Optimization of multioutlet hydrant location and pressurized irrigation network layout using the GRASP metaheuristic

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Abstract

The cost-effectiveness of collective irrigation networks hinges on several factors, encompassing both construction and operational expenses. Optimizing these networks is crucial for the profitability of irrigation communities. Additionally, the placement of network elements on the irrigable surface significantly impacts future maintenance and repair costs. In conventional irrigation network sizing methods, only the optimization of pipe diameters is taken into account, leaving aside the rest of the factors. This study delves into the significance of factoring in the cost of multioutlet hydrants during network design and how their positioning affects the overall cost. Typically, the design phase overlooks this aspect, resulting in suboptimal placements that strain hydraulic capacity and neglect associated costs. To address this, the study proposes an optimization approach utilizing geographic information systems (GIS) and the greedy randomized adaptive search procedures (GRASP) algorithm. By determining the optimal location and number of multioutlet hydrants required, the methodology aims to enhance network efficiency, on the one hand, in hydraulic terms when considering the sizing of the multioutlet hydrant and in economic terms in reference to the cost of installation and subsequent maintenance. Comparative analysis with networks designed using conventional methods reveals significant improvements, with up to 31.1% more hydrants required and a 14.8% reduction in overall costs. By obtaining a greater number of multioutlet hydrants, both the diameter and the linear meters of connections to the plot to be drawn are considerably reduced, which greatly reduces land excavation. This underscores the importance of strategically siting multioutlet hydrants to minimize expenses associated with network elements like conduits and civil works. Ultimately, optimizing hydrant placement enhances service quality while simultaneously reducing operational costs, thus enhancing the sustainability of collective irrigation systems.

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Key words: GRASP; metaheuristic; multioutlet hydrant; optimization.

Contributions: all authors made a substantive intellectual contribution, read and approved the final version of the manuscript and agreed to be accountable for all aspects of the work.
Conflict of interest: the authors declare no competing interests, and all authors confirm accuracy.
Availability of data and materials: the datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Received: 13 November 2024.
Accepted: 22 July 2025.

Journal of Agricultural Engineering 2025; LVI:1633
doi:10.4081/jae.2025.1633

Introduction

Water management is one of the current topics in both public and private policies at local, national, and international levels (Palacios, 2024). In this context, studies focusing on the implementation of new technologies in irrigation management are of great importance for water sustainability policies and their infrastructures (United Nations, 2015). It is evident that the scarcity of water resources increases the need to optimize the available ones and the associated costs (Boopathi, 2024). According to works such as (Allan, 1999; Lecina *et al.*, 2010; Playán and Mateos, 2006), improving technical efficiency is an option that benefits the living conditions of sectors such as agriculture and industry. Currently, the trend in modernizing irrigation systems is to replace traditional gravity irrigation systems through channels or canals with pressurized conduits that carry water from the collection network (wells, channels, rivers, reservoirs, etc.) through a distribution network to consumption nodes or hydrants from which individual intakes extend to the base of each plot (Chen *et al.*, 2022; Gurung *et al.*, 2015). This provides pressurized water at the plot base, allowing for localized irrigation. It is worth noting that this current trend in modernizing irrigation cannot be understood without the use and application of information and communication technologies (ICT) both in the design and operational phases (Bonet *et al.*, 2010; González Villa and Garcia Prats, 2011; Jímenez-Bello *et al.*, 2015), just as the modernization of irrigation cannot be understood without the use of renewable energies (Almarshoud, 2024; Elnozahy *et al.*, 2024) which ensure high efficiency in water and energy use, thus increasing the profitability of the network itself and crops (Prieto *et al.*, 2015; Tariq *et al.*, 2021), and meeting the Sustainable Development Goals SDG6 "Clean Water and Sanitation" and SDG7 "Affordable and Clean Energy" of the 2030 Agenda, which must ensure the availability of water and its sustainable management and sanitation for all (Cepal, 2019), as well as access to affordable, safe, sustainable, and modern energy (Tabieres, 2018).

For a correct design of irrigation systems, methodologies ensuring both high water and energy efficiency and minimum installation and operation costs (Horst, 1998) must be used. Additionally, networks must be designed in such a way that they meet minimum technical requirements such as functionality, service capacity, durability (Farshad, 2011), and accessibility (Prats and Picó, 2007) to facilitate tasks during the operational phase. These types of irrigation networks, almost entirely branched, are dimensioned using technical-financial optimization techniques aiming to minimize a cost function that encompasses installation fixed costs, such as pipes, multioutlet hydrants, plot intakes, etc., and operating costs (Arviza-Valverde, 2017) such as energy or maintenance-related costs or only operating costs (Lapo *et al.*, 2020), but not all participating costs are always considered, leading to networks with higher costs than strictly necessary which implies a problem in ensuring the profitability of the works if all the associated costs are not considered (Alandí *et al.*, 2007; Fan *et al.*, 2024).

In the Mediterranean framework where the productive model is based on intensive agriculture of small and medium-sized plots (average areas not exceeding 0.5 ha), the water distribution system from the network to the plot is usually carried out through multioutlet hydrants. These can be classified according to different criteria, among which stand out: by the number of outlets, by their function, by their dimensions, or nominal pressure. These classifications are based on the UNE-EN 14267 Standard, Irrigation techniques - Irrigation hydrants.

The design of the distribution network must have a prior recognition of the terrain where the layout of the network and the location of hydrants are defined, which, on numerous occasions, is carried out without any technical criteria or even knowledge or study of the irrigable area (García Prats, 2005). Incorrect placement of these hydrants can generate excessive lengths of intakes to the plot or leave them in inaccessible locations (González Pavón, 2023) with the numerous future problems it may bring such as deficient pressures or excessive head losses (González-Pavón *et al.*, 2020). Furthermore, in areas where the plots are small, the number of multioutlet hydrants to be obtained is high, so it is advisable to take this into consideration in the design and consider their costs.

Faced with this problem in the design phase, there is no single solution to the distribution of hydrants over an irrigable area. Finding a location and assignment of plots to them involves conducting complex spatial analyses, and the problem is not currently solved. While there are works such as (González Villa and Garcia Prats, 2011) where location-allocation criteria are proposed for this specific case of hydrants applying geographic information systems (GIS).

The problem to be solved resembles the P-median problem. It is a basic model in discrete location theory. The first studies date back to 1964 and 1965 with the work of Hakimi for locating switching centers and police stations (Hakimi, 1965). The main objective of the problem is to locate P facilities so that the sum of weighted distances or transportation costs between demand nodes and facilities (medians) is minimized.

In this study, the assignment of plots to multioutlet hydrants is studied through a cost minimization function where potential locations of the latter are considered. Starting from a large number of potential locations, the algorithm assigns plots to hydrants and evaluates the cost of each solution. Afterward, it begins to make changes in the assignment, assessing whether the changes reduce the overall cost of the pressurized irrigation network. Finally, it stops when it finds a solution of minimum cost.

Since these are problems of high complexity, the optimization process will be addressed using the GRASP metaheuristic (Feo and Resende, 1995). The method is a multi-start procedure where each pass consists of a construction phase and an improvement phase. In the construction phase, a heuristic procedure is applied to obtain an initial solution with good results. Metaheuristics have been used in a multitude of investigations on optimization processes in irrigation engineering (Akbari *et al.*, 2018; Chetty and Adewumi, 2013; Niu *et al.*, 2023; Yan *et al.*, 2023) but there is no bibliography that addresses the problem of multioutlet hydrants.

Therefore, through this study, a methodology based on a cost function will be developed to obtain objective criteria on where to locate multioutlet hydrants in a distribution network and which plots should be assigned to them. The objective is to minimize the cost function by performing different iterations seeking a correct solution among those evaluated from the application of the greedy randomized adaptative search procedures (GRASP) metaheuristic method. Metaheuristics are designed to efficiently explore solution spaces, allowing for searching in promising regions and avoiding getting trapped in local optima. This is crucial for complex problems with multiple local optima. GRASP has proven effective in solving complex problems for which finding the optimal solution is difficult or impracticable within a reasonable time. Its combination of local search and solution construction provides a balance between exploration and exploitation (MirHassani and Jalaeian Bashirzadeh, 2015). The application of these methods in recent years for the optimization of different processes or algorithms is applied from the most theoretical fields for solving complex mathematical problems (Vahedinori *et al.*, 2011), railway track layout (García-Archilla *et al.*, 2011), urban transport route design (Laporte *et al.*, 2011; Marín and Jaramillo, 2009) as well as in current issues such as artificial intelligence, operational research (Pérez *et al.*, 2023) and cost optimization (Antunes *et al.*, 2014; López-Sánchez *et al.*, 2019; López􀀀Sánchez *et al.*, 2018; Ronconi and Manguino, 2022).

Objective

The main objective of the study is to obtain a multioutlet hydrant location solution and plot allocation that minimizes total installation costs while ensuring predetermined hydraulic operating conditions. To achieve this, given the high complexity of the problems, it will be approached using the GRASP metaheuristic (Feo and Resende, 1995). The method is a multi-start procedure where each pass consists of a construction phase and an improvement phase. In the construction phase, a constructive heuristic procedure is applied to obtain an initial solution with good results. Furthermore, by considering the sizing of multioutlet hydrants, the operating conditions of these elements are improved.

The final costs are compared with networks sized by technicians with extensive experience in the field, and conclusions are drawn regarding how the number and location of hydrants affect the different costs of the distribution network.

Materials and Methods

The methodology obtains, using GRASP, possible solutions to the problem of multioutlet hydrant location and plot allocation in pressurized irrigation networks. Starting from an initial cloud of multioutlet hydrants and irrigable plots to be supplied, the algorithm, following the necessary technical criteria, optimizes the process by selecting the best solutions in each case, resulting in a final solution where the overall cost is minimized.

The entire process is carried out using QGIS 3.X software. A calculation process programmed in Python language is proposed within it, where solutions for multioutlet hydrant locations and plot allocation will be obtained. This software is used in the design of pressurized irrigation networks (Khasan *et al.*, 2020) as well as for modeling due to the existence of plugins that facilitate this task (Martínez Alzamora *et al.*, 2019; Nibi *et al.*, 2022). In Figure 1 a flow chart illustrates the methodology applied and the previous studies carried out.

The complementary study used in this case is the work by (González-Pavón *et al.*, 2024) which evaluates layout resistances for different types of roads in order to improve optimization.

Case studies

The validation of the proposed methodology has been carried out on twelve case studies. These are located in different municipalities in the Valencian Community, Spain. They are areas where all crops are citrus fruits. The case studies include irrigable areas ranging from 119.08 ha to 180.83 ha. They have an average plot size ranging from 0.25 to 1.25 ha per plot. Multioutlet hydrants, the main element of this research, are usually used in irrigation areas with small plot surfaces. This is why these case studies have been selected, as the study is intended to be reproducible in areas of similar sizes and aims to optimize the costs of a collective distribution network. On the other hand, the initial data taken for the twelve case studies are shown in the Table 1. In all cases, the predominant crop is citrus fruits of different varieties, with an average consump-

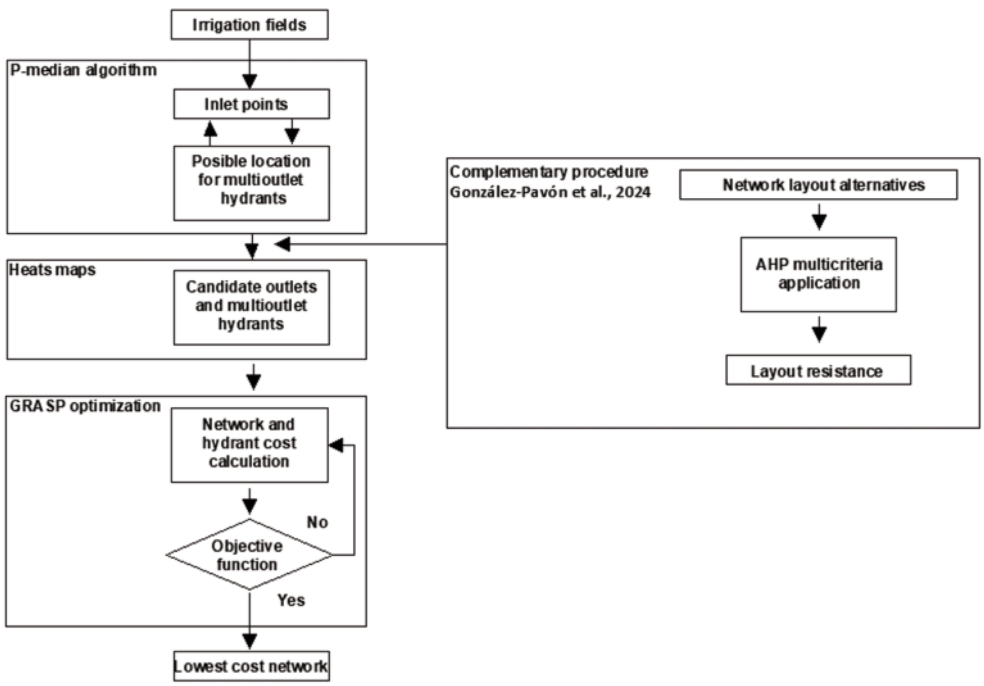

Figure 1. Methodology flow chart.

Table 1. Case studies.

Case	Irrigated area (ha)	Number of plots	Cost of the irrigation network (€/ha)
Enguera_1	119.52	253	5,482.86
Enguera_2	126.58	270	4,606.92
Llíria_1	119.76	149	4,108.69
Llíria_2	180.83	261	6,084.81
Palmeral_1	116.80	227	5,855.84
Palmeral_2	148.76	148	4,973.24
Picassent_1	120.61	153	5,715.03
Picassent_2	131.33	172	5,529.16
Picassent_3	120.32	252	6,775.83
Picassent_4	120.02	163	5,772.43
Sellent_1	119.08	256	5,834.38
Sellent_2	140.70	169	4,651.28

tion flow rate parameter of 4.0 L/s·ha^{-1}. The cost data correspond to the cost of the network as designed using conventional methods (without applying the proposed method) by qualified engineers. Cost data were provided by the network manager.

Formulation as a P-median problem

In a network N composed of a finite set of vertices, the vertices represent two distinct elements: on one hand, the potential and randomly distributed locations of multioutlet hydrants, denoted as I = {1, 2,…, n}, and on the other hand, the known, fixed locations of the agricultural plots that need to be supplied, denoted as J = {1, 2,…, m}. Each hydrant location n_i from set I and each plot point m_j from set J are connected through a set of edges E. These edges represent the physical connections that can be established along existing paths, roads, or property boundaries, which are the feasible corridors for laying the pipeline network.

Each edge in E is associated with a resistance value h_k, which varies depending on the type of surface or infrastructure (*e.g.*, dirt path, paved road, field boundary) it follows, as well as its length. These resistance values influence the optimization of the network layout, as they reflect both physical and economic constraints.

Furthermore, each tap associated with a plot mi is linked to a specific water demand q_i, which represents the flow rate required to adequately supply that plot. In summary: n_i refers to multioutlet hydrant i, m_j corresponds to plot j to be supplied, h_k is the resistance associated with road or path k, and q_j is the flow demand of plot j.

Multioutlet hydrant location methodology

At this point, the methodology for locating multioutlet hydrants on an irrigable surface using GIS is established. This methodology allows obtaining an initial cloud of hydrants located in specific areas of the irrigable surface and subsequently, using the described optimization method, retaining those that result in the lowest overall cost. By using GIS and establishing initial criteria, it is possible to obtain the initial cloud of candidate hydrants and discard those locations that cannot be part of the final solution.

Hydrant typology

For this point, where the maximum and minimum number of hydrants that an irrigable surface should have defined, it starts with a multioutlet type hydrant. All hydrants must comply with Standard UNE-EN 14267, Irrigation techniques - Irrigation hydrants. There are not many defined examples in the consulted bibliography, so it is decided to use the Costella device for this study (Balbastre-Peralta *et al.*, 2021). For the calculations to be performed, we start from its capacity data and available typologies.

This type of hydrants is characterized because the main collector remains in a vertical position while the intakes and the rest of hydraulic equipment remain in a horizontal position. The collector is fed from the midpoint. The entrance is taken through the midpoint of the main collector in a vertical position. The collector remains in a vertical position where the individual intakes are inserted horizontally, with the meters also placed horizontally, which is their correct position (Palau *et al.*, 2019). Figure 2 shows a Costella type multioutlet hydrant, where each element is:

1. Cut-off valve at the entrance of the main collector.
2. Main collector with up to 10 intakes per plot.
3. Measurement and regulation elements in each plot intake.
4. Air valve.
5. Outlet to each plot.

Maximum and minimum number of hydrants

Knowing the type of hydrant to be used, the average parameters representing the irrigated surface should be known, such as the average flow per plot (Q_p) and the number of plots (N_p). From the selected hydrant type, it is known that the maximum number of intakes it can accommodate is 10 (Balbastre-Peralta *et al.*, 2021). Therefore, the minimum number of hydrants (NH_{min}) for a given irrigable surface would be obtained as follows:

$$NH_{min} = max\left[\frac{Q_t}{QNB_{max}}, \frac{Q_t}{QNB_{red}}\right] \quad \text{(Eq. 1)}$$

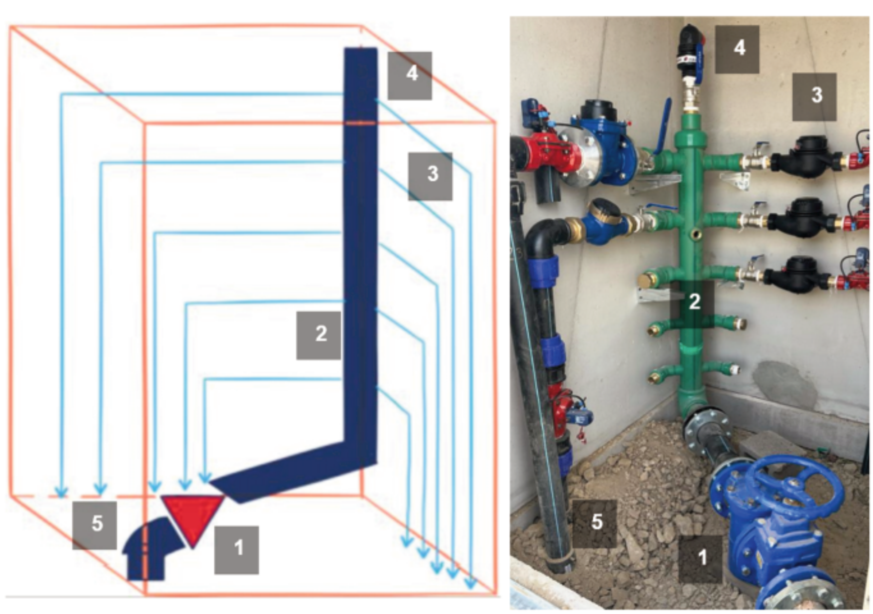

Figure 2. Morphology (left) and image of Costella-type hydrant (from Balbastre Peralta, 2016; with permission).

where: Q_t, total flow demanded by the irrigable surface (L/s); QNB_{max}, maximum flow of the selected hydrant type (L/s); QNB_{red}, Mmaximum flow demanded by a hydrant with 10 intakes with average surface (L/s).

On the other hand, the maximum number of hydrants (NH_{max}) to be installed must be obtained. The calculation procedure is identical to the previous case, but taking hydrant typologies of lower capacity and reducing the number of intakes per hydrant. According to consulted bibliography, in irrigation networks the average minimum number of intakes per hydrant is 4 units as indicated (Guillem Picó, 2000).

In the present study, for obtaining the minimum number, a DN 150 mm hydrant with 10 intakes (Balbastre Peralta, 2016) has been taken as the hydrant type, while for obtaining the maximum number, a DN 100 hydrant with 4 intakes (Guillem Picó, 2000) has been taken as the hydrant type.

Taking more extreme values could lead to solutions with an excess or deficit of candidate hydrants, which could result in extremely long calculation processes or undervalued results.

Initial number of candidate hydrants

With the values obtained from NH_{min} and NH_{max}, it is time to obtain the number of candidate hydrants (NHC) that will go through the optimization process using the GRASP metaheuristic.

To avoid excessive accumulation of points in some areas, an equidistant sampling will be carried out following the following criteria:

1. The distance between definitive hydrants will never be greater than the maximum length of intake established. The maximum intake length is defined with the objective of reducing the distances between hydrants and irrigable plots and corresponds to the maximum permitted distance between a hydrant and an irrigable plot. In the case of finding hydrants with greater separation, it could happen that an intake could not be assigned to any hydrant. In addition, those paths or routes through which it is desired to trace the conduits and locate the multioutlet hydrants must be defined. These routes must be easily accessible both for the execution phase and for the operation phase of the irrigation network. Therefore, the minimum number of candidate hydrants will be the relationship between the total length of available paths and the maximum intake distance, as follows:

$$NHC_{min,d} = ENT\left[\frac{L_{path}}{L_{max}}\right] \quad \text{(Eq. 2)}$$

2. The number of candidate hydrants will never be less than the maximum established previously in the calculation for flows (NH_{max}). Therefore:

$$NHC_{min,d} \geq NH_{max} \quad \text{(Eq. 3)}$$

In order to obtain a cloud of points where there are more possibilities of assignment and where a greater number of candidate locations are represented, the maximum value of the two previous ones will be duplicated, resulting in:

$$NHC_{min} = 2 \cdot \max\left[NH_{min} \quad NHC_{min,d}\right] \quad \text{(Eq. 4)}$$

Therefore, the distance between candidate hydrants will be:

$$L_{HC} = \frac{L_{path}}{NHC_{min}} \quad \text{(Eq. 5)}$$

where: $NHC_{min,d}$, minimum number of candidate hydrants due to distance criteria; L_{path}, total length of available paths (m); L_{max}. intake, maximum intake length established (m). It is important that the candidate cloud be as homogeneous as possible, since the needs of each hydrant are not known as they depend on the demands of each plot, hence the equidistant generation of these is a good solution (Hanson and Seeger, 2017). As an example of the result obtained and integrated into a GIS, one of the cases studied is presented in Figure 3. As can be seen, through a simple calcula-

Figure 3. Equidistant candidate hydrants on irrigable surface.

tion process with average values, a reliable interval can be obtained where the final number of hydrants that optimizes the cost of the network will be found. The algorithm generates a cloud of equidistant points in each line. As can be seen, between perpendicular lines it generates points closer together because they do not belong to the same path or route.

Final number of candidate hydrants

The generation of equidistant hydrants along roads or pathways can result in elements that are far from the irrigation zone and would never be part of the final solution. Therefore, prior to the start of the optimization process, those with the lowest probability of being definitive will be eliminated. Removing those that could never belong to the final solution will expedite the optimization process and reduce the amount of data to be processed. By using heat maps, the population density (connections in our case) of an area can be obtained based on a parameter. Heat maps are widely used to understand the density and spatial distribution of the population in large geographical areas (Pokojski *et al.*, 2021; Sharma *et al.*, 2020). If we create one over the study area, knowing the locations of the connections within an influence distance of 125 m, we obtain the following result. This value was previously estimated based on the distance between plots and hydrants for these case studies.

In Figure 4, the red lines indicate that there is at least one connection located within 125 m from the end, so in that area, there must be at least one multioutlet hydrant. The blue areas indicate that there are no points that need to be supplied. Thus, the candidate hydrants reflected in red would be excluded in this preliminary screening, while the green ones would move to the definitive list of candidate hydrants (NHC_{def}).

Figure 5 shows the process of obtaining the candidate hydrants that will go to the optimization process.

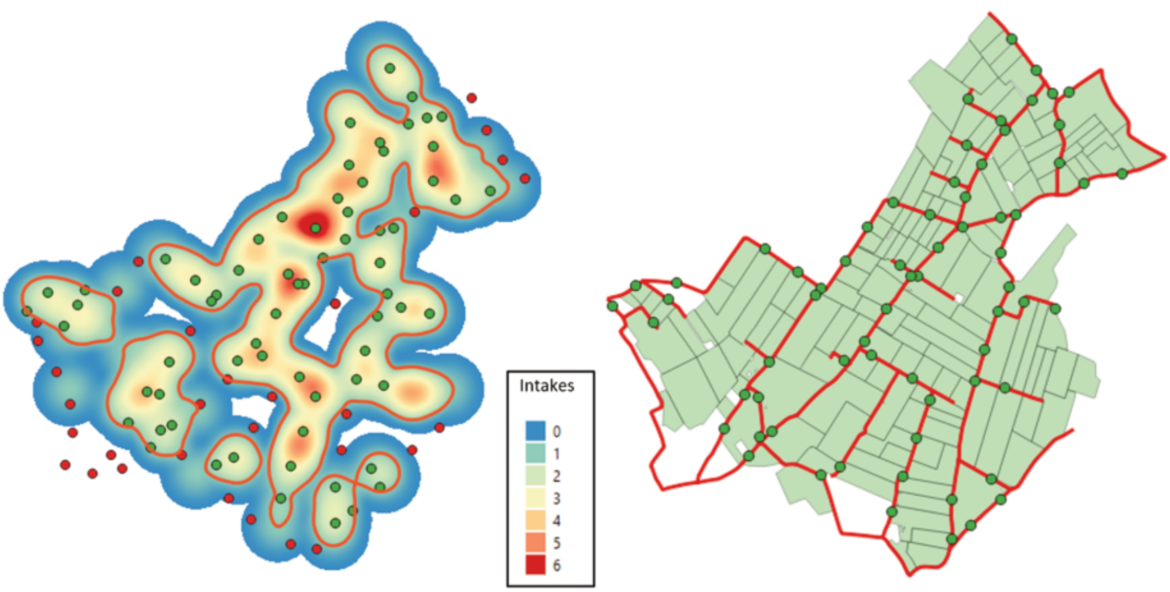

Figure 4. Candidate hydrants on heat map (left) and hydrants for processing in GRASP.

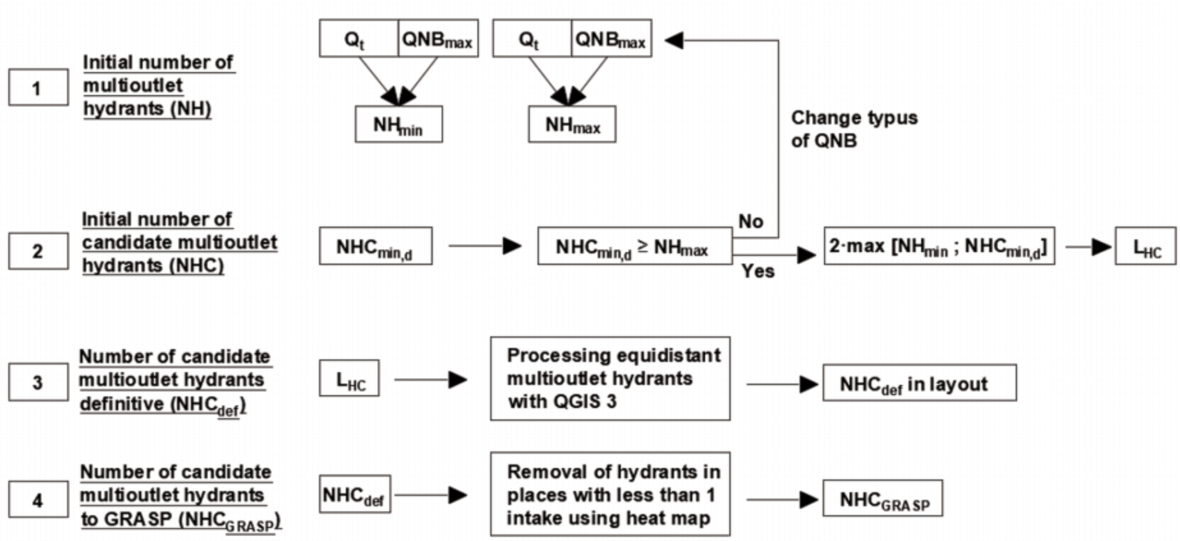

Figure 5. Obtaining process of the number of candidate hydrants for GRASP

Cost of an irrigation network

The main costs that are evaluated to obtain the most economical network applying the proposed methodology are those derived from the tertiary network, which includes plot intakes and multioutlet hydrants, and those derived from the distribution network that mainly include the installation of pipes.

In both the tertiary network and the distribution network, the costs derived from the installation of pipes take into account the excavation, sand bed and covering of the trench as well as the labor costs of installing the pipe. In addition, the replacement costs of materials for the roads and tracks along which they are laid are considered.

As for multioutlet hydrants, the costs of the type of main collector, its shut-off and protection valves, as well as the house where they are introduced are considered.

All these costs are reflected both in the sizing of the networks applying the methodology and, in the sizing, carried out by engineers where the proposed methodology is not applied.

All these costs are variable depending on the dimensioning obtained from the network. Fixed costs such as meters or solenoid valves on the plot are not considered.

GRASP methodology

With NHC_{def}, it is possible to start the optimization process. It consists of obtaining a solution with the number of hydrants and plots assigned to them that minimizes the installation cost. In the initial phase, a possible solution is iteratively constructed, considering one element at a time. In each iteration, the choice of the next element to be added to the partial solution is given by a greedy function. This function considers and evaluates the benefit of adding each of the elements according to the objective function and selects the best one. Remember that this algorithm is myopic, meaning it only considers what will happen in the current iteration, not in successive iterations.

It is known that the greedy heuristic is adaptive, meaning that in each iteration, the benefits obtained by adding the selected element to the partial solution are updated. This implies that the evaluation of adding a certain element to the solution in iteration j may not necessarily coincide with that in iteration j+1.

On the other hand, the heuristic is randomized because it does not select the best candidate according to the adapted greedy function, but, in order to diversify and not repeat solutions in two different constructions, a list is created with the candidates with the best results from which one is randomly chosen. Since the initial phase does not guarantee local optimality with respect to the neighborhood structure being worked on, a local search procedure is applied as a post-processing step to improve the initial solution obtained.

In each iteration of this phase, the choice of the next element to be part of the solution is determined by creating a candidate list (LC) with all the elements that can be part of the solution in this iteration. These elements are ordered according to the greedy function that measures the benefit associated with each of them, thus creating a restricted candidate list (LRC). This list contains those elements whose values of the greedy function are more beneficial from the optimization criterion's point of view. Once the list is completed, one element is randomly selected from it, which automatically becomes part of the initial solution.

A pseudocode for the construction phase can be illustrated as:

```
Procedure construction phase (α)
        E <– Read Data () // Reading problem data.
        S0 = ø // Initializing the initial solution.
        For each element in E // Cost function for each problem element.
                E (element) <– fe (element)
        End for
        i = 1
        While E ≠ ø
                LRC <– Create LRC (E) // Randomly
                select an element from LRC
                e <– Random from LRC () // Add
                element to the initial solution.
                So [i] <– e // Remove element e from the
                set of elements.
                E –> Remove (e)
                For each element in E
                        E (element) <– fc (element)
                End for
                i = i + 1
        End while
        Return S0 // Get the initial solution.
End Procedure
```

The construction stage aims to generate initial solutions with a controlled degree of diversity in order to explore different areas of the solution space. However, these solutions must be treated with a local search algorithm, which typically improves the found solution (Glover and Kochenberger, 2006). This is the second stage of GRASP.

In a local search algorithm, a partial modification called a move (Britto-Agudelo *et al.*, 2007) is iteratively applied to an initial solution to find new alternative solutions. The algorithm stops when the solution cannot be further improved. One factor affecting the efficiency of a local search algorithm is the size of the neighborhood. If many neighbors are considered, the process can be very costly. This is affirmed if the search takes many steps to reach a local optimum and/or each evaluation of the objective function requires a significant amount of computation (Voudouris *et al.*, 2010). The pseudocode for the improvement phase can be illustrated as:

```
Procedure local search phase (So)
        SK <– S0 // SK represents the current solution.
        i = 1
        While i < |S0|
                SC <– SK // Swap element i with element j.
                SC –> Swap (i,j)
                OC = Objective function (SC)
                OK = Objective function (SK)
                If OC < OK THEN // Update current solution.
                        SK <– SC
                End If
                j = j + 1
        End While
        Return SK // Get the improved solution
End Procedure
```

Finally, with the integration of the two phases, the pseudocode of the GRASP metaheuristic is completed as shown below:

```
GRASP procedure (iterations, α)
        SK = ∞
        i = 1
        WHILE i ≤ iterations
```

S_o <– Constructive Phase (α)
S_C <– Local Search Phase (S_o)
O_C = Objective Function (S_C)
O_K = Objective Function (S_K)
IF $O_C < O_K$ THEN
S_K <– S_C // Update current solution
END IF
i = i + 1
END WHILE
RETURN S_K // Final solution.
END PROCEDURE

For this case, the biggest limitation that GRASP may have is that it is a heuristic-based algorithm, it does not guarantee to find the global optimal solution. In some cases, it may get stuck in sub-optimal local solutions if the search space is irregular or has many local minima.

Application of iterations on a GIS

The constructive phase of GRASP applied to the case study consists of the progressive assignment of intakes to different candidate hydrants until all of them have been assigned. Throughout each assignment to a hydrant, the assignment constraints are:

- The same intake cannot be assigned to two different hydrants.
- The intake cost must be the lowest from the list of all possible intakes for each plot.
- The intake length must not exceed 250 m.
- The maximum positive gradient plot - hydrant must be 10 m.
- No more than 10 intakes can be assigned per multioutlet hydrant.

In this phase, each intake is assigned to the nearest hydrant, *i.e.*, the one with the minimum intake tracing cost. It may happen that during this process, more than 10 intakes are attempted to be assigned to a hydrant. To prevent this from happening, a condition is introduced where:

- The costs of all intakes assigned to the hydrant with more than 10 intakes are evaluated.
- All necessary intakes are reassigned until the hydrant has a maximum of 10 intakes.
- The reassignment order is by costs, reassigning first those with the highest cost, *i.e.*, the farthest ones.

Finally, from the initial hydrants (NHC_{def}), some will have no intake assigned in the initial solution (S1). Those with at least one will be added to the restricted candidate list (LRC) formed by a list of the best candidates susceptible to being introduced, and will move on to the improvement phase to obtain a more optimized result, if possible (in Solution 2 and subsequent ones).

After completing this phase, there will be hydrants with only one assigned intake and hydrants where no more intakes can be assigned, having reached the limit of 10. As a general rule, in this first solution, S1, a large number of hydrants that supply intakes of shorter length will be obtained, and therefore, with a low number of intakes assigned to each of them as seen in Figure 6.

In summary, the objective in the following phases (S2, S3...Sn) is to reassign intakes to plots to complete the hydrants' capacity and, consequently, reduce their number.

The code introduced to assign intakes to candidate hydrants is as follows. It is introduced in the algorithm called "Solution 1". The Python code introduced through the PyQGIS library is attached.

```
CASE
WHEN
"fid" =array_first (array_agg( "fid", group_by:= "ID_T_max" ,filter:= "Coste tub" =minimum( "Coste tub" ,group_by:= "ID_T_max"))).
THEN 1
ELSE 0
END
```

The improvement phase takes as starting data the initial solution (S1, Figure 7a). At this point, the goal is to reassign plots of hydrants with a low number of intakes to those that are still capable

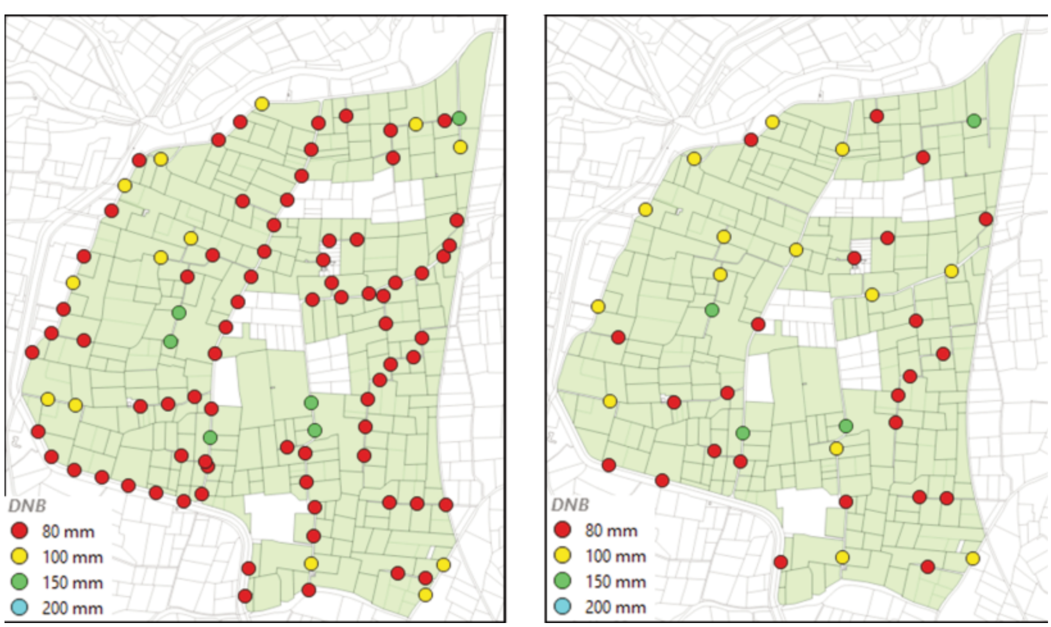

Figure 6. Difference in the number of hydrants between initial (left) and final (right) solutions for each type of DN.

of supplying more than they contain, both in number and flow rate. This improvement phase is carried out until the solution does not improve in terms of the objective function. The mathematical process followed is explained in the pseudocode of point 3.5.

This reassignment will lead to an increase in the cost associated with the intake (as its length and possibly its diameter will increase) but it allows for a greater concentration of intakes, reducing the installation cost of the multioutlet hydrant, as one of them is completely eliminated. It is also true that by increasing the flow demanded by a hydrant with more plots, the cost of some of its elements also increases, but not all of them, so in the end, an improvement in the overall result is achieved in each iteration as they are not linear costs. Each of the iterations carried out is described in the following points.

In solution two (S2), the aim is to reduce the overall cost of the tertiary network by leaving all hydrants with a minimum of two intakes. With this, as far as possible, all hydrants with only one intake disappear, and these are reassigned to the next candidate hydrant that represents the lowest cost.

The iterative process followed by the optimization method in one of the studied irrigable areas is shown in Figure 7. It starts from the initial solution (S1, Figure 7a) until the end of the optimization process in the successive iterations. In S2, corresponding to Figure 7b, the algorithm eliminates all hydrants supplying fewer than 2 plots. In this case, they are H-126 and H-127. It prioritizes the elimination of the hydrants farthest from the initial point of the distribution network, in this case, H-127, so it reassigns intake 132 to H-126. This change, while minimally increasing the cost of the intakes, considerably reduces the cost of the multioutlet hydrants by eliminating them completely. For the next iteration, S3 corresponding to Figure 7c, the starting point is the result of S2. Once again, the goal is to reduce the overall cost of the tertiary network, this time by reassigning intakes belonging to hydrants with 2 or fewer assigned intakes. Now, as far as possible, none should have fewer than 3 intakes. It is observed how the intakes of H-122 have been reassigned to H-123. In this case, the algorithm has searched for the option with the lowest cost for each intake, reassigning it to the corresponding hydrant and eliminating H-122. Continuing with the iterations, the starting point is the previous S3. Now, as far as possible, none should have fewer than 4 intakes. In this case, hydrant H-123 supplied 4 intakes, which have been reassigned to H-121 and H-124. The algorithm has searched, for each intake, for the option of the lowest cost and eliminated H-123. Now H-121 supplies 6 intakes and H-124 supplies 7 intakes, as can be seen in Figure 7d.

In Figure 8, it can be observed how as the iterations progress and the intakes are grouped into hydrants, the cost associated with the tertiary network is reduced until a point is reached where it increases again, where the algorithm stops giving the best result it is able to obta

Results

Number of hydrants

From each case study, the total number of multioutlet hydrants required has been obtained, both in the method application and in the conventional design. At this point, the relationships obtained with the characteristics of each network are exposed. On one hand, the values of hydrants necessary per hectare are presented, comparing the result applying the method and the result with conventional methodology. To verify if the differences are significant, an

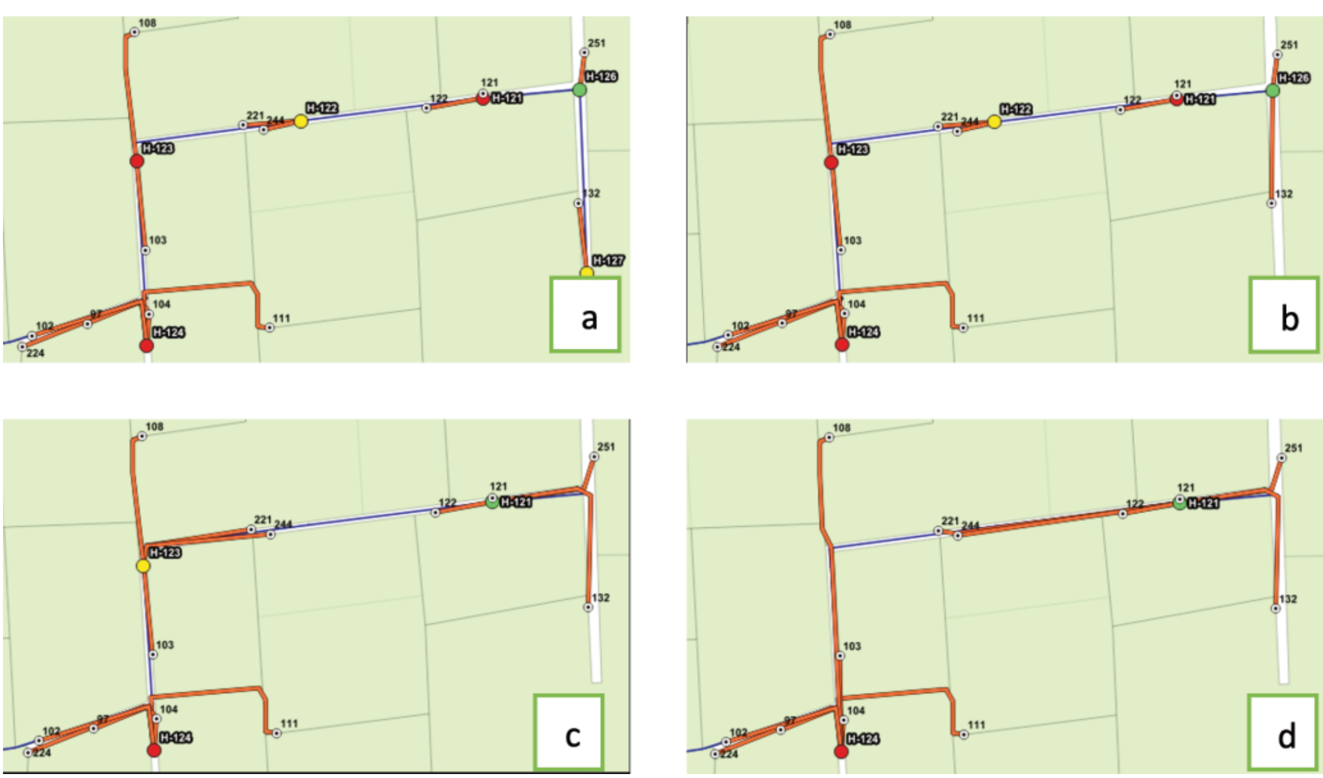

Figure 7. Example of hydrants and intakes in S1 (**a**), S2 (**b**), S3 (**c**) and S4 (**d**).

ANOVA with one factor was performed, obtaining a p-value of 0.01, concluding that the observed differences are statistically significant.

Figure 9 shows how, in all studied cases, a greater number of hydrants is required when applying the method compared to the results with standard design. The highest detected difference is 0.13 hydrants/ha compared to the lowest of 0.02 hydrants/ha. Therefore, it is evident that applying the method implies obtaining a higher number of hydrants versus a decrease in total costs. On average, 31.1 % more multioutlet hydrants are required using the GRASP methodology.

On the other hand, Figure 10 shows the average number of plots supplied by each multioutlet hydrant.

Continuing with the previous trend, a greater number of plots assigned to each multioutlet hydrant is detected in all results with conventional methodology compared to the application of the method. This highlights the trend in these types of projects to complete the hydrant intake capacity with the aim of installing the fewest possible number of hydrants where it is stated that each multioutlet hydrant must supply between 4 and 12 outlets (Guillem Picó, 2000) or multioutlet hydrants that supply only up to 4 outlets (Labye *et al.*, 1988).

The average number intakes per hydrants to be installed using the methodology is 5.8, whereas for cases with conventional methodology it is 7.7, meaning that on average, 33 % fewer hydrants are installed. On average, the hydrants supply 32.5 % fewer plots using GRASP than conventional allocation methods.

Furthermore, the methodology for obtaining the maximum and minimum number of hydrants required for each irrigable area was previously explained. At this point, it is checked if the final result obtained falls within the defined interval initially.

As seen in Figure 11, the lowest-cost network for all cases contains a number of multioutlet hydrants between the maximum and minimum initially established, validating the method used, which means that the initial data considered to obtain the maximum and minimum number of hydrants are correct. Additionally, obtaining the maximum and minimum numbers initially can serve as a simple methodology to obtain a preliminary sizing of the pressure irrigation network.

Utilization of multioutlet hydrants

To define the capacity of the multioutlet hydrant, data on maximum flows and maximum number of intakes for the Costella-type hydrant were considered. In each simulation, the flow carried by each hydrant was defined, and thus, the utilization percentage was obtained, being the ratio between the carried flow and the maximum flow it can carry. It should be noted that with another type of multioutlet hydrant the result would be identical. Less utilization of the maximum capacity of the multi-user hydrant is beneficial to improve its hydraulic parameters and reduce the overall cost as demonstrated in the following points.

As seen in figure 12, in almost all hydrants with GRASP sizing, a lower utilization is obtained. However, this lower hydraulic utilization also brings a considerable decrease in costs both in the tertiary network (from the multioutlet hydrant to the plot) in particular and in the overall cost. On average, a utilization of 62.2% using GRASP and 68.5% for conventional methodology was obtained.

The final location of the multioutlet hydrants and the assignment of intakes to each of them have a direct influence on the tertiary network. The length of the tertiary network from each hydrant to the plots is determined by the hydrant's location, while the diameter depends on the number of plots supplied. The average intake lengths were obtained for each case study using both the GRASP method and conventional methodology.

In all cases, a shorter average intake length is achieved with GRASP, implying that for the same hydraulic design criteria, the associated cost is lower. This is the main reason why installing a

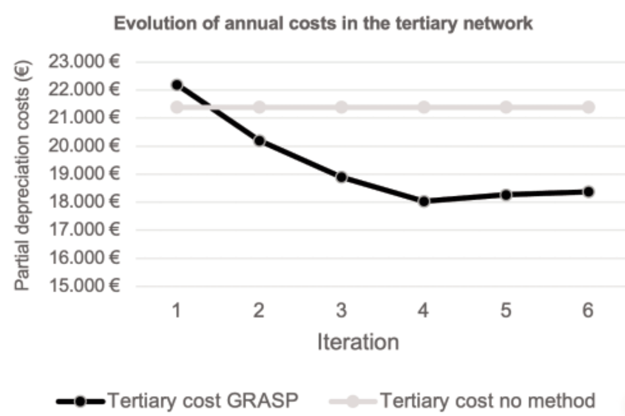

Figure 8. Evolution of annual costs in the tertiary network.

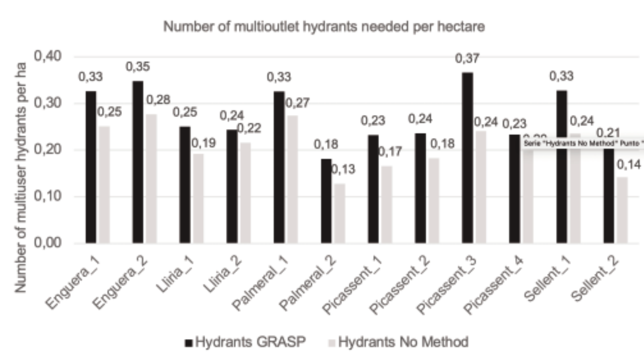

Figure 9. Number of multioutlet hydrants needed per hectare applying the method and without application.

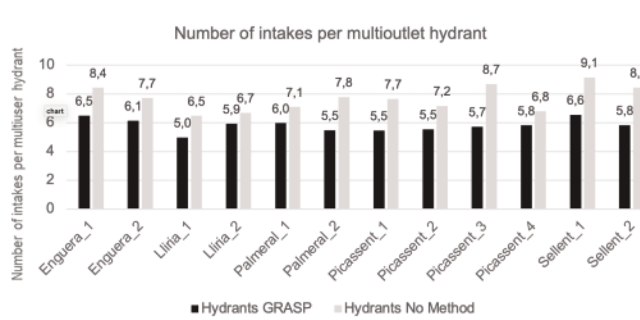

Figure 10. Average number of plots per multioutlet hydrant applying the method and without application.

greater number of multioutlet hydrants reduces the overall cost, as will be analyzed in the following section. A significant portion of the total network cost is due to the installation of plot intakes. On average, applying GRASP results in 43.4% shorter intake lengths compared to the conventional methodology. On the other hand, this excess length due to lack of optimization in hydrant location influences the nominal diameter of the intake conduit. As observed in Figure 13, in all cases, the average nominal diameter of the intake conduits tends to increase with no optimization methods, resulting in an increase in the overall cost. The average increase of di analyzed diameter in the case studies is 6.2%.

Cost reduction

Once the evolution of the geometrical (or topological) aspects of the costs has been analyzed, it is appropriate to break them down to better understand the behavior of the irrigation network. Regarding cost variations in each part of the pressurized irrigation network, a distinction is made between the tertiary network -which includes multioutlet hydrants and plot intakes- and the distribution network, consisting of conduits supplying the multioutlet hydrants from the intake. Figure 14 shows the cost differences when comparing dimensioning results using conventional methodology and the optimization methodology. Figure 14 shows that, in all cases, there is a significant decrease in costs in the tertiary network, up to 32%. In some cases, this decrease in tertiary network costs results in a difference in distribution network costs of up to 7.8%, but in all cases, this is compensated by a lower total cost, which is the main objective. Total cost reductions reach up to 14.8%. It is worth noting that, both in the application of the methodology and in cost comparison, constant factors such as those derived from valve fittings inside hydrants or measurement elements like counters have not been considered.

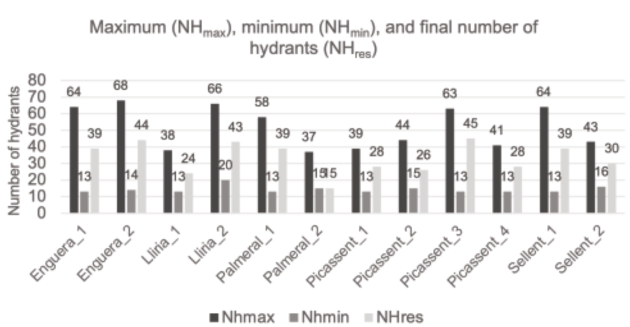

Figure 11. Maximum (NHmax), minimum (NHmin), and resulting number of hydrants (NHres).

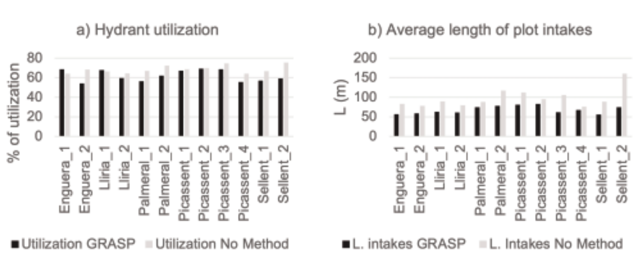

Figure 12. a) Hydrant utilization. **b**) Average length of plot intakes.

Conclusions

The implementation and automation in a GIS of the optimization process facilitate the task of obtaining the actual measurements of the conduits and locations of the multioutlet hydrants, achieving reasonable times for obtaining the layouts that make the use of the defined algorithms useful. The results obtained through the application of the GRASP metaheuristic show a considerable improvement in the overall costs derived from the installation of the pressurized irrigation network compared to the conventional methodology. It is demonstrated that the location of multioutlet hydrants on the irrigable surface and, consequently, the allocation of intakes to plots and their layout, influences the overall cost. By obtaining a greater number of multioutlet hydrants, both the diameter and the linear meters of connections to the plot to be drawn are considerably reduced, which greatly reduces land excavation. The need to incorporate a methodology for obtaining potential locations in the design phase is highlighted, allowing, through an optimization process, to obtain those locations that entail lower costs, ensuring operating conditions. Furthermore, during the optimization process in each of the networks, it can be observed how the overall cost decreases until a turning point is reached where it starts to increase again, so it is necessary to search for that minimum in the cost function.

The optimization process based on the GRASP metaheuristic

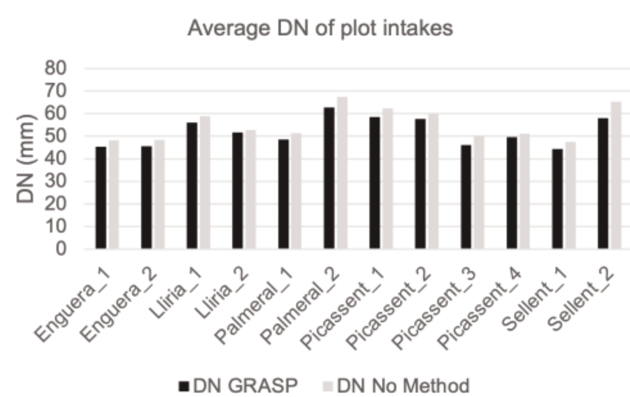

Figure 13. Average DN of plot intakes.

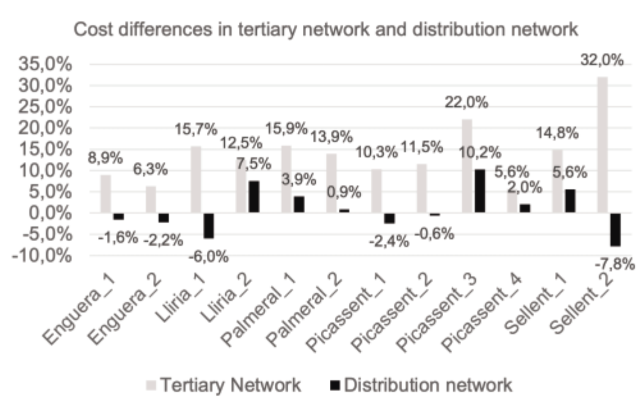

Figure 14. Cost differences in tertiary network and distribution network.

has achieved improvements in the cost of the tertiary network in all case studies. The results show savings compared to conventional methods ranging from 6.3% to 32.0%. On the other hand, in some cases, this reduction in the cost of the tertiary network results in an increase in the distribution network but ultimately balances out in the overall cost with savings ranging from 1.8% to 14.8%.

In particular, the results obtained from the use of hydrants and the average length of intakes to plots have been studied, showing that installing a greater number of hydrants and not reaching their total capacity, both in terms of the number of intakes and flow rate, reduces overall costs. This saving is achieved because with a greater number of hydrants, on average, 43.4% less length of intakes to plots is traced. These savings, and therefore a lower cost in the investment required, may lead to a greater number of collective irrigation networks wanting to modernize their facilities to save water, which is of great relevance with a scarce resource in some areas. In addition, in the event that the investment corresponds to the public administration, it will make it possible to cover a larger irrigated area with a given budget. On the other hand, this study has direct application on the procedures of engineers and technicians. This optimization process, well implemented in calculation software, optimizes the design of irrigation networks and offers more economical projects. It therefore represents an advance in the design tasks, paying attention to an undervalued aspect such as the location of the hydrants.

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