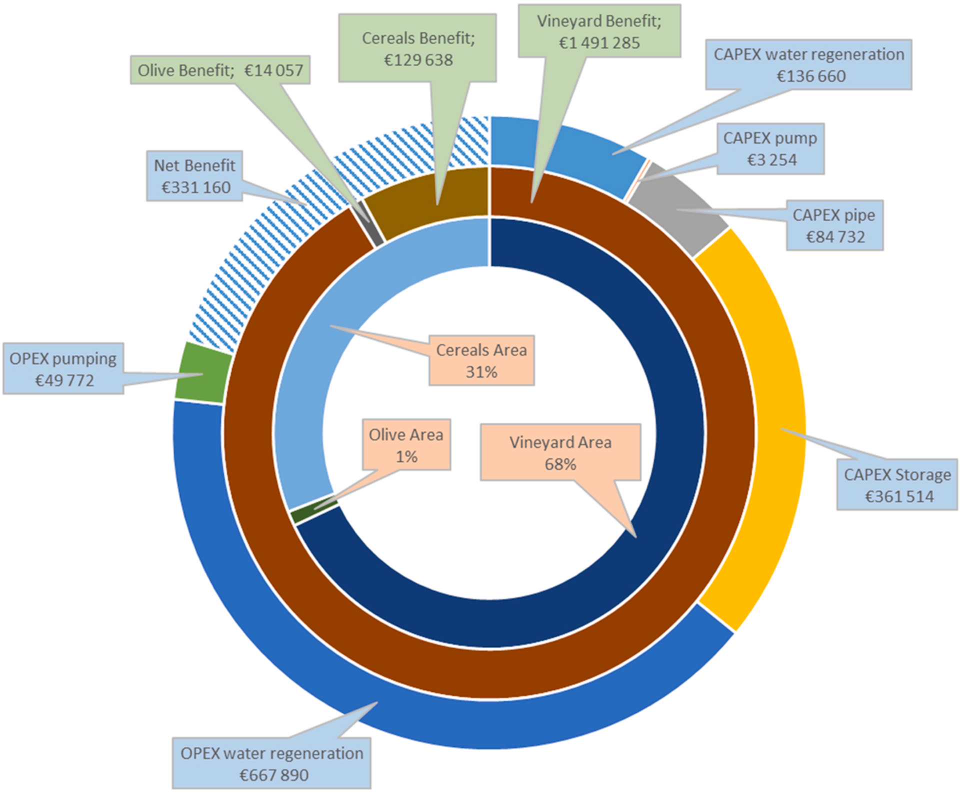


Fig. 8. Cost and benefit structure of Tomelloso reuse project. Reuse of wastewater all year long.

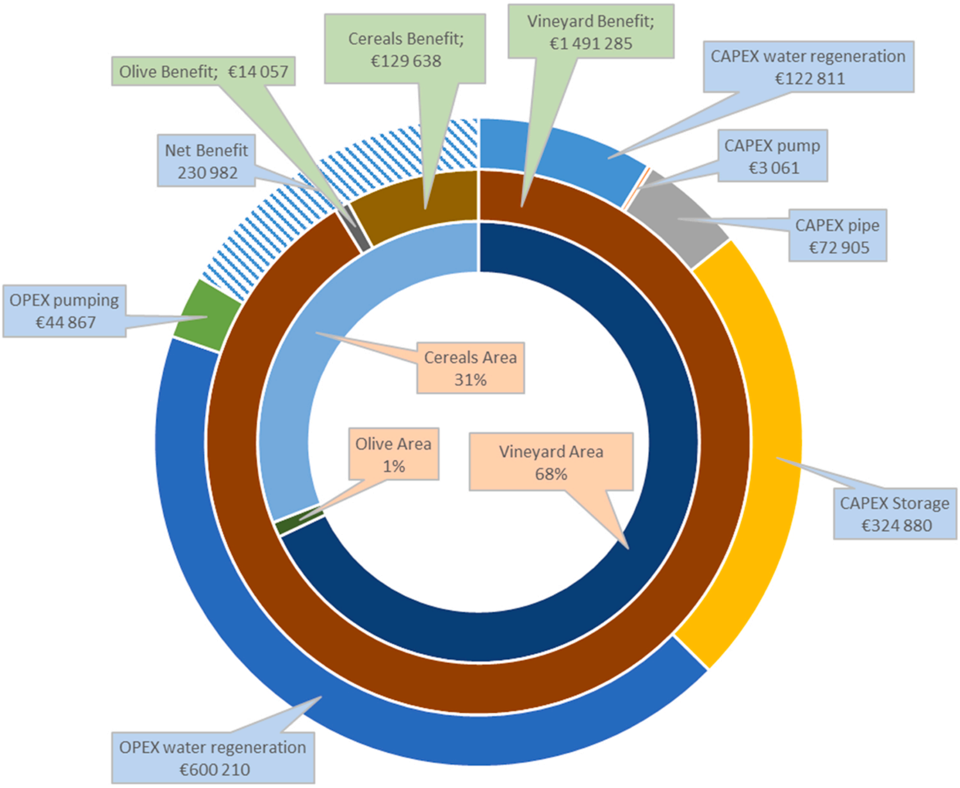


Fig. 9. Cost and benefit structure of Tomelloso reuse project (all year) with 10% effluent restriction.

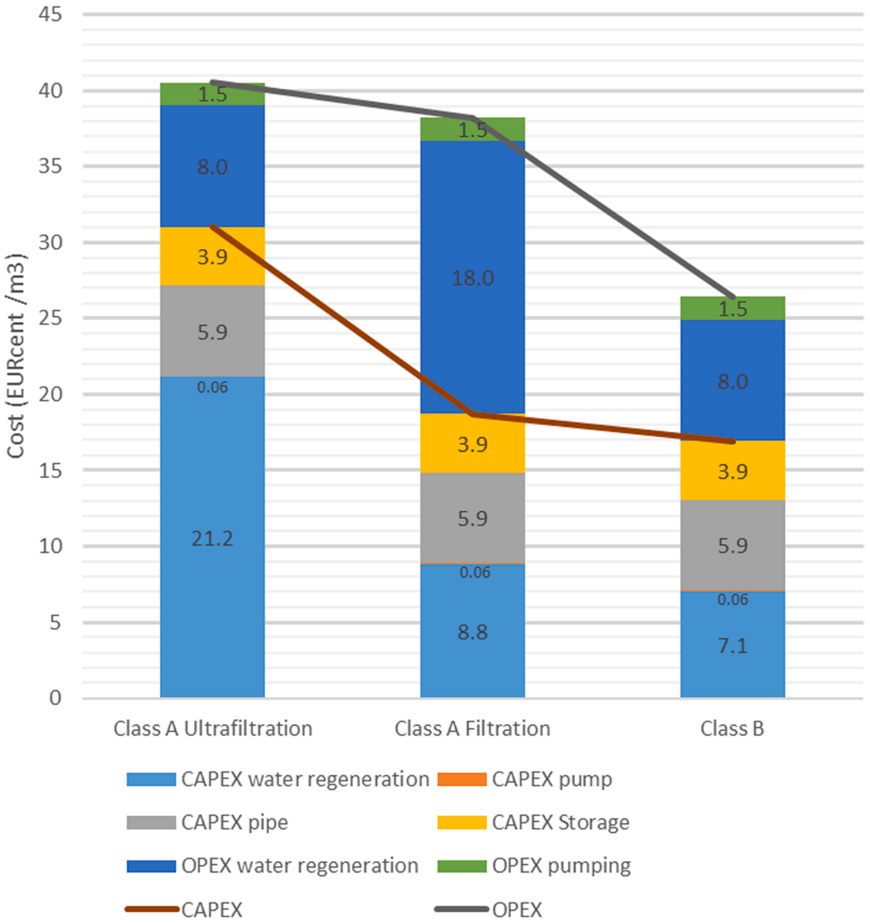


Fig. 10. Cost structure of Alcazar project according to quality class output and regeneration technology.

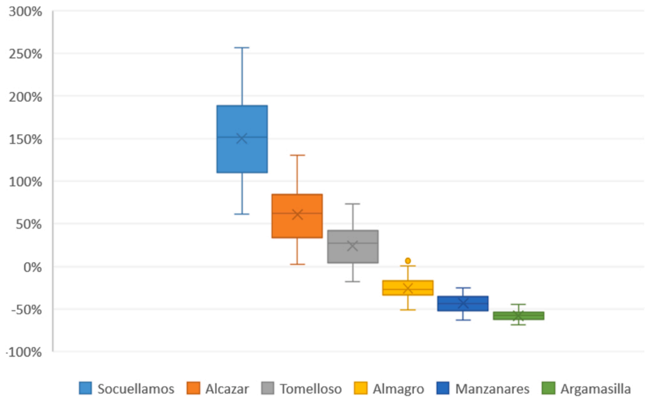


Fig. 11. Box and whiskers plots of net benefit / cost ratio when inputs are allowed to change within value range.

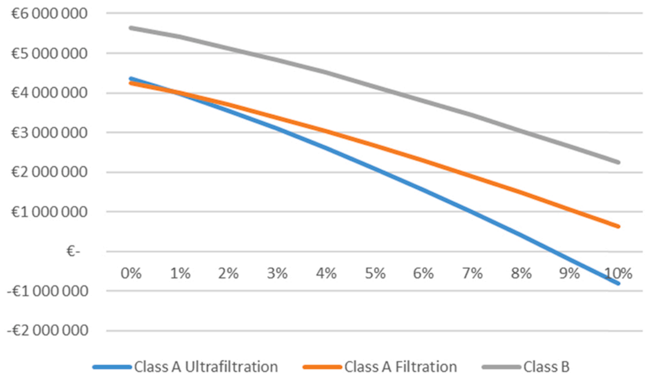


Fig. 12. Net benefit sensibility to interest rate.

Another result that can be extracted from the study is the sensitivity of the net benefit to changes in one of the input factors. Fig. 12 shows the values for Alcazar WWTP in the case of interest rate changes. In the envisaged scenarios, both a regeneration station with Class B quality water and Class A quality with Filtration technology would produce benefits even for high interest rates. In the case of the more capital-intensive Ultrafiltration technology, the sensibility would be higher although the break-even scenario would still happen at high interest rates. The analysis also shows that for this case Ultrafiltration technology can be cost competitive for low interest rates.

Similar analysis can be made to take account of the volatility of other input factors such as electricity price or benefits of agricultural production, and further analysis may identify the parameters with a higher influence on the outputs and assess scenario uncertainty (Marchau et al., 2019).

4. Discussion

The results presented show the wide variety of options available to Water Authorities to deal with the management of regenerated water resources. The methodology allows for a quick assessment of the costs and benefits implied in different reuse projects and scenarios, providing science-based evidence to support water policy decisions. The flexibility of the model facilitates the quantitative comparison of concrete choices, such as the particular technology of the Water Regeneration Plant, the volume of the storage tank and the extent of the distribution network.

The baseline scenario shows that prioritization is driven by the benefits obtained, rather than the cost structure that has minor differences between projects. Since the water regeneration costs considered (section ↱2.2.3) are independent of the plant size, the equivalent costs are equal for all candidate projects. However, more detailed data on these cost structures may show economy of scale advantages and diminishing costs per cubic meter for larger projects (Arborea et al., 2017). At the same time, these economies of scale may be counterbalanced by capital and operating costs of the distribution networks (Guo et al., 2014). In this regard, the methodology proposed in this research can contribute to the design of distribution networks that take full advantage of potential economies of scale.

The generation of a net benefit depends highly on the presence of crops where irrigation implies an important additional value. Previous studies (Calatrava et al., 2011; Ofori et al., 2021), demonstrate that the use of alternative sources of water (desalinization, water reuse) can be beneficial in areas with highly profitable crops. In areas where agricultural plots close to the WWTPs are devoted to crops for which the added value of irrigation is low, some choices should be made to achieve the economic feasibility. One could be to avoid the current low benefit crops and extend the water distribution network to reach existing high benefit crops. This would increase the distribution and pumping costs, and permanently neglect land plots in the vicinity of the water source. Another choice would be the change of the crop type of the land plots in the vicinity of the WWTP. Although more advantageous in the long term, this option would imply to sacrifice the productivity of the time period required by the new crops to develop (which may imply several years in the case of woody crops). The proposed methodology can quantify these scenarios.

The length of the irrigation season is often also considered a relevant technical barrier to the exploitation of the full potential of wastewater reuse (Giannoccaro et al., 2019). In our study, we assessed the effect of all year reuse by simulating the effect of increased water storage capacity. In this scenario, users could benefit from the full potential of the WWTP, and the unit cost per cubic meter of treated water could be reduced. However, the results of the analysis showed that the increased storage costs and the cost of the enlarged distribution network to reach new users would outweigh potential benefits of having additional water.

The results also show how critical on the benefit-cost structure is the decision of the quality of reused water. The choice of a less strict class within the options of Annex I of the European Regulation (European Parliament and Council, 2020) implies lower costs, quantified in section ↱3.3 but also restricts current and future uses of the reclaimed water. Complying with the new European Regulation could also imply important transaction costs (e.g., in terms of negotiation, adoption of risk assessment plans). Future research should take these costs into account to accurately assess new water reuse projects.

In line with other studies (Alcon et al., 2013; Birol et al., 2010; Giannoccaro et al., 2019), our research indicates that the interest rate remains a key determinant of changes in net benefit for water reuse projects. The interest rate and the project lifespan are consistent with the authorities recommendations (European Commission, 2014), in the lower range of the rates for the case of the baseline scenario. At higher rates, only Class B quality water and Class A quality with Filtration technology would produce net benefits. Interestingly, at low interest rates, ultrafiltration technology is also competitive. This finding supports recent studies demonstrating the economic viability of ultrafiltration technology (Bai et al., 2020).

It must be noted that these decisions should take into account other externalities to the project that are not included in this analysis and should be considered for future developments.

The first externality is the effect on surface bodies of water. The exploitation of reused water can have unintended consequences on the functioning of the integral water cycle. In particular, in inland areas (as it is the case for the study area) where the effluent from the treatment plants constitutes a non-negligible part of the circulating flow through the rivers, an excessive reuse could lead to a decrease in flow that compromises the sustainability of aquatic ecosystems (Mezger et al., 2019; Valerio et al., 2020) or the guarantee of supply downstream of WWTP discharge points (Andreu et al., 1996). Any wastewater reuse project should analyze the impact on receiving waters and the risk to compromise the ecological flows defined by the water authorities, which may impose restrictions on the minimum effluent flow as shown in Section ↱3.3.

A second externality, positive in this case, is the effect of the reuse project on the current extraction pressures of water resources. In a context of scarcity, water reuse projects should not be designed as an increment of the offer, but rather as a diversification tool and a relief on the natural resources (Hristov et al., 2021). In this case, the implementation of a project should be linked to the decrease in the exploitation level of natural resources, supporting the long-term sustainability of the water use. This contribution should be considered a non-market benefit to society. In many instances, this benefit is neglected, but it could be very high, even exceeding the cost of treating wastewater for reuse (Alcon et al., 2013; Ofori et al., 2021). In addition, the difficulties inherent to a practical implementation of groundwater abstraction restrictions should be acknowledged. Groundwater abstraction policing can be challenging, in particular in the area of study where even water theft has been reported (Loch et al., 2020). Another risk to be addressed is the possibility that further availability of water create an increase in water demand, as identified in previous literature (Randall, 1981).

Furthermore, the potential effects of a water reuse project on surface water quality cannot be ignored, although the positive and negative attributes and their balance may be hard to assess. On the positive side, the implementation of a water reuse project normally implies the reduction of the nutrient concentration in the effluent, which implies a reduction in the point load pollution of the plant discharge. On the negative side, agricultural reuse of water may introduce new sources of non-point pollution.

Another consideration is the effect of water quality parameters on crop efficiency that are not included in the urban wastewater treatment or reuse legislation. These parameters can be divided in two groups. On the one hand, the presence of macronutrients in the wastewater can imply a reduction in the fertilization costs of agricultural users (Chojnacka et al., 2020). The European Urban Wastewater Treatment Directive (Council of the European Communities, 1991) does include a limitation on Total Nitrogen and Total Phosphorus on WWTP effluents, but these only apply when the receiving waters are identified as sensitive to eutrophication to one of these elements. There is room for additional integration of the Wastewater Directive and the Reuse Regulation for Agriculture (European Parliament and Council, 2020) in this aspect to optimize the opportunities of exploiting these untapped resources, minimizing the risks on the receiving waters. On the other hand, the presence of heavy metals and ions that increase the salinity and conductivity in regenerated urban wastewater may have a negative impact on the irrigated crops (Gola et al., 2016; Salgot and Folch, 2018). None of these concentrations are limited in the European legislation. The negative effect may be tackled through the mixture of regenerated water with water coming from natural resources. Further investigation is needed to better understand the best way to combine these resources and optimize the water management in the new scenarios opened by the availability of regenerated water.

5. Conclusions

The technological advances in water treatment and microbiological pollution reduction, and the evolution of the regulation for the reuse of water for agricultural production are widening the number of water regeneration projects that are economically feasible. The main conclusions can be summarized as follows:

- The proposed methodology can analyze the relative weights of the different cost and benefits of a particular regeneration project with low requirements of initial data and time.
- Regeneration project candidates with higher potential benefits can be identified, and different scenarios can be projected to optimize the choice of design variables: annual volume of regenerated water, storage and distribution costs, regeneration technology.
- In the Upper Guadiana where the methodology is applied, results show that prioritization is driven by the benefits obtained, rather than the cost structure that has minor differences between projects.
- The generation of net benefits is restricted to candidate projects where high benefit crops are present in the vicinity of the Wastewater Treatment Plant.
- The regeneration plant initial investment and operation and maintenance costs represent the biggest portion of the overall costs.
- With the current cost structure, ultrafiltration technology is only competitive at very low interest rates.

Having such a prominence in the cost structure, further price cuts in the water regeneration technology will have a major impact in the availability of economically feasible projects.

Several aspects require further investigation to fully assess the effect of a water regeneration project. In inland locations, a negative externality is the reduction in circulating waters that may affect the depending ecosystems and downstream users. A positive externality is the reduction of the pressure on natural resources, although its quantification remains elusive and the regulation tools that manage the transition from natural to regenerated resources are yet to be developed. Finally, a better understanding of the effect of nutrients, heavy metals and conductivity of regenerated water on irrigated crops will help to define water management policies that combine all the resources available.

Funding

This work was supported by the Spanish Ministry of Science and Innovation, State Research Agency, as part of the National Plan for Scientific and Technical Research and Innovation 2017–2020. Project R&D&i - Challenges 2019: The contribution of water REuse to a resourCe-efficient and sustainabLe wAter manageMent for irrigatiOn (RECLAMO) [grant number PID2019-104340RA-I00].

CRediT authorship contribution statement

Antonio Bolinches: Conceptualization, Methodology, Writing - Original Draft. **Irene Blanco**: Writing - Original Draft, Review and Editing, Project administration, Funding acquisition. **Sergio Zubelzu**: Validation, Writing - Review and Editing. **Paloma Esteve**: Data Curation, Writing - Review and Editing. **Almudena Gómez-Ramos**: Validation, Writing - Review and Editing.

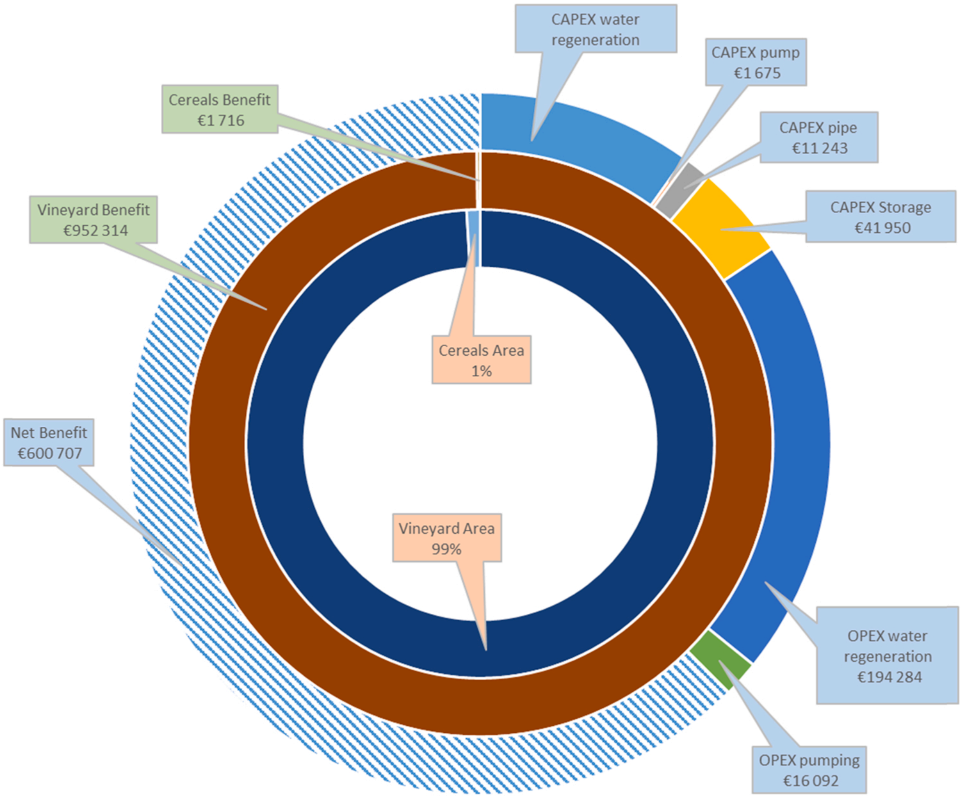
Declaration of Competing Interest

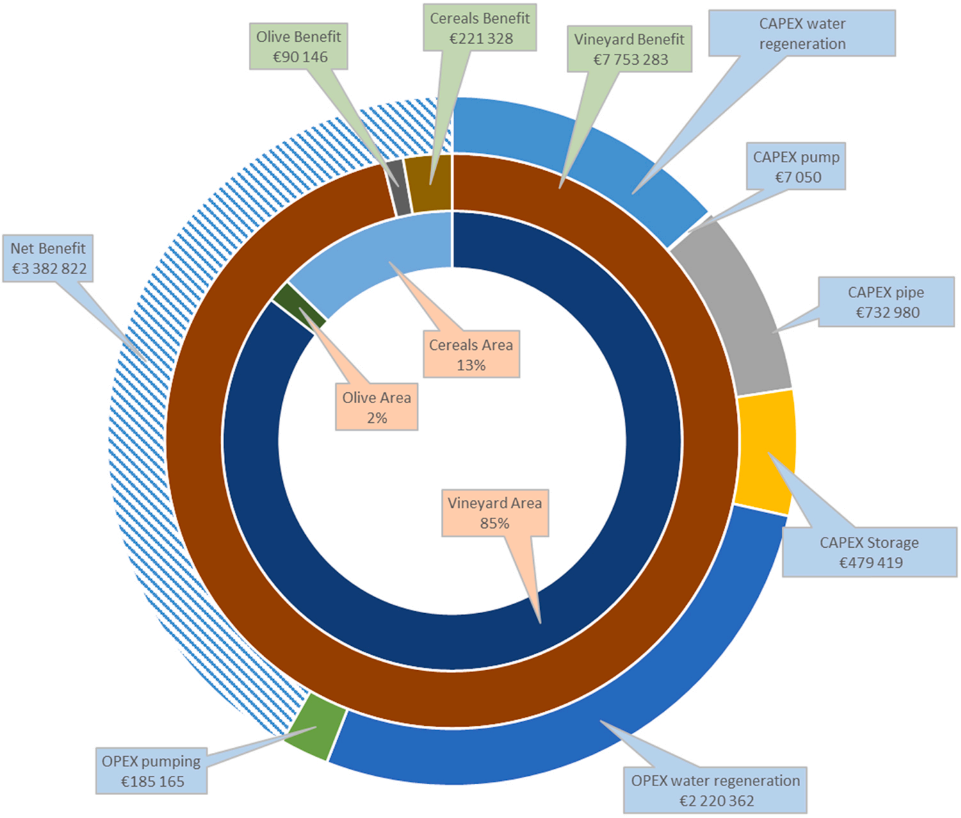
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors wish to acknowledge the support of Alberto Garrido, Augusto Arce, Raul Sánchez, Carlos Gregorio Hernández, and Javier Calatrava, for their valuable comments during the development of this paper.

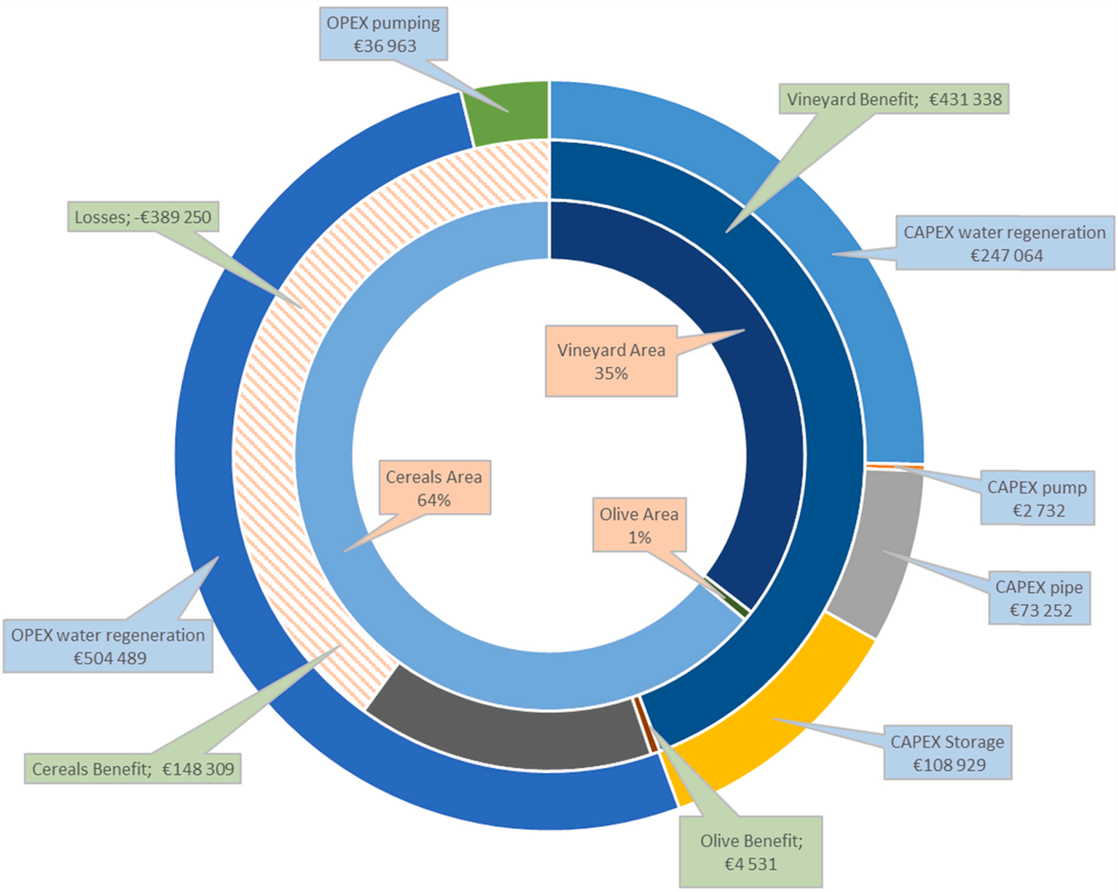
Appendix: Detailed results



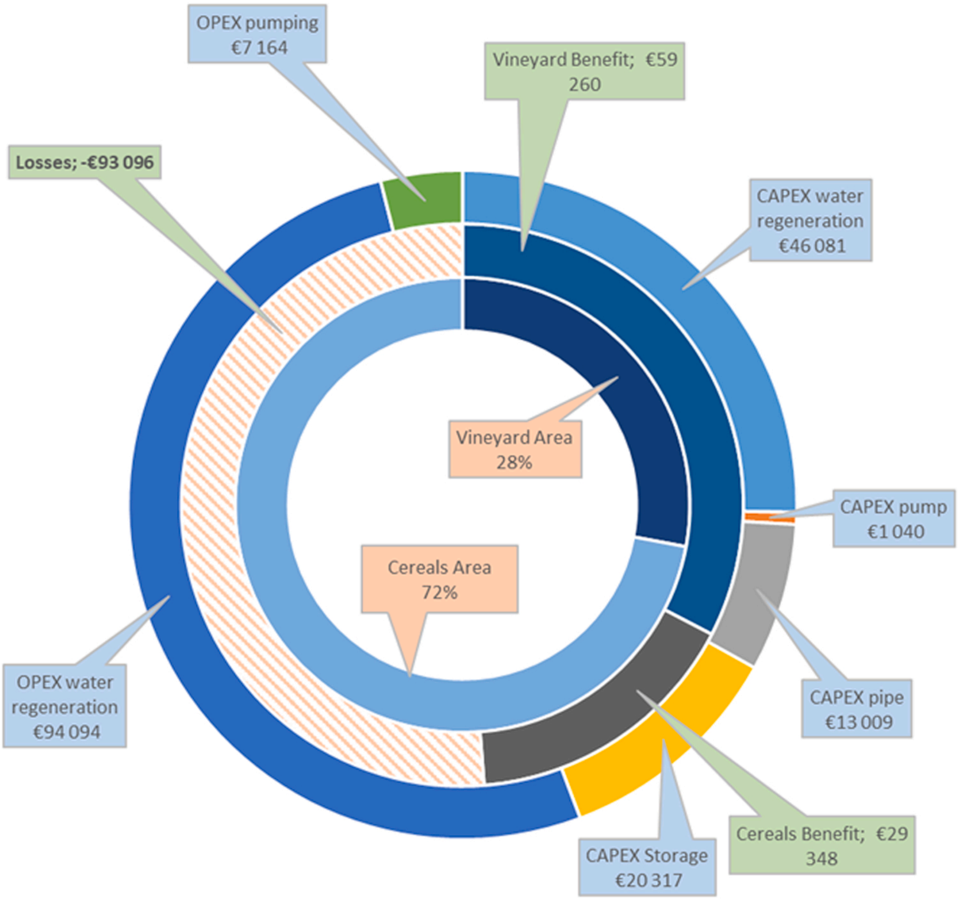


Socuéllamos

Alcázar


OPEX pumping €36 963
Vineyard Benefit; €431 338
CAPEX water regeneration €247 064
Losses; -€389 250
Vineyard Area 35%
Cereals Area 64%
Olive Area 1%
CAPEX pump €2 732
CAPEX pipe €73 252
OPEX water regeneration €504 489
CAPEX Storage €108 929
Cereals Benefit; €148 309
Olive Benefit; €4 531

Manzanares



Argamasilla

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