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WISCHE: A decision support system for water irrigation scheduling[1]

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Abstract

In this paper we describe software and algorithms which are being used as a decision support system (DSS) tool to determine water irrigation scheduling. The DSS provides dynamic planning of the daily irrigation scheduling for a given land area by taking into account the irrigation network topology, the water flow technical conditions and the logistical operations. The system has been validated by the technicians of the Agriculture Community of Elche and incorporated into their Supervisory Control and Data Acquisition system (SCADA). We present two approaches to solve the mixed 0-1 separable nonlinear program for irrigation scheduling implemented with free software.

Keywords: water resource scheduling, agricultural irrigation, mixed 0-1 separable nonlinear program.

1 Introduction

In 1968 the Council of Europe published the European Water Charter (http://assembly.coe.int/), which states fundamental principles for the consevation of water resources and establishes criteria for their rational use. Besides outlining the fundamental principles for the protection of this indispensable and vital asset, the European Water Charter points out the need for the inventory, control and management of water resources.

The need for rational water management has become greater in many Mediterranean regions as a result of changes in the availability of water, changes in general climatic conditions and the adverse effect of the actions of human beings on the evironment. See [4] and the references therein for more details of water-related problems in Mediterranean regions.

Over the last years the traditional irrigation scheduling systems have been changed for other new systems in the southeast of Spain because of the scarcity of water resources in this arid Spanish region. The traditional inundating irrigation systems have been progressively substituted by drop (sprinkler) irrigation systems, in which the water is channeled to the irrigation

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points where it is necessary and the required quantity is completely regulated and controlled. This kind of irrigation systems is more common day by day in the above mentioned region.

The ability to help the decision maker in the planning and distribution scheduling of the water resource systems depends on the level of sophistication of the tools and techniques available. A comprehensive approach may remedy the inadequacies of the tools currently available, by developing a hydrologic modelling framework and a highly numeric intensive computation decision support system. See [7, 8, 9, 10, 12] and the references therein.

We should differentiate between water resource planning over a time horizon which is usually long and water distribution scheduling which is usually on a daily basis. For the case of planning see [2] for the deterministic environment, and [6, 11] for the stochastic case by considering the uncertainty in the main parameters (water inflow and needs).

The Agriculture Community of Elche (ACE), Elche being a city in the southeast of Spain, belongs to a group of people who are constantly looking for new irrigation systems in order to conserve the natural environment and to save as much water as possible, because they realize the future of the region depends in some way on the management of the scarce and important resource which water is. At this moment, the ACE is in a first phase of modernization of the channelling systems and the distribution of irrigation water among its members. The first phase in this work was the substitution of the water canalization for a new system consisting of underground pipes and pumps. The pumps send the water from the dam to each irrigation area. The system is controlled by means of a SCADA (Supervisory Control and Data Acquisition) which controls and regulates the available flow in each irrigation area. The advantages of this improvement to the installations are obvious. On the one hand, the water lost by evaporation and filtering is reduced and, on the other hand, each member of the ACE has the guarantee of a fixed quantity of irrigation water with a specific pressure on his land.

This improvement in the infrastructures of the irrigation system is very important in order to save irrigation water but there are two technical problems to be resolved; (i) the design of the pipe network does not guarantee the irrigation service to all members of the ACE simultaneously, therefore some priority criteria are needed in the management of the system.; (ii) the overall pressure of the pipe network has to be controlled to avoid possible breakage of the pipes or water losses. To determine the irrigation scheduling we have considered a set of time periods. In each period the members of the ACE are divided into two groups: active and non-active. Each member of the active group has a certain water flow volume and a minimum pressure in that period of time guaranteed and each member of the non-active group has the service of the irrigation water blocked. The SCADA controls the opening and closing of the valves.

The DSS WISCHE (Water Irrigation for SCHEduling) provides a solution to the problem of assigning each member of the ACE to a period of time in the daily irrigation scheduling, such that the flow and the minimum service pressure are guaranteed. In addition, the solution provided guarantees that the water flow speed in the network does not exceed a previously fixed maximum value.

As the preferences of the members of the ACE over all daily periods could be the same or coincide in some periods and, very likely, it is impossible to satisfy all preferences simultaneously, a special module has been incorporated into the system which records the past consumption of water and preferences for each hydrant. Thus, we are able to determine indices of efficient use and the service times. These indices allow us to determine a priority of use for each member of the ACE. The optimization model implemented in the software maximizes the number of members served according to their preferences weighted by their priority indices. A more detailed description of the problem can be found in [1], where a mixed zero-one separable non-linear model for the water irrigation scheduling is presented; it is solved by successively optimizing mixed 0–1

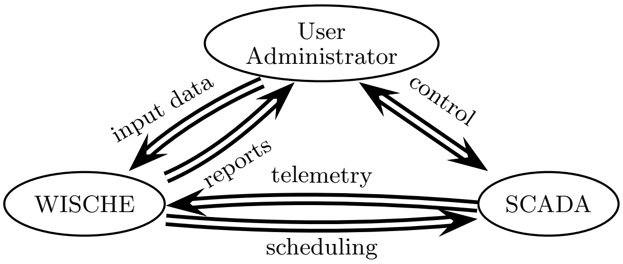


Figure 1: Components of the decision support system and flow of data

Figure 2: Control Panel

linear programs.

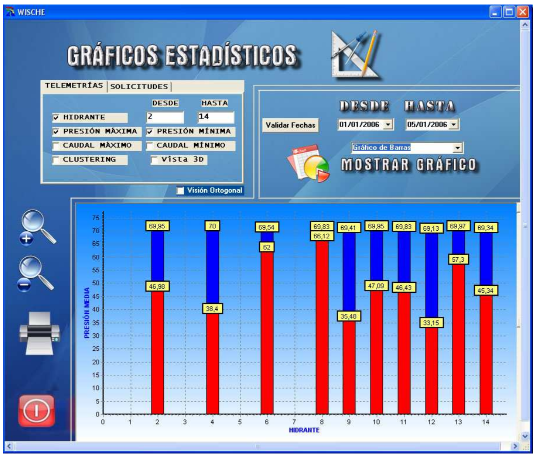
For a good exposition of mixed 0–1 linear programming, see e.g. [13], and see [3] for a mixed-integer linear programming in a irrigation scheduling problem in another context . The decision support system presented in this work has been tested by for solving a real-life problem presented by “La Comunidad de Regantes, Riegos de Levante, Canal 2nd”, which belong to ACE. Its irrigation area comprises 2188 Has and is distributed in 20 pipe sectors (i.e., 20 head nodes) with a total number of 2831 nodes (2025 of them are hydrants with their own water demand needs). The irrigation is needed on a daily basis for a set of time periods. The water flows from a reservoir with a capacity of 13Hm^3, and the full system has an arborescent structure.

The remainder of the paper is organized as follows. In Section 2 we describe the structure of the decision support system WISCHE. Section 3 is devoted to describing the priority system for the hydrants. In Section 4 we present the optimization models implemented in the software WISCHE. Finally, Section 5 concludes.

2 WISCHE structure

WISCHE is a decision support system connected to the a SCADA. It sends to the control system the weekly planning of the irrigation system, providing information about which hydrant users will be served in each period, and receives information from the control system on the water consumption of each hydrant. A scheme illustrating the implemented systems and the relation between them is shown in Figure 1.

WISCHE consists of three modules. Figure 2 shows the software main menu. The first

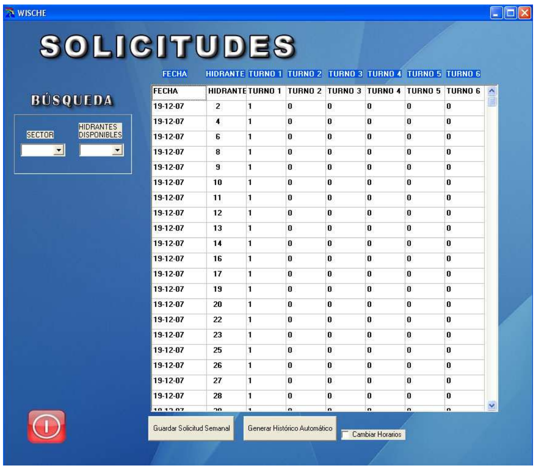


	DESDE	HASTA
☑ HIDRANTE	2	14

☑ PRESIÓN MÁXIMA ☑ PRESIÓN MÍNIMA
☐ CAUDAL MÁXIMO ☐ CAUDAL MÍNIMO
☐ CLUSTERING ☐ Vista 3D
☐ Visión Ortogonal

DESDE 01/01/2006 HASTA 05/01/2006
Gráfico de Barras

Figure 3: Graphics Form



FECHA	HIDRANTE	TURNO 1	TURNO 2	TURNO 3	TURNO 4	TURNO 5	TURNO 6
19-12-07	2	1	0	0	0	0	0
19-12-07	4	1	0	0	0	0	0
19-12-07	6	1	0	0	0	0	0
19-12-07	8	1	0	0	0	0	0
19-12-07	9	1	0	0	0	0	0
19-12-07	10	1	0	0	0	0	0
19-12-07	11	1	0	0	0	0	0
19-12-07	12	1	0	0	0	0	0
19-12-07	13	1	0	0	0	0	0
19-12-07	14	1	0	0	0	0	0
19-12-07	16	1	0	0	0	0	0
19-12-07	17	1	0	0	0	0	0
19-12-07	19	1	0	0	0	0	0
19-12-07	20	1	0	0	0	0	0
19-12-07	22	1	0	0	0	0	0
19-12-07	23	1	0	0	0	0	0
19-12-07	25	1	0	0	0	0	0
19-12-07	26	1	0	0	0	0	0
19-12-07	27	1	0	0	0	0	0
19-12-07	28	1	0	0	0	0	0

Figure 4: Turns Form

module is *Telemetría* (Telemetry) and it processes historical data of telemetry, debugs reading errors and provides tools to create graphs of water consumption, pressure, etc. Figure 3 shows a graph illustrating minimum and maximum pressures of a set of hydrants generated from the telemetry data obtained during a period of 5 days. The second module, called *Asignación de Prioridades* (Priorities' Assignment), allows to introduce the periods preferred by each hydrant user, see Figure 4. Additionally it allows to modify the priority criteria, see Figure 5. Finally, the planning and assignment module provides the optimal assignment of irrigation periods to each member of the ACE. The diagram shown in Figure 6 describes the structure of the files that the three modules of WISCHE and the SCADA share among each other. The module *Priorities' Assignment* is responsible for processing all the information in the file telemetry, together with the history of the members preferences and their new preferences for the following week. Taking into account all this information, the module generates a set of priorities for each hydrant user and time period. This set of priorities is used by the optimization module. The optimization module will be described in Section 4.

The *Priorities' Assignment* module is in charge of processing the information from the telemetry file, jointly with the file of past requests and the current preferences of the users for the next weekly planning. It generates a set of priorities for each hydrant user and time period

PRIORIDADES

$$W(h,t) = \sum_{i=1}^{n} F_i\,(h,t) * I_i$$

Última fecha en registro Hco. Solicitudes: 01/01/07

Introduzca primera fecha significativa: 19/12/2007

FACTOR:	IMPACTO	
F1: Aprovecham. anterior del turno solicitado y asignado	I1	0,6
F2: Porcentaje de turnos solicitados y no asignados	I2	0,4

Figure 5: Priorities' Assigment Form

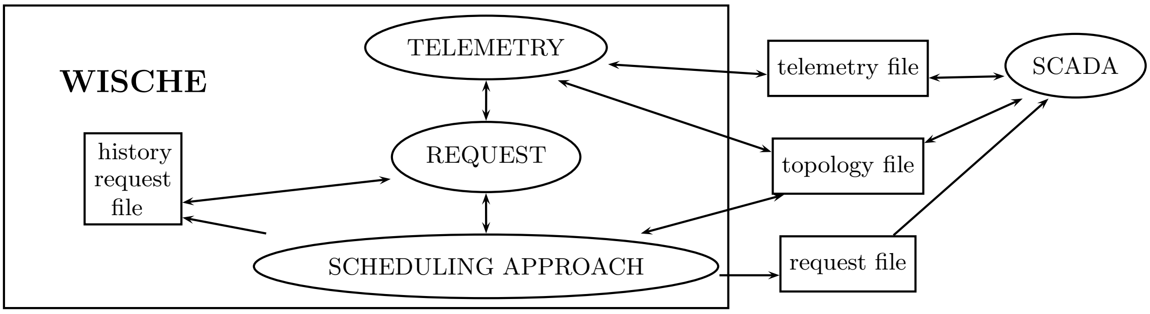


Figure 6: WISCHE elements

Nº TURNOS: 5

VELOCIDAD MÁXIMA: 2,5

PRESIÓN MÍNIMA: 25

PRESIÓN CABECERA: 40

☐ Minimizar velocidad máxima

☐ Minimizar presión máxima

☐ Utilizar heurística

Figure 7: Generating irrigation time periods form

to be used by the optimization module. The components of this module, see Figure 7, are described in section 4.

3 Hydrant priorities

As it is probably impossible to satisfy the preferences of all the members of the ACE because of the design and dimension of the irrigation network and the constraints on the pressure and the speed of the water, it is absolutely necessary to have a mechanism which prioritizes the assignment of a particular hydrant to a period of irrigation when there are several hydrants with the same or coincident preferences.

The *Priorities's Assigmenment* module of WISCHE receives the preferences of the members of the ACE in a table-form (see Figure 4). These preferences are then combined with the past history of use of the hydrant. We have taken into account two significant factors to determine the assignment of a hydrant to a particular irrigation period:

- Factor 1: Efficiency in the use of the preferred assigned periods in a number of previous weekly plannings.
- Factor 2: Percentage of preferred periods and not assigned in a number of previous weekly plannings.

Both factors provide two indices (in $[0, 1]$) which measure, for each hydrant user, the efficiency in the use of the preferred irrigation period (Factor 1) and the percentage of times that their preferred periods have not been assigned (Factor 2). These factors are used in the system to calculate the users' weights in the assignment of the irrigation scheduling, i.e., the weight $W(t, h)$ being evaluated as an adjusted average of both factors, average adjusted by an impact value of each factor. The software allows to modify the impact that both indices will have in the weight assigned to the hydrants for each irrigation period. The priority of hydrant h for the irrigation time period t is computed as follows:

$$P(h,t) = \frac{W(h,t)}{|t - t_0| + 1}$$

where $W(h, t)$ is the weight assigned to hydrant h for the irrigation time period t, and t_0 is the preferred irrigation period for the current irrigation planning.

4 Optimization Models

The optimization module (Figure 7) needs four parameters, namely, number of irrigation time periods, maximum speed of the water flow, minimum pressure and pressure in the head hydrants. See Appendix A for more details on all these parameters. This module allows for the optimization of three models with two different approaches.

4.1 Models

MPF_ISP: Maximize the priority factor in the irrigation scheduling problem. In Appendix A.1 we provide a description of a mixed zero-one separable non-linear problem for the irrigation scheduling. See in [1] the solution aproach that we have proposed.

MM_S: Minimize the Maximum Speed in the whole network. See Appendix A.2 for a description of this model.

MM_P Minimize the Maximum Pressure in the whole network. See Appendix A.3 for a description of this model.

We present two approaches to solve the model:

- Optimization approach using the free GLPK library: Approximated procedure to solve the quadratic mixed 0-1 model of irrigation planning.
- Heuristic approach: Heuristic algorithm to find a feasible solution in a relatively short time.

Depending on the characteristics of the instance, *MPF_ISP* can be non-feasible. In this case the modification of certain constraints in the system could be required, either the minimum pressure or the maximum speed of the water. The user can compute the minimum maximum-speed of the system with all other parameters fixed, so he can adapt the maximum speed parameter to obtain a feasible value for the instance in hand. For example, the default maximum value in the system is 2.5 m/s. This maximum speed is feasible in the whole system provided the irrigation planning for the 2831 hydrants is in 5 periods per day. If the user of the control system makes the decision to offer only 3 irrigation periods per day, but, simultaneously, wants to provide an irrigation service to the 2831 hydrants, then he should modify the maximum speed constraint to obtain feasible solutions to the planning problem. Next he can compute the minimum maximum speed required by the system; in our particular case, there are points in the system where the water flow speed is 3.68 m/s. Then, he can solve the irrigation planning problem with only 3 periods per day fixing the maximum speed at a value above 3.68 m/s.

The running times for each optimization approach are shown in Table 2, for a real-life instance whose dimensions are given in Table 1 and the headings are as follows: m, number of constraints; n_c, number of continuous variables; $n01$, number of 0-1 variables; nel, number of nonzero elements in the constraint matrix; and $dens$, matrix density. Notice the large dimensions of the separable nonlinear model. See in Figure 8 the instance's topography.

4.2 Optimization approach using library GLPK

We have implemented the algorithm described in [1] over a windows platform with the free software GLPK (see, http://www.gnu.org/software/glpk/). Due to the complexity of the model

Table 1: Model Dimensions

m	44390
n_c	14155
$n01$	9848
nel	332231
$dens$	0.031 %

Table 2: Computing effort for different optimization approaches

Optimization model	machine	processor	memory	Obj. value	time	GAP
MPF_ISP (CPLEX approach)	SUN W2100	Opteron 2.6 GHz	4 Gb	97346	2 min	-
MPF_ISP (GLPK base heuristic)	PC	Pentium 1.6 GHz	2 Gb	97308	40 min	0.04 %
MPF_ISP (heuristic approach)	PC	Pentium 1.6 GHz	2 Gb	90159	1.5 min	4.7 %
MM_S (GLPK based heuristic)	PC	Pentium 1.6 GHz	2 Gb	2.211 m/s	40 sec.	
MM_P (GLPK based heuristic)	PC	Pentium 1.6 GHz	2 Gb	68.53 mca	4 sec.	

MPF_ISP the optimization engine GLPK did not provide the results in the affordable computation time, therefore, we developed a GLPK- based heuristic procedure in order to solve the problem. It can be summarized as shown in the following 6 steps:

1. Solve the approximate linear relaxation (R_MPF_ISP) of the continuous model of the irrigation scheduling problem (MPF_ISP), where the linear Taylor series expansion approximation of the quadratic variables is used and the 0-1 variables are relaxed to continuous variables. We use the GLPK library.
2. Update the water flow volumes for the obtained solution.
3. If the linear solution is a solution for the quadratic continuous problem, then we go to the next step. Otherwise, we update the approximation point of the Taylor series to the quadratic model and go to step 1.
4. Fix the relaxed 0-1 δ variables with value 1 in the solution of the linear relaxation.
5. Solve the linear integer approximation of the integer quadratic problem only taking as 0-1 variables those with a fraction value in the previous step.
6. If the integer solution is a solution of the quadratic integer problem, then we stop. Otherwise, we update the approximation point to the quadratic model and go to step 4.

The flow diagram of the the algorithm is shown in Figure 9.

The optimality GAP is 0-04% (see table 2), what is very good but the elapsed time is 40 minutes. This time is valid for planning and simulation studies but is not affordable for scheduling work. The models MMS and MMP are optimized by using the same GLPK-based procedure.

4.3 Heuristic approach

For scheduling work we have implemented a faster heuristic algorithm to obtain a quasi-optimum solution in an affordable computational time.

The algorithm can be summarized in the following 7 steps:

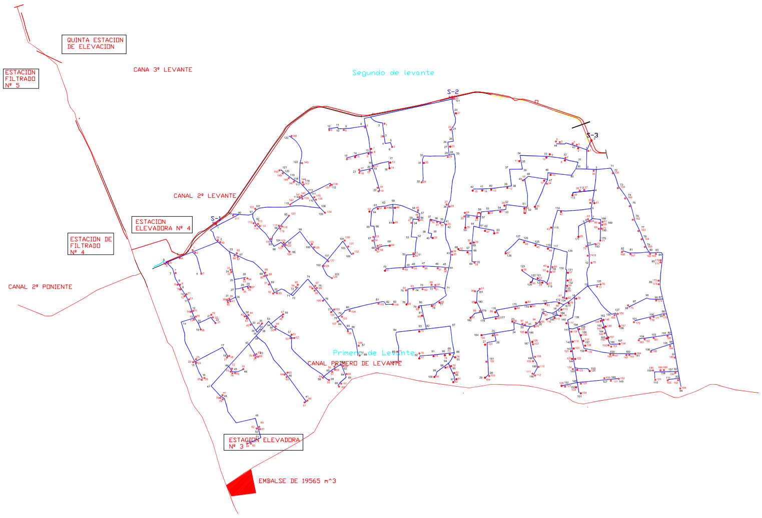


Figure 8: Instance topography

1. Order the hydrants by the non-increasing value *priority/water-flow-volume*. Let A be the set of hydrants provisionally assigned to an irrigation period, and let $\bar{A}$ be the set of non-yet assigned hydrants in the algorithm.

2. For hydrant h with highest priority for the irrigation time period t, call the function $evaluatey_{ht}$. This function updates the water flow volume from hydrant h to its head node analyzing whether it is feasible to assign hydrant h to the irrigation time period t, i.e., whether the pressure and speed constraints are satisfied along the path from hydrant h to its head node.

3. If hydrant h can irrigate during time period t, then we update set A and go to step 2.

4. If there are still irrigation time periods to assign to hydrant h, then increase t and go to step 2.

5. Remove the hydrants which are ancestors of hydrant h and have less priority than it, such that their accumulate water flow volumes exceed the water flow volume required by hydrant h. Let us call P_h to this set of hydrants. In such a case the assignment of hydrant h to its maximum priority irrigation time period is feasible.

6. If hydrant h can be assigned to the irrigation time period t, then we try to assign the previously removed hydrants included in set P_h, update the sets A and $\bar{A}$ and go to step 2.

7. Otherwise, restore the removed hydrants of P_h and, again, update the sets A and $\bar{A}$.

Note: If after a complete iteration of the algorithm the set of non-assigned hydrants $\bar{A}$ is nonempty, then again run the algorithm given priority to these nodes.

The flow diagram of the algorithm is shown in Figure 10.

Table 2 shows the time (1.5 minutes) and the optimality GAP (4.7%) of the heuristic, what is fully affordable for scheduling work.

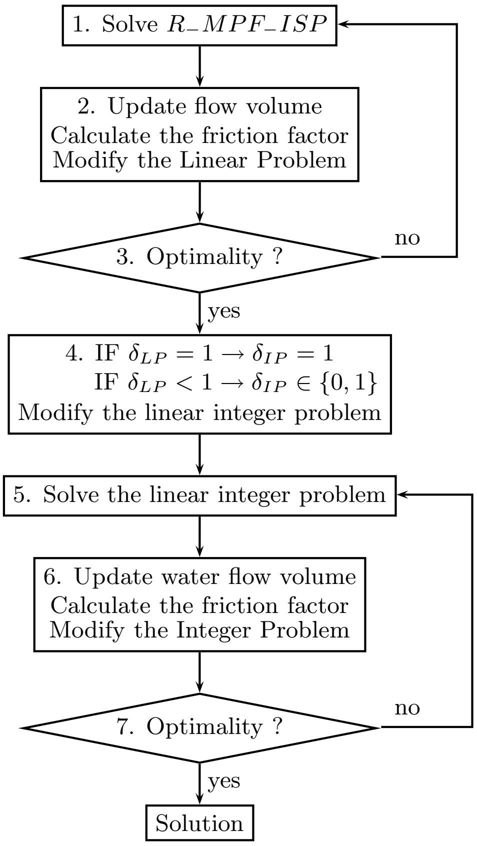


Figure 9: Optimization approach

4.4 Computational results

In this section we show different solutions of the algorithms by varying the number of irrigation time periods. The computational experience was executed on an Intel Core Duo 1.66 GHz. processor, with 2 GB. RAM running under Micrososft Windows XP operating System. Note that the network only can satisfy the water demand for all the hydrants when 5 or 6 time periods are considered. For less than 5 periods we need to minimize the maximum pressure to obtain a feasible water flow speed in the network. Table 3 shows the solution for the MPF_ISP model using WISCHE. The headings are as follows: $nper$, is the number of periods in daily planning, Z_{GLPK} and Z_H provide the solution value using the GLPK-based heuristic and Heuristic approaches respectiely, V_{max} is the solution of the MM_S problem, this solution is the maximum water flow speed allowed for the scheduling problem, except for $V_{max} = 2.5m/s$ since it is the default value. Notice that the Heuristic solution does not differ from the optimal solution in more than $GAP = 11\%$, where $GAP = (Z_H - ZGLPK)/Z_{GLPK}$ and on the other hand the elapsed time is very affordable.

5 Conclusions

WISCHE is an application built jointly with Riegos de Levante (the main group from the Agriculture Community of Elche, ACE), irrigation community which has a real need for irrigation

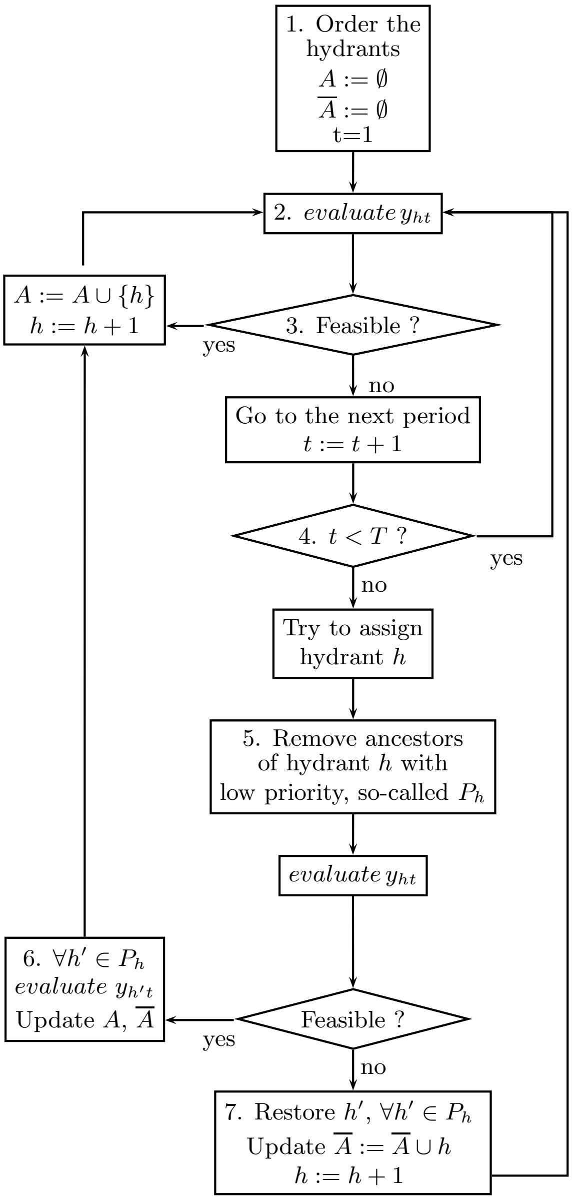


Figure 10: Heuristic approach

Table 3: Computational effort for different planing daily basis

nper	$GLPK$	time	$Heuristic$	time	GAP (%)	V_{max}
1	107.895	1 sec.	107.895	1 sec.	0.0	8.87 m/s
1	infeasible	-	infeasible	-	-	2.5 m/s
2	115966	25 sec.	114.552	15 sec.	1.2	5.30 m/s
2	infeasible	-	infeasible	-	-	2.5 m/s
3	108.577	2 min.	104.914	35 sec.	3.3	3.70 m/s
3	infeasible	-	infeasible	-	-	2.5 m/s
4	100.527	20 min	93.392	40 sec.	7.1	2.78 m/s
4	infeasible	-	infeasible	-	-	2.5 m/s
5	92.900	35 min	83.932	90 sec.	9.9	2.23 m/s
5	97308	60 min	90.158	90 sec.	7.3	2.5 m/s
6	86.555	72 min	77.805	80 sec.	10.1	1.84 m/s
6	97.489	48 min	93.476	8 sec.	4.1	2.5 m/s

scheduling because water demand usually exceed water availability. This software allows irrigation community managers to schedule hydrant turns one week in advance. Scheduling is as flexible as possible and the priority system presented allows for all farmers to be seviced according to their previous usage, so farmers who make early applications and usually make reasonable use of their demand benefit from the proposed support system.

Appendix

A Mathematical Models for irrigation scheduling

In order to describe mathematically the irrigation scheduling problem, we need to take into account technical, topographical and logistic irrigation scheduling parameters. The technical and topographical parameters are related to the physic properties of the fluids. The logistic parameters are related to the management of the irrigation system and, finally the irrigation scheduling parameters are related to constraints in the way of assigning the irrigation time periods. Finally, the decision variables are related to the water volume of flow though each node at each time period and to when each hydrant may sink down.

The notation for all relevant elements and parameters in the WISCHE system is the following:
Sets of general elements:

$\mathcal{T}$, set of time periods for water irrigation purposes.

$\mathcal{I}$, set of hydrants and bifurcation nodes in the geographical area under consideration.

$\mathcal{I}_0$, set of bifurcation nodes.

$\mathcal{I}^\tau \subset \mathcal{I} - I_0$, subset of hydrants whose irrigation starting period has already been fixed to time period τ, $\tau \in \mathcal{T}$.

Γ, set of sector heads, and $\gamma(i) \in \Gamma$ is the root node (sector head) of the subtree to which hydrant i belongs.

$\mathcal{R}_i$, set of upstream nodes to hydrant i, in its path back to its sector head, including the same hydrant i, for $i \in \mathcal{I} - I_0$.

$\mathcal{S}_i$, set of successor nodes to node i, including the same hydrant i, for $i \in \mathcal{I}$. Notice that the nodes in set $\mathcal{S}_i$ can belong to different successor paths (this is the case where the successor path has bifurcation nodes).

Technical and topographical parameters:

f_{it}, friction factor for obtaining the pressure in the immediate upstream pipe segment of hydrant i at time period t, to be updated iteratively, for $i \in \mathcal{I} - \mathcal{I}_0, t \in \mathcal{T}$. The friction factor can be calculated by using the Colebrook-White equation (see e.g., [5]). The computation of f will be iteratively performed each iteration of the algorithm for a given water discharge. Colebrook-White formula is a nonlinear equation in f, but we make use of the Newton-RAphson procedure to obtain its roots.

E_i, elevation of node i, for $i \in \mathcal{I} \cup \Gamma$.

$\mathcal{L}_i$, length of the immediate upstream pipe segment of node i, for $i \in \mathcal{I} \cup \Gamma$.

$\mathcal{D}_i$, diameter of the immediate upstream pipe segment of node i, for $i \in \mathcal{I} \cup \Gamma$.

g, gravity acceleration coefficient.

H_γ, pressure at sector head γ, for $\gamma \in \Gamma$.

H_{min}, minimum pressure required by any hydrant at any time period.

v_{max}, maximum water flow speed allowed along the immediate upstream pipe segment of any node at any time period.

K, hydromodule (l/s/ha), i.e., constant to obtain the water flow volume to irrigate the land area through any hydrant at any time period.

Irrigation scheduling parameters:

$\hat{N}_i$, duration (i.e., number of time periods) of the irrigation by hydrant i based on the dimensions (has) of its respective land area, for $i \in \mathcal{I} - \mathcal{I}_0$.

Logistic parameters provided by the system operator:

c_{it}, priority coefficient for selecting hydrant i to begin a non-preempted irrigation at time period t, for $i \in \mathcal{I} - \mathcal{I}_0$.

F_i, effective land area (has) to be irrigated by hydrant i, for $i \in \mathcal{I} - \mathcal{I}_0$.

$\hat{y}_{i\tau}$, fixed value to 0 or 1 for the variable $y_{i\tau}$ due to logistic considerations, for $i \in \mathcal{I}^{\tau}$.

Variables:

q_{it}, water discharge to flow through node i at time period t to satisfy its own needs, if any, and the water needs of its successor nodes, for $t \in \mathcal{T}, i \in \mathcal{I} \cup \Gamma$.

y_{it}, 0–1 variable, such that its value is 1 if the irrigation in hydrant i begins at time period t and, otherwise, it is zero, for $t \in \mathcal{T}, i \in \mathcal{I} - \mathcal{I}_0$. Notice that the irrigation is carried out in periods $t, \ldots, t + \hat{N}_i - 1$ such that $y_{it} = 1$.

A.1 *MPF_ISP*: Mixed 0–1 separable nonlinear approach for water irrigation scheduling

The mathematical expresion of the model for maximizing the priority factor in the irrigation scheduling problem (*MPF_ISP*) is as follows:

$$\max \sum_{i \in \mathcal{I} - \mathcal{I}_0} \sum_{t \in \mathcal{T}} c_{it} y_{it} \tag{1}$$

$$\text{s.t.} \quad H_{\gamma(i)} + E_{\gamma(i)} - E_i - \sum_{j \in \mathcal{R}_i} \left(\frac{8 f_{jt} L_j}{\pi^2 g D_j^5} \, q_{jt}^2 \right) \geq H_{min} \qquad \forall t \in \mathcal{T}, i \in \mathcal{I} - \mathcal{I}_0 \tag{2}$$

$$q_{it} = \sum_{j \in \mathcal{S}_i - \mathcal{I}_0 - \Gamma} K F_j \Big(\sum_{\tau = t - \hat{N}_j + 1, \ldots, t} y_{j\tau} \Big) \qquad \forall t \in \mathcal{T}, i \in \mathcal{I} \cup \Gamma \tag{3}$$

$$\left(\frac{4}{\pi D_i^2} \right) q_{it} \leq v_{max} \qquad \forall t \in \mathcal{T}, i \in \mathcal{I} \cup \Gamma \tag{4}$$

$$\sum_{t \in \mathcal{T}} y_{it} = 1 \qquad \forall i \in \mathcal{I} - \mathcal{I}_0 \tag{5}$$

$$y_{it} = \hat{y}_{it} \qquad \forall i \in \mathcal{I}^{\tau}, \tau \in \mathcal{T} \tag{6}$$

$$y_{it} \in \{0, 1\} \qquad \forall t \in \mathcal{T}, i \in \mathcal{I} - \mathcal{I}_0 \tag{7}$$

A.2 MM_S: Minimization of the maximum water speed

The model to minimize the maximum speed (MM_S) is as follows:

$$\min \quad V_{\max} \tag{8}$$

$$\text{s.t.} \quad (2)-(3),(5)-(7) \tag{9}$$

$$\left(\frac{4}{\pi D_i^2}\right) q_{it} \leq V_{max} \quad \forall t \in \mathcal{T}, i \in \mathcal{I} \cup \Gamma \tag{10}$$

where $V_{\max}$ is the variable that gives the maximum water speed along the time horizon

A.3 MM_P: Minimization of the maximum water pressure

Another interesting objective function is the minimization of the maximum pressure of water in the irrigation network at any time period.

$$\min Pr_{\max} \tag{11}$$

$$\text{s.t.}(2)-(7) \tag{12}$$

$$Pr_{\gamma(i)} + E_{\gamma(i)} - E_i - \sum_{j\in\mathcal{R}_i} \left(\frac{8\overline{f}_{jt}L_j}{\pi^2 g D_j^5} Q_{jt}^2\right) \leq Pr_{\max}, \forall i \in \mathcal{I} - \mathcal{I}_0, t \in \mathcal{T} \tag{13}$$

where $Pr_{\max}$ is the variable that gives the maximum water pressure along the time horizon.

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