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WP3

D3.3 Water distribution service

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Abbreviations

ICT	Information and Communication Technologies
CBEC	Consorzio di Bonifica Emilia Centrale (Italian pilot)
WDA	Water Distribution Application
WDG	Water Distribution Gatekeeper
WDM	Water Distribution Manager

Executive Summary

Deliverable D3.3-Water Distribution System results from Task 3.3, which is part of the Work Package 3 - Estimation and Optimisation Services. This task is aimed at optimizing the irrigation scheduling among multiple requests and under several concurrent interests (farmers, water district manager) and constrains (such as water availability, network limitation). In particular, the task deals with the definition of the optimal irrigation scheduling in case of large and complex water distribution network that provides the water from the available sources (e.g., reservoirs, rivers, canals, wells, etc.) to several farms. The deliverable arguments the methodological choices taken within the project and presents solutions and tools developed by the members of the SWAMP consortium. Background concepts are briefly introduced in order to support the modelling solutions adopted in the work. Methodology and developed tools are first described from the theoretical point of view and then tested on both synthetic and real case studies. Finally, the deliverable presents the methodological framework for the implementation of the procedure and the performance assessment plan.

1. Introduction

The SWAMP project develops IoT-based approaches for smart water management in precision irrigation domain, testing the developed approaches in several pilots in both Europe and Brazil. The present document is an output of Task 3.3 (Water Distribution System), within Work Package 3 (Estimation and Optimisation Services). Activities summarized within this document have been conducted considering the outcomes of other investigations within WP3 (D3.1 - Water Need Models and D3.2 - Water Distribution Optimisation).

The main goal of Task 3.3 is the optimization of the water distribution scheduling through which the water from the available sources (e.g., reservoirs, rivers, canals, wells, etc.) can be allocated to the fields served by a shared system of irrigation canals and hydraulic infrastructures. The analysis has been conducted in the wake of data collected by the SWAMP platform (WP1 and WP2), and considering water requirements estimated at specific site (as per D3.1) and irrigation scheme (as per D3.2), with the aim to identify services, criteria, rules and management practices in order to reduce leakages and water wastages. The present document contains the rules, criteria and operations intended to optimize the water distribution system for the irrigation purpose. The theoretical basis and the optimization architecture have been designed considering a general application context, thus not considering in advance a given pilot configuration. To demonstrate this, the developed criterion has been tested and validated on a synthetic case study.

The remainder of this deliverable is organized into the following sections.

1. Section 2 recalls some background concepts concerning the optimization problem in agriculture. It briefly presents some traditional approaches and the state-of-the-art concerning the optimization approaches.
2. Section 3 defines the conceptual problems and provides the numerical formulation for the optimization solution. In this section, problem variables, constrains and the objective functions are identified and analytically described.
3. Section 4 presents the application of the optimization framework considering a synthetic case study. Together with the application, this section also provides the validation of the proposed approach.
4. Section 5 exemplifies how the general approach developed within this deliverable will be applied in the Italian pilot. Integration with the current management system and the plan for the assessment of the proposed are also presented.

2. Modelling the water distribution system in agriculture

2.1. Optimal irrigation scheduling in SWAMP

This document summarizes the activities performed in the context of task 3.3 (Water Distribution System), which is part of Work Package 3 (Estimation and Optimisation Services). This task focuses on the optimization of the water distribution among multiple farmers and crops served by a common irrigation network and typically managed by an external water distribution manager (WDM). Focussing on this aspect, Task 3.3 is based on the underlying distinction among the water distribution system that serves a large irrigation region and the final irrigation system adopted at farm level, the latter under direct control of the farmer.

SWAMP WP3 covers all aspects concerning the irrigation matter. In brief, task 3.1 deals with the question of how much water the crops demand in the near future in order for the plants to grow healthy. Task 3.2 deals with the problem of finding optimized solutions and practices to guide the on-farm irrigation scheduling under different real-world constraints. In particular, on-farm irrigation aims at optimizing the water usage within a farm by a proper use of irrigation technologies based on detailed evaluation of crop needs. On the other hand, Task 3.3 focuses on the optimal scheduling of water allocations to several farmers served by a common water distribution network, generally managed by public or private bodies in charge of the management of water resources. Activities related to this latter task are summarized in the present document.

2.2. State-of-the-art for optimal scheduling

Optimum management of gravity irrigation systems is a fundamental objective to reduce water waste, trying as much as possible to meet the demands of farmers and the real needs of crops (Hashemy Shahdany et al., 2018). These suggest that irrigation systems improvements are strategic measures on the way to sustainable food security (Jägermeyr et al., 2015). For this reason, the research activity focuses on the development of algorithms that seek the best solution for canal management, trying to mediate between the possible objectives to be achieved (Malaterre, 1998; Ding et al., 2018). The hydraulic behaviours of irrigation canals show that these systems are complex, with a dynamicity characterized by important time lags, strong nonlinearity and numerous interactions between different consecutive sub-systems (Baume et al., 1998). One of the main problems in water management of irrigation systems is the control of the equitable distribution of water (Bonet et al., 2016) especially in a context of limited water availability. In the light of the growing relevance of this topic, the scientific and technical literature have provided a plethora of approaches characterized by different degree of complexity that depends on the hydraulic network, as well as on the purpose and level of automation of the system. The state of art is focused on the optimal scheduling of gravity irrigation canals. Furthermore, the modality of application must be contextualized to the level of automation of each irrigation system.

A feature that distinguishes mathematical programming methods is the ability to handle a large quantity of linear constraints, and therefore, finding suitable optimal solutions. However, in general, there is a limit to the ability of linear formulations to model such non-linear problems. Consequently, such methodologies should be applied with care to complex systems. For scheduling the distribution of water in a canal network for serving irrigation in a group of farms, Anwar & Clarke (2001) apply a mixed-integer linear programming algorithm. The duration of flow of each outlet and a target start time is specified by users. Typically, the model does not consider the travel time. In de Vries & Anwar (2004) is implemented an integer program for flexible schedules based on users' requested start time, incorporating sequence dependent travel times. The method was applied on small problems due to the computational demand of the algorithm. Hong et al. (2012) use MIQP (Mixed Integer Quadratic Programming) and three parameters as input to the problem are introduced: irrigation start time, duration of irrigation process and flow rate. These parameters represent the requests of the farmers. The problem is how to manage multiple irrigation requests, minimizing the differences between the required parameters and the actual availability to satisfy them. They also consider that the difference in types of crops creates different needs and for this, they insert priority coefficients. Another variable that is considered is the number of operations; in fact, the water is diverted to the farms through the gates that are often maneuvered manually, thus the number of operations must be also minimized. To be able to keep track of the gatekeeper's trajectory, Hong et al. (2014) consider the dynamic propagation of the water flow by using hydraulic delay times. The optimization problem is solved with mixed integer linear programming (MILP). Three hypotheses are formulated to represent the dynamics of water: inflow variations are regulated only by the upstream gate and are not affected by the variations of the other sections; the water travel time from the upstream node to downstream node depends of the characteristics of the section, moreover, the time of delivery to the outlet placed in the stretch is assumed equal to the maximum time of distance of the stretch; the canal sections do not have storage capacity, so inflow must be equal at outflow.

In the approach proposed by Hong et al. (2014), three objectives are considered: the first one is written with the aim to minimize the gap between scheduled and demanded time and duration, the second one in order to minimize water losses (the ratio of supplied volume to diverted volume into the system), and the last one in order to minimize the trip of the gatekeeper. The objective function is the sum of tree previous functions, each multiplied by a weight coefficient. In this case, problem constrains concern the water delivery process, gate operation, gatekeeper trajectory, and water distribution policies.

Finally, the variables that contribute to defining the management of an irrigation system are numerous and characterized by significant temporal variability. To take in consideration the temporal evolution of the boundary conditions, which may vary the system from the hypothetical optimal operating conditions, optimal scheduling algorithms used for the daily management of the irrigation systems should be applied recursively over limited time horizons. This could allow improving the management and use of water resources even in the contexts characterized by low automation level.

3. Water Allocation and Distribution Problem

Here, the water distribution network that allocates water to the farmers is typically made of open canals and free-flow pipes that need to be managed (manually, most of the time) by operators (Water Distribution Gatekeeper-WDG- or gatekeeper from now on). In particular, the irrigation network has been designed following a hierarchical structure, in which major canals collect that water from water supplies (i.e., large rivers, wells plant, retention basins), sometimes several kilometers away from the irrigation area, and brings the water to the farmers by means of a series of gradually smaller canals and pipes. This setting requires a constant presence of WDGs who surveys the proper water allocation by acting on gates, sluice, spillways, in order to deliver the water to farmers in relation to water requirements and water availability.

While major canals are normally kept full through the irrigation period, the delivering of water to remote farmers forces the filling of canals and pipes for many kilometers, which entails the use of a relevant water volume that is not always recoverable for irrigation purposes. In addition, the network is characterized by water losses due to infiltration through canal banks and bottom. In this scenario, adopting an optimal irrigation scheduling is essential to ensure a proper use of manpower and water resources.

Typically, water allocations to farmers is scheduled adopting an arrangement based approach. This means that water demands (off-takes) placed by users (i.e., farmers) are collected and managed by the irrigation manager (Water Distribution Manager-WDM- usually a member of a public institution in charge of the management and governance of the irrigation districts) by means of a scheduling lasting from 1-2 days, up to a week. This scheduling is the result of a trade-off among different interests (i.e., farmers' satisfaction, management restrictions and duties, water saving etc.), as well as possible general management rules introduced to guide the managers when dealing with multiple instances (e.g., first come-first served basis; spatial location of the farmers, etc.). Once identified, the scheduling must then be shared with the farmers in advance (e.g. 1 or 2 days) in order to check their availability. The identification of a proper scheduling is fundamental to reduce service costs and water saving. This is especially true for requests at the tail-end of the irrigation district, for which the water delivering requires the filling of several kilometers of canals and possible delays on gate operations may imply large water losses (e.g., the upstream water delivery is still unchanged although the downstream off-takes has been stopped). All these considerations need to respect some boundary conditions, which relate to the maximum hydraulic capacity of the network, irrigation equipment constraints of the farmers, water travel time across the network to reach the farms, or other case specific conditions. Furthermore, in case of droughts, the water delivered should be arranged within specified acceptable ranges.

Depending on the level of automation of the irrigation district, all or a portion of these activities are made manually by the gatekeeper who also has additional duties (i.e., maintenance responsibility, administrative work, meetings, etc.). Thus, the optimal scheduling must also consider the time required for each WDG operation, including the travel time from one gate to the following one, as well as the working time during a day (irrigations during night are considered as exception for security reason and to reduce operators efforts).

Starting from these general considerations, in the optimization process developed to achieve the optimal scheduling we divide the time horizon into N time intervals. The goal of the optimization process is to define for every time interval:

- Quantity of water flowing into each canal;
- Operations on the gates;
- Movements of the gatekeeper;
- Starting irrigations;
- Active/ongoing irrigations.

The time horizon of the scheduling can change according to the water distributor needs. It can be a working day 12 hours, or an entire irrigation plan spanning a week. The duration of the time intervals can be chosen accordingly. In the following, the duration of the time intervals is indicated with δt. Furthermore, there could be some limitations to the water supply. In this case, the system manager could remove some requests or postpone them before the optimization or define different priorities during the optimization process itself.

The objective function must take into account not only the satisfaction of the users, but also the needs of the water distributor, like minimising the travelling times of the gatekeeper and the water loses. Therefore, the objective function is composed by several terms that consider such necessities.

3.1. Formulation assumption

The water distribution network is divided into l canals and every canal has an upstream gate that regulates the quantity of water flowing into it. Every canal has a certain length and therefore a water travelling time from upstream (the gate) to downstream. To avoid mismatch between the water supply and the water demands, we consider the travelling times $\tau_i, i = 1, \dots, l$ in the optimization formulation. The travelling time τ_i is scaled on the time interval duration δt. Every canal has also a maximum inlet volume capacity: $c_i, i = 1, \dots, l$.

The outlets from which farmers can withdraw the water are called off-takes; every off-take is associated with a canal, assuming it is positioned at the end of the canal in order to ensure the canal is full when the off-take is activated.

The operations of the gatekeeper are associated with the time needed to travel from one gate to another and perform the operations. Therefore, there is a matrix ψ of dimension $\mathbb{R}^{l \times l}$ that reports the average times to travel from one gate to another to perform an operation, scaled on δt. We assume that these operations consist not only in manipulating the gates, but also checking that the irrigation is going as intended.

Differently from what is done in Hong et al. (2014), we assume that the network canals can store water. To this aim the inlet flow is measured in m^3 per time interval defined as $V_i^n, i = 1, \dots, l, n = 1, \dots, N$. Knowing the duration of the time intervals it is possible to compute the inlet flow in litres per seconds with a simple proportion. The m^3 of water remaining in the i-th canal at time interval n are defined by the variable $R_i^n, i = 1, \dots, l, n = 1, \dots, N$. Both the water entering and remaining in the canal can be used for the irrigation.

This choice allows the optimiser to set the initial state of the network. In large networks, the canals could take several hours to fill up and send the water to the downstream canals. For this reason, there could always be water flowing in the canals, even during the night, in order to make a minimum volume enter. The inlet volume and stored water at time zero must be taken into account during the optimization. Furthermore, in the case there are several sensors positioned along the canals that return the levels of water, it is possible to easily set the initial conditions of the irrigation. Finally, we assume that both V_i^n and R_i^n have continuous values to simplify the optimization problem.

An optimization formulation is composed by an objective function that defines the target of the optimization and a series of equalities and inequalities that define the constraints and the relations between the variables. In the next section, we define the elements of the following optimization problem:

$$\begin{aligned} min_x \quad & f^T x \\ s.t. \quad & Ax \leq b \\ & Aeqx = beq \\ & lb \leq x \leq ub \end{aligned}$$

Where x is the vector containing all the variables of the problem, f is the coefficient of the objective function, A is the matrix of the linear inequality constraints, b is the vector of the known terms for the linear inequality constraints, Aeq and beq are the matrix and the known terms for the linear equality constraints and lb and ub are the lower and upper bounds for the variables respectively.

We underline that the form we write the optimization problem is the way many optimization solvers, such as CPLEX and the mixed integer linear programming solver in MATLAB $intlinprog(\cdot)$, accept linear optimization problems in input.

3.2. Problem variables

As said in the previous section, we are interested in determining the inlet water volume for every canal at every time interval:

$V_i^n, i = 1, \dots, l, n = 1, \dots, N, \Longrightarrow$ Total volume of water in m^3 entering in the canal i during time interval n;

And the associated water stored in the canal in every time interval:

$R_i^n, i = 1, \dots, l, n = 1, \dots, N, \Longrightarrow$ Total volume of water in m^3 stored in the canal i at time interval n;

These two quantities are bounded by the water balance constraints shown in the next section.

The second group of variables are those related to the gate operations. A first variable is the Boolean variable that defines if the i-th gate has been operated at time n:

$G_i^n, i = 1, \dots, l, n = 1, \dots, N, \Longrightarrow$ 1 if gate i has been operated at time n, 0 otherwise;

The second variable is the one indicating how much the gate has been opened. This variable varies between [0,1], where 0 indicates that the gate is closed, and 1 that the gate is open to its maximum inlet volume capacity:

$H_i^n, i = 1, \dots, l, n = 1, \dots, N, \Longrightarrow$ Ratio to which the i-th gate is open at time n;

For every time horizon we define the number M of maximum operations that can be performed by the gatekeeper. To keep track of the route that the gatekeeper follows in order to perform the operations we introduce the following Boolean variable:

$E_i^{n,m}, i = 1, \dots, l, n = 1, \dots, N, m = 1, \dots, M, \Longrightarrow$ 1 if operation m is performed at gate i at time n, 0 otherwise;

Then, we introduce the variable that determines the movement of the gatekeeper from one gate to another to perform an operation:

$F_{ij}^{n,m}, i = 1, \dots, l, n = 1, j = 1, \dots, l, n = 1, \dots, N, m = 1, \dots, M, \Longrightarrow$ 1 if the gatekeeper moves from gate i to perform operation m at gate j at time n, 0 otherwise.

Variable G_i^n is connected to variable $F_{ij}^{n,m}$ through a series of constraints that involve variable $E_i^{n,m}$. In the next section we show that such constraints together with the integer constraints on $E_i^{n,m}$, force G_i^n and $F_{ij}^{n,m}$ to assume {0,1} values without imposing integer constraints directly on such variables, speeding up the algorithm to solve the problem.

The third and final group are the variables strictly related to the irrigation. We assume that there are K water requests in the considered time horizon, and every request is associated with a different off-take. We are interested in defining when the irrigation starts:

$S_k^n, k = i, \dots, K, n = 1, \dots, N, \Longrightarrow$ 1 if off-take k is activated at time n, 0 otherwise;

And we are also interested to know if a certain off-take is active during a time interval:

$D_k^n, k = i, \dots, K, n = 1, \dots, N, \Longrightarrow$ 1 if off-take k is active at time n, 0 otherwise.

Therefore, variable S_k^n informs the optimiser when an off-take is activated and can assume value 1 only once during the irrigation, while variable D_k^n informs the optimiser if the off-take is active in that time interval, assuming values equal to 1 from the irrigation start to its end.

3.3. Objective Function

The objective function must keep into account both the satisfaction of the farmers and the efficiency of the irrigation. The satisfaction of the farmer can be measured in terms of adequacy, which is in turn represented in terms of time displacement between the water request and time the irrigation is enabled by WDM (time adequacy), and in terms of the ratio between the requested and the delivered volume (volume adequacy).

Regarding the time adequacy, the objective function must minimise the difference in time among the request and water delivery:

$$j_1 = \sum_{k=1}^{K} \frac{\alpha_k |s_k - \sum_{n=1}^{N} n S_k^n |}{\sum_{k=1}^{K} \Delta t_k}$$

Where $\alpha_k, k = 1, \dots, K$ are the priorities of the starting times for every off-take; $s_k, k = 1, \dots, K$ are the requested starting times for every off-take and $\Delta t_k, k = 1, \dots, K$ is the maximum possible delay, computed as:

$$\Delta t_k = \max\{s_k - 1, N - s_k - \epsilon_k \, d_k\}$$

where, $d_k, k = 1, \dots, K$ is the expected duration of the irrigation for every off-take and $\epsilon_k \in [0,1], k = 1, \dots, K$, is the minimum ratio of water that must be given to the off-take.

For volume adequacy, the difference of the requested volume and the supplied volume is minimised:

$$j_2 = \sum_{k=1}^{K} \frac{\beta_k q_k (d_k - \sum_{n=1}^{N} D_k^n)}{\sum_{k=1}^{K} \Delta v_k}$$

where, $\beta_k, k = 1, \dots, K$ are the priorities for the volume deliveries, $q_k, k = 1, \dots, K$ are the volumes of water that the farmer takes per time interval and $\Delta v_k, k = 1, \dots, K$ is the maximum possible gap between scheduled and demanded volume, computed as:

$$\Delta v_k = (1 - \epsilon_k) q_k d_k$$

as d_k indicates the number of times intervals necessary for the irrigation and q_k the volume taken per time interval. The multiplication of these two numbers results into the total water volume required by the farmer.

The WDM (Water District Manager) wants to increase the efficiency of the network by minimising the possible losses, which are of two kinds: water loss in the network and extra working load for the gatekeeper. In our application, principal water losses are due to water seepage of the water through the canals. Although the seepage during the phase of canal filling is inevitable, it is better avoiding storing large amount of water volume in the canals for long period. On the other hand, allowing the storage of water in the canals gives the system more flexibility for the irrigation scheduling. For this reason, the third term we consider in the objective function is:

$$j_3 = \frac{\sum_{i=1}^{l} \sum_{n=1}^{N} R_i^n}{\sum_{n=1}^{N} r^n}$$

where r^n is the total available volume at time slot n.

Another possible inefficiency is the total workload of the gatekeeper that can be reduced by minimising his travelling time. This issue is known as the travelling salesman problem in the optimization literature. If we consider the parameter matrix ψ composed by the elements ψ_{ij} that reports the time needed for the gatekeeper to travel from i to j and perform the operation at gate j and the variable $F_{ij}^{n,m}$, which is 1 if the gatekeeper moved from i to j to perform operation m at time n, the total working time of the gatekeeper that must be minimised is:

$$j_4 = \frac{\sum_{i=1}^{l} \sum_{j=1}^{l} \sum_{n=1}^{N} \sum_{m=1}^{M} \psi_{ij} F_{ij}}{\Psi}$$

Where Ψ is the total time the gatekeeper is available in the considered time horizon.

All the reported terms are summed to form the objective function with suitable weights $w_t, t = 1, \dots, 4$; such that $\sum_{t=1}^{4} w_t = 1$, in order to stress the terms the irrigation manager considers more important for the optimization. Furthermore it is easy to notice that $j_t \in [0,1], t = 1, \dots, 4$, that is the weighting optimization technique.

3.4. Constrains

The constraints are of several types, according to what are their effects on the formulation. Each constrain has a tag that specifies if it composes the matrix A or the matrix Aeq.

The first is the water balance constraint, $Aeq1$:

$$(1-\gamma_i)^{\tau_i}\left(V_{i-\tau_i}^n + R_{i-\tau_i}^n\right) - \sum_{k\in K_i} q_k D_k^n - \sum_{j\in I_i} V_j^n - R_i^n = 0, \forall i = 1,\dots,l, \forall n = \max_{i=1,\dots,l}\{\tau_i\} + 1,\dots,N$$

This constrain imposes that the inlet volume plus the volume stored in the canal at time $n-\tau_i$ must be equal to the volume flowing downstream, plus the volume taken from the farmers and the volume that remains in the canal at time interval n. The ratio $\gamma_i \in [0,1), i = 1,\dots,l$ is the water lost due to seepage in the canal per time interval. The sets $K_i, i = 1,\dots,l$ are the sets of the off-takes on the i-th canal, and the sets $I_i, i = 1,\dots,l$ are the sets of the canals directly downstream to the i-th canal.

This constraint shows that the off-takes are served by the water in input to the canal at time $n-\tau_i$, which is first the water that arrives from upstream and then pumped in the field during the following time interval. From now on we assume that $max\{\tau_i\} = 1$, which is the duration of the time interval δt, is greater than the water travelling time for each canal.

Associated with this constraint there are the initial network conditions at time n=1, Aeqini:

$$\sum_{k\in K_i} q_k D_k^1 - \sum_{j\in I_i} V_j^1 - R_i^1 = (1-\gamma_i)R_i^0, \forall, i = 1,\dots,l$$

where R_i^0 for $i = 1,\dots,l$ is the known water stored in the canals at time 0.

The next two constraints are related to the water delivery process. The first imposes that if a gate is not operated then its opening ration cannot change from one time interval to the next one, A1:

$$G_i^n = 0 \rightarrow H_i^n - H_i^{n-1} = 0, \forall\ i = 1,\dots,l, \forall, n = 2,\dots,N$$

with the associated initial condition, Aini1:

$$G_i^n = 0 \rightarrow H_i^1 - H_i^0 = 0, \forall i = 1,\dots,l$$

where $H_i^0, i = 1,\dots,l$ is the known initial states of the gates.

In order to handle the implication constrain in A1 and Aini1, we use a well know strategy in the optimization literature (Belotti et al., 2016) and write:

$$G_i^n = 0 \rightarrow H_i^n - H_i^n - 1 = 0, \forall\ i = 1,\dots,l, \forall\ n = 2,\dots,N$$

$$\Leftrightarrow$$

$$H_i^n - H_i^{n-1} \le \Omega_i G_i^n, \forall i = 1,\dots,l, \forall n = 2,\dots,N$$

$$H_i^{n-1} - H_i^n \le \Omega_i G_i^n, \forall i = 1,\dots,l, \forall n = 2,\dots,N$$

$$G_i^1 = 0 \rightarrow H_i^1 - H_i^0 = 0, \forall i = 1,\dots,l,$$

$$\Leftrightarrow$$

$$H_i^1 - H_i^0 \le \Omega_i G_i^1, \forall i = 1,\dots,l,$$

$$H_i^0 - H_i^1 \le \Omega_i G_i^1, \forall i = 1,\dots,l,$$

Where Ω_i is a big enough value that guarantees that the constraint is inactive if $G_i^n = 1$. In our case, as the variable H_i^n is positive and constrained to be less than 1, we set $\Omega_i = 1$ for every i.

The inlet volume has an upper bound defined by the minimum between the canal inlet volume capacity c_i and the maximum available volume r_n multiplied the opening ratio, A21:

$$V_i^n \leq H_i^n \min\{c_i, r_n\}, \forall\, i = 1, \dots, l, \forall\, n = 1, \dots, N$$

Furthermore, we introduce a quantity $\rho_i \in [0,1], i = 1, \dots, l$ and set the ratio of the minimum quantity of water that must pass through the gate if it is open, A22:

$$V_i^n \geq H_i^n \rho_i \min\{c_i, r_n\}, \forall\, i = 1, \dots, l, \forall\, n = 1, \dots, N$$

Next family of constraints are those concerning the operations and gatekeeper trajectories. The first imposes that the gates cannot be operated in the time intervals the gatekeeper is not available, Aeq2:

$$\sum_{i=1}^{l} G_i^n = 0, n \in t^p$$

Where t^p is a vector composed by the time intervals in which the gatekeeper rests or is not working. On the other hand, concerning the variables $E_i^{n,m}$, operation m can be performed only once, A3:

$$\sum_{i=1}^{l} \sum_{n=1}^{N} E_i^{n,m} \leq 1, \forall m = 1, \dots, M.$$

Variables G_i^n and $E_i^{n,m}$ are linked in the following fashion, Aeq3:

$$G_i^n - \sum_{m=1}^{M} E_i^{n,m} = 0, \forall i = 1, \dots, l, \forall n = 1, \dots, N,$$

this constraint imposes that gate i cannot be operated at time n if no operation has been performed at i at time n.

The next two constraints strictly bound variables $E_i^{n,m}$ and $F_{ij}^{n,m}$,A4, Aeq4:

$$E_i^{n,m-1} - \sum_{j=1}^{l} \sum_{p=n}^{N} F_{ij}^{p,m} \leq 0, \forall i = 1, \dots, l, \forall n = 1, \dots, N, \forall m = 2, \dots, M$$

$$E_j^{n,m} - \sum_{i=1}^{l} F_{ij}^{n,m} = 0, \forall j = 1, \dots, l, \forall n = 1, \dots, N, \forall m = 1, \dots, M$$

Constraint A4 imposes that if operation $m-1$ has been performed at time n and at gate i, then the movement in the future to perform operation m must start from gate i. Constraint Aeq4 imposes that if there is a movement arriving to j to perform operation m at time n, then operation m must be performed at gate j at time m.

Given these constraints, it is possible to report a property of the formulation, that allows the practitioner to relax the Boolean constraints on the variable $F_{ij}^{n,m}$ that constitute the majority of the integer variables of the problem.

Theorem

Assume that $E_i^{n,m} \in \{0,1\}$ and that $F_{ij}^{n,m} \in [0,1]$, then constraints A3, A4 and Aeq4 imply that:

$$F_{ij}^{n,m} \in \{0,1\}$$

Remark

A similar argument to Theorem 1 can be used together with constraints A3 and Aeq3 to relax the Boolean constraints on the variable G_i^n. In this way the large majority of the integer variables of the formulation in Hong et al. (2014) have been relaxed to continuous ones with no cost, resulting in a far less difficult problem to solve.

Two operations cannot be performed in the same time interval if the travelling time between the two gates is bigger than the time interval itself, A5:

$$\sum_{i=1}^{l}\sum_{j=1}^{l}\sum_{n=1}^{N}\psi_{ij}F_{ij}^{n,m}+\sum_{i=1}^{l}\sum_{n=1}^{N} nE_i^{n,m-1}-\sum_{i=1}^{l}\sum_{n=1}^{N} nE_i^{n,m-1}\leq 0,\forall m=2,\dots,M,\psi_{ij}>1.$$

Finally, more than one operation can be performed in the same time interval if the sum of the times to perform the operations does not exceed the duration of the time interval, A6:

$$\sum_{i=1}^{l}\sum_{j=1}^{l}\sum_{n=1}^{N}\psi_{ij}F_{ij}^{n,m}\leq 1,\forall n=1,\dots,N,\psi_{ij}\leq 1.$$

The last family of constraints are the water distribution constraints. The first imposes that irrigation can start only once, Aeq5:

$$\sum_{n=1}^{N} S_k^n=1\,\forall k=1,\dots,K,$$

then the off-take cannot be active unless the irrigation started in that time interval or the irrigation was active in the previous time interval, A7:

$$S_k^n=0\rightarrow\ D_k^n-D_k^n-1\leq 0,\forall k=1,\dots,K,\forall n=2,\dots,N,$$

With associated initial conditions, Aeq6:

$$S_k^1-D_k^1=0,\forall k=1,\dots,K,$$

The irrigation must end before the last time interval, A8:

$$\sum_{n=1}^{N} nS_k^n+\sum_{n=1}^{N} D_k^n\leq N,\forall k=1,\dots,K,$$

the delivered water must satisfy the minimum request and not exceed the quantity requested by the farmer, A9:

$$\epsilon_k q_k d_k\leq q_k\sum_{n=1}^{N} D_k^n\leq q_k d_k,\forall k=1,\dots,K.$$

4. Synthetic test application and validation

In order to evaluate the methodological approach, the optimization model has been tested in a simplified case study. In fact, the linear optimization model implies a simplified scheme to reproduce the motion of the water in the canals (Aeq1), which suggest the opportunity to preliminary validate the reliability of the provided results.

To this end, in this section we refer to an ideal case that does not include specific hydraulic singularities (such as: canals with a slight counter slope, intubated sections that go under pressure, inverted siphons, large capacity for the accumulation of the canals), but that can be consider as reference for a generic irrigation district, which behaviour can be reproduced and understood with high degree of confidence. Another advantage of applying this model on an ideal case in the first phase is the possibility to evaluate the methodological flexibility and its potential of being extended to different cases study. Modifications of the constrains and the network architecture are always possible to deal with the peculiarities of each specific case.

The synthetic case study is composed of four canals, the first two being open canals and the second two being final pipes (see Figure 4.1). The canals system is powered by a water source settled at constant piezometric head of 11 m (arrow in Figure 4.1). The entrance of water in the system is regulated by a weir gate, while an adjustable weir gate allows the water flowing into canal 2. Canals 3 and 4 are powered by canal 2 and their flow is regulated by different orifices. White circles represent the location of water off-takes due to potential irrigations.

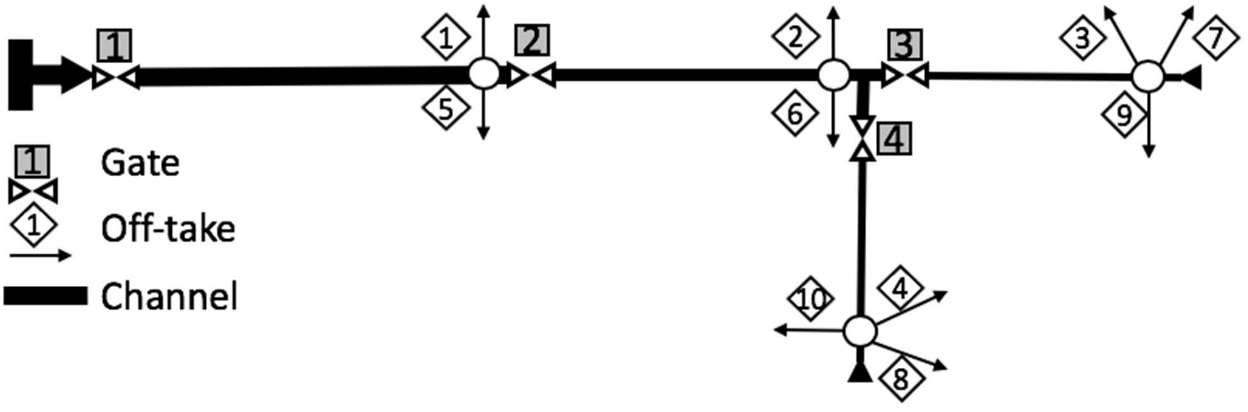

FIGURE 4.1: SCHEMATICS OF THE CONSIDERED WATER DISTRIBUTION NETWORK. THE GREY SQUARES REPRESENT THE GATES AND THE WHITE diamonds THE OFF-TAKES.

Table 4.1 reassumes the characteristics of the canals and pipes adopted in the synthetic scheme.

Canal	Length (m)	Slope	Material	Roughness ($m^{1/3}/s$)
1	2000	0.001	Clay	43
2	1000	0.001	Clay	43
3	400	0.0015	Concrete	70
4	350	0.0015	Concrete	70

TABLE 4.1: LENGTH AND MATERIALS FOR THE CANALS AND PIPES WITHIN THE NETWORK.

Table 4.2 summarizes the hydraulic characteristics of the network. The maximum discharge flowing within the network has been calculated adopting the Chezy formula under the condition of permanent flow, while the maximum water levels have been chosen deliberately with a large freeboard to prevent for potential overflow (due, for example, to backward effects associated to operations on sluice gates).

Canal	Section	Base (m)	Slope of lateral sides	Radius (m)	Max Level (m)	Max High (m)	Flow (l/s)
1	trapezoidal	0.55	45°	-	0.55	1	358.21
2	trapezoidal	0.45	45°	-	0.45	1.2	209.76
3	Circular	-	-	0.30	0.48	0.6	211.52
4	circular	-	-	0.30	0.48	0.6	211.52

TABLE 4.2: GEOMETRIC AND HYDRAULIC CHARACTERISTICS OF THE NETWORK.

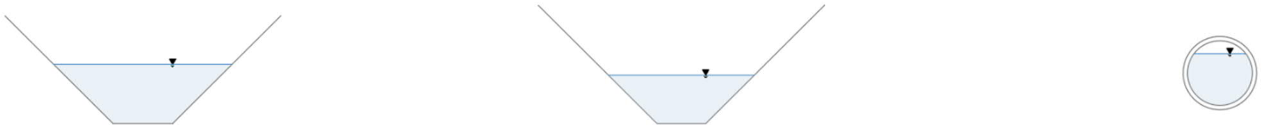

FIGURE 4.2: TRAPEZOIDAL SECTIONS OF CANALS 1 AND 2 (LEFT AND CENTER, RESPECTIVELY) AND CIRCULAR SECTION OF CANALS 3 AND 4 (RIGTH).

When it comes to efficiency of canals, there is a large variability due to several aspects including different types of canals (lined/unlined), different materials, the hierarchy (main, secondary or link canals) and different maintenance and management (Habib, 2004). In our simplified case study, we have decided to attribute 80% efficiency to each canal, and by doing so we have estimated the water wastage to be approximately 20% of the water flowing through the canals.

4.1. Algorithm application

The benchmark we consider for our test application has 10 off-takes to be supplied in a 12 h period. We assume that the irrigation period starts at 6 AM and stops at 6 PM. The four gates upstream the canals are operated manually by a gatekeeper, whose resting period is settled between the 12:00 and the 13:00. The schematics of the network are reported in Figure 1.

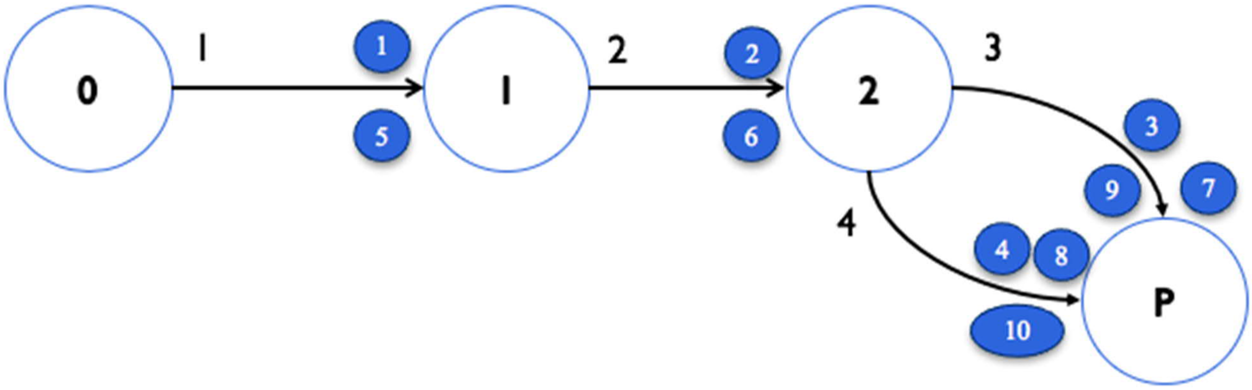

FIGURE 4.3: SCHEME OF THE SYNTHETIC BENCHMARK AS REPRODUCED WITHIN THE OPTIMIZATION MODELLING.

The characteristics of the canals are reported in Table 4.3. The maximum value for τ (50 min) is smaller than 60 minutes and δt is set to 60 min. The seepage ratio γ is set to 0.2 for all the canals resulting in a non-trivial quantity of water lost during the irrigation.

Canal	τ(min)	C(m^3)	γ	ρ
1	50	1152	0.2	1
2	30	752.4	0.2	0.8
3	7	824.4	0.2	1
4	7	824.4	0.2	1

TABLE 4.3: SPECIFIC CANAL CHARACTERISTICHS: WATER TRAVELLING TIME (τ), MAXIMUM VOLUME THAT CAN PASS THROUGH THE GATE PER TIME INTERVAL (C), SEEPAGE RATE (γ) AND MINIMUM QUANTITY OF WATER DELIVERED WITHIN A GIVEN CANAL (ρ; EXPRESSED AS RATE OF C).

The requested water demands are reported in Table 4.4. Considering that farmers express preferences only about the day the water is needed, all requests are scheduled to start at the same time.

k	i	α	β	ϵ	Hour	d(min)	V(m3)
1	1	1	1	0.8	8	660	72
2	2	1	1	0.8	8	540	72
3	3	1	1	0.8	8	360	72
4	4	1	1	0.8	8	240	72
5	1	1	1	0.8	8	300	47
6	2	1	1	0.8	8	360	50
7	3	1	1	0.8	8	180	90
8	4	1	1	0.8	8	540	90
9	3	1	1	0.8	8	360	90
10	4	1	1	0.8	8	420	54

TABLE 4.4: OFF-TAKE NUMBER (k), DELIVERING CANAL (i), PRIORITY COEFFICIENTS (α, β), MINIMUM RATIO OF WATER THAT MUST BE DELIVERED (ϵ), DURATION OF THE IRRIGATION IN MINUTES (d) AND WATER TAKEN FROM THE CANALS PER TIME INTERVAL (V).

In this test, all the considered off-takes have the same priorities (α). By changing this parameter, it is possible to take into consideration potential priorities and anticipate some irrigations. The available inflow at the district entrance is 320 l/s that translates to 1152 m^3 per time interval of 60 minutes (see C in Table 4.3). This is also assumed as the maximum amount of water available in the network, $r_i = 1152, i = 1, \dots, N$.

Gatekeeper's travel times from gate to gate (which are comprehensive of the time required for the gate operation and following checks) are reported in the double entry matrix of Table 4.5.

ψ_{ij}	1	2	3	4
1	25	45	60	60
2	45	20	30	30
3	60	30	15	20
4	60	30	20	15

TABLE 4.5: TRAVELLING TIME OF THE GATEKEEPER TO GO FROM GATE I TO GATE J IN MINUTES.

In this example, every single irrigation request requires much less water that the amount available within the system; however, the total required volume is larger than the one that can be supplied through the network at each time step because of the long duration of many irrigations and the presence of losses due to seepage. For example, the system manager must input to canal 1 almost double the water requested on canals 3 and 4 in order to cope with the seepage.

4.1.1. Computations and Results

The computation is carried out over an Intel (R) Core (TM) i5 2415M CPU@2.3 GHz and 8 Gb of ram. The matrices and the vectors necessary to obtain the formulation have been composed by using the Matlab software. IBM-Ilog Cplex is the solver used for the final mixed integer linear optimization problem. The considered data of the problem are K=10 off-takes, N=12 time intervals, I=4 canals, M=10 operations for a total of 2112 continuous variables and 720 boolean variables. There is a total of 806 inequality constraints and 620 equality constraints. The network is empty at the beginning of the optimization, with no water in the canals and all the gates closed.

A heuristic method is applied to find an initial feasible solution. This heuristic fills the canals with as much water as possible in order to be sure to satisfy the minimum water requirements for the irrigations. It can happen that some irrigations are not allocated by this heuristic. This scenario indicates that it could be risky to launch the optimization with the current setup as there could not be any feasible mixed-integer solution that satisfies all the current irrigations in the considered time horizon. However, such solution(s) could be found by the solver after extensive computational time. One approach to solve this issue is to lower the corresponding ϵ_k, and then let the solver improve the initial solution so that the water sent to the k-th off-take is increased.

For the presented instance of the irrigation problem, the solver reduces the gap between the current best integer solution and the lower bound to zero in 58 seconds. The fact that the gap is reduced to zero indicates that the reported solution is the global mixed integer solution of the problem. The choice of the weights for the objective function is: $w_1 = 5 * 10^{-3}, w_2 = 0.495, w_3 = 0.495, w_4 = 5 * 10^{-3}$ (see section 3 for details on specific weights). By adopting these weights, we give higher priority to satisfy farmers' requests, reducing as much as possible the water stored in the canals, while keeping under control the travelling time for the gatekeeper.

The optimal scheduling resulting from the run is shown in Figure 4.4. Because the network has no water at the beginning of the optimization, the irrigations are delayed according to the time needed for the water to go from the source to the canals, meaning 2 time intervals for canal 1, 3 for canal 2 and 4 for canals 3 and 4. The irrigations that do not receive the requested water are the # 1, 8 and 9. It is possible to notice that the irrigations that begin the earliest for every canal are the ones that last the most, while shorter irrigations are delayed. One example is irrigation #5 that begins at n=4, even if it could have been activated as early as n=2, considering that it is located on canal 1. This could have delayed the activation of other off-takes down-stream.

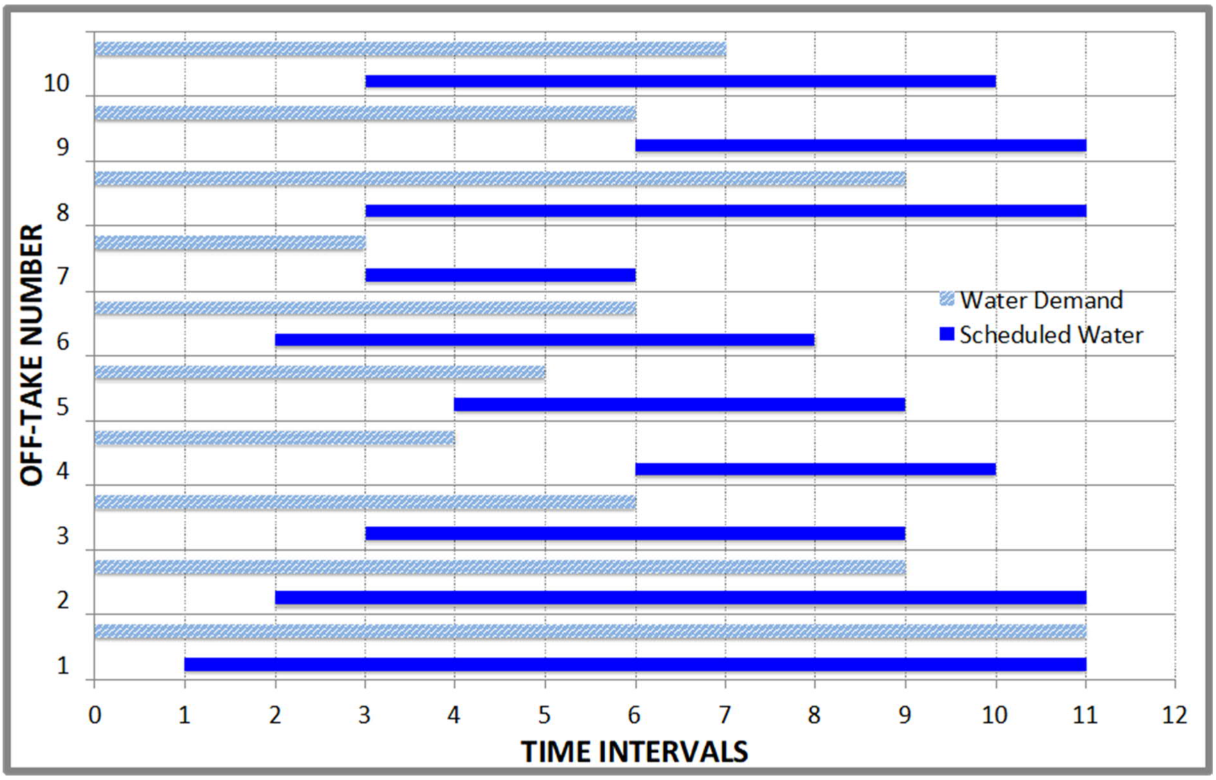

FIGURE 4.4: DEMANDED AND SCHEDULED OFF-TAKES.

Tables 4.6 and 4.7 report the inlet and stored volumes, respectively, for every canal (lines) and every time interval (columns).

	1	2	3	4	5	6	7	8	9	10	11	12
1	878	878	878	1077	1077	1077	1077	440	440	440	440	440
2	0	630	630	630	742	743	742	684	280	280	280	350
3	0	0	203	203	202	202	203	202	202	41	41	41
4	0	0	180	180	180	270	270	270	270	112	113	113

TABLE 4.6: WATER VOLUME (m^3) IN INPUT TO EVERY CANAL FOR EVERY TIME INTERVAL (1 HOUR).

	1	2	3	4	5	6	7	8	9	10	11	12
1	0	0	0	0	0	0	0	59	0	0	0	2
2	0	0	0	0	0	0	0	0	3	1	0	71
3	0	0	0	0	0	0	0	0	0	72	0	32
4	0	0	0	0	0	0	0	0	0	0	0	90

TABLE 4.7: WATER VOLUMES (m^3) STORED IN EVERY CANAL FOR EVERY TIME INTERVAL (1 HOUR).

Looking at values in Table 4.6, it is worth noting that in the time period 4-7, the network is put under intense stress as the maximum respective inlet volumes are almost reached on both Canals 1 and 2. This is due to the large number of irrigations performed in intervals 7 and 8, as it is possible to see in Table 4.8, which summarizes the irrigation active in each canal (line), in each time step (columns). As a matter of facts, nine out of ten irrigations are active in such time intervals.

	1	2	3	4	5	6	7	8	9	10	11	12
1	0	1	1	1	2	2	2	2	2	1	1	0
2	0	0	2	2	2	2	2	2	1	1	1	0
3	0	0	0	2	2	2	2	2	2	1	1	0
4	0	0	0	2	2	2	3	3	3	3	1	0

TABLE 4.8: NUMBER OF IRRIGATION ACTIVE FOR EVERY CANAL AND EVERY TIME INTERVAL.

The gatekeeper trajectory is reported in Figure 4.5. It is possible to notice that the first four operations are performed in order to open the four gates of the network and start the irrigation, while three operations are performed going from gate 1 to gate 4 in order to manage the water during the irrigation. The final three operations are used to close the gates. Time intervals (n) 5 and 7 do not appear in Figure 4.5 since no gate operations were required.

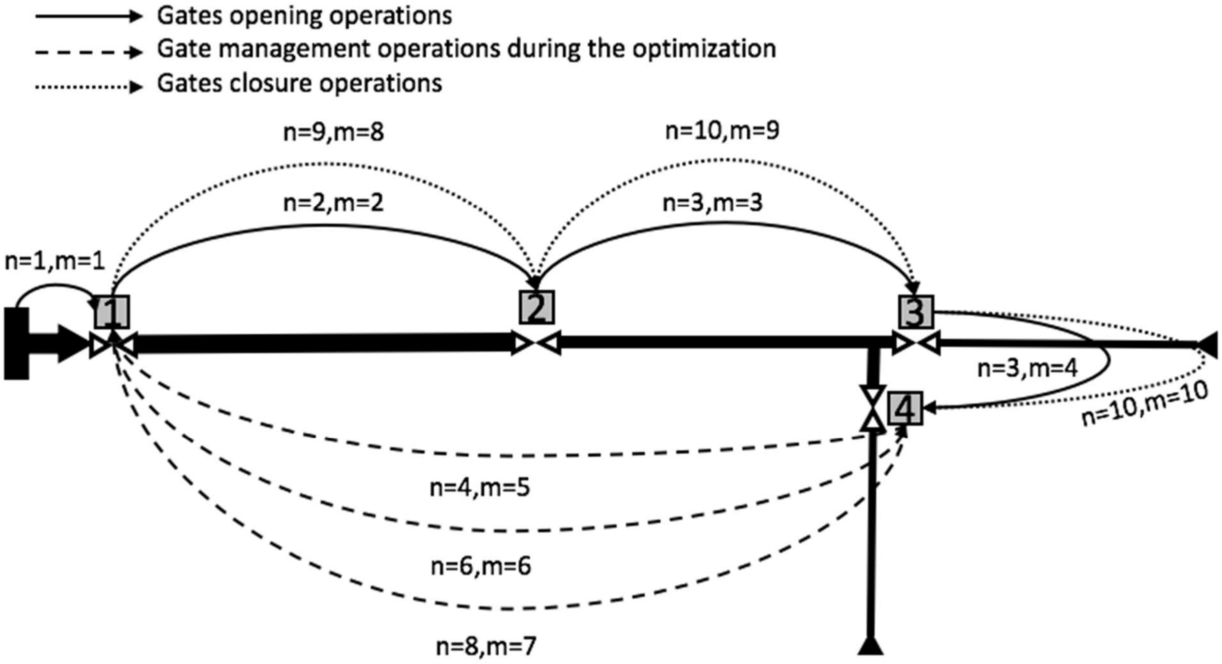

FIGURE 4.5: GATEKEEPER TRAJECTORY DURING THE IRRIGATION; n INDICATES THE TIME INTERVAL THE OPERATION IS PERFORMED AND m THE NUMBER OF THE OPERATION.

The solver performance is summarized in Figure 4.6 that shows the values of the gap between the current optimal solution and the lower bound against the computational time. The initial mixed-integer solution has a value of the gap of 98.53% that is quickly reduced by the algorithm. Giving an initial feasible solution greatly helps the solver. As a matter of facts, even if the initial integer solution is quite inefficient, CPLEX uses methodologies in integer optimization to quickly improve such solution. This explains the fast decrease of the gap in the first half of the optimization. The second part is more focused on improving the lower bound, that is the current continuous solution, so that the gap reaches zero.

For what regards the performance of the final scheduling, we can state that most of the irrigations received the requested quantity of water. The delays are generally due to the geometry of the network and to the time necessary for the water to reach the off-takes locations, starting from an empty network. Small amounts of water are stored in the canals; the majority of the water inflow is used either for the requests active on that canal or to satisfy other requests downstream. There is a great deal of wasted water due to seepage. Of the 9139 m^3 of water that passes through gate 1, only 4437 m^3 are delivered to the farmers. Therefore, around the 50% of the water introduced in the system is lost due to seepage. On the other hand, the total water requested by the farmers amounts to 4689 m^3, resulting in the satisfaction of the 95% of the requested water. Water lost to seepage is an inevitable problem of open canal irrigation and this application shows how the considered formulation also takes into account such an issue. The water remaining in the canals at the end of the irrigation is 195 m^3 (nearly 2% of the overall volume).

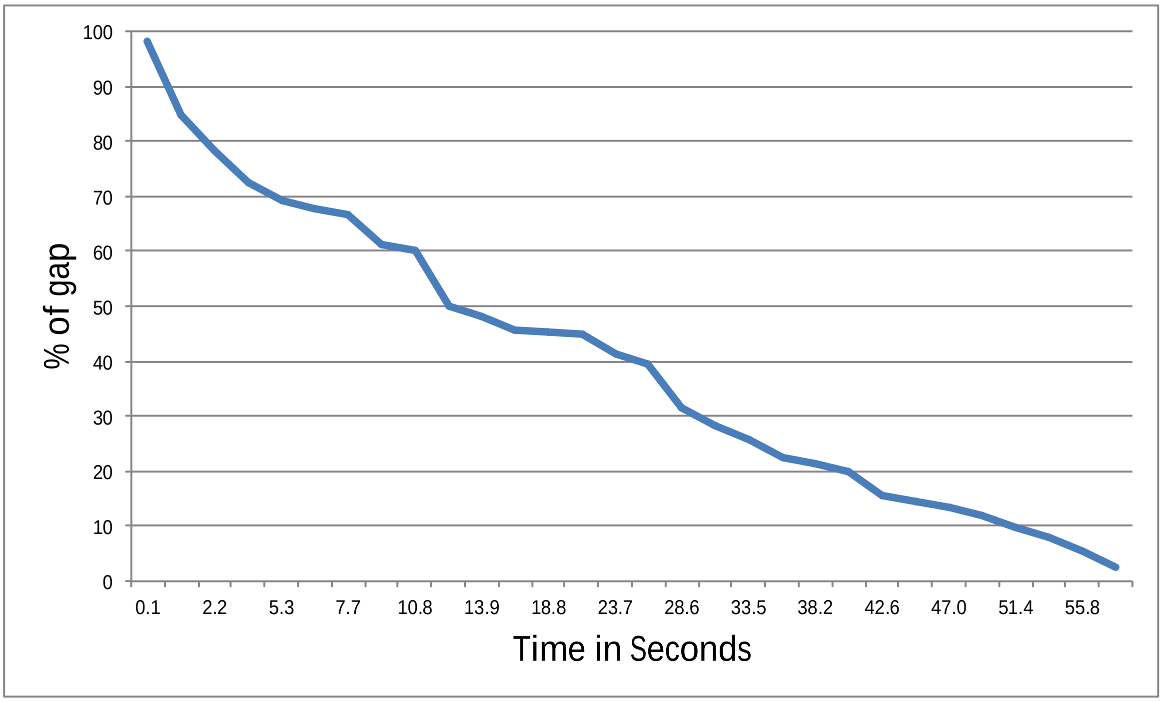

FIGURE 4.6: DUALITY GAP BEHAVIOUR DURING THE OPTIMIZATION.

4.2. Validation method

The results of the optimization model have been verified via hydraulic simulation (Dynamic Wave Analysis) using the SWMM (Storm Water Management Model by EPA Environmental Protection Agency of USA) simulation software. The movement of water through a conveyance network of canals and pipes is governed by the conservation of mass and momentum equations for gradually varied, unsteady free surface flow. Dynamic Wave analysis solves the complete forms of these equations and therefore produces the most theoretically accurate results (Rossmann, 2017). The two equations, known as the De Saint Venant Equations, could be expressed as the following (the first representing the continuity eq. and the second the momentum equation):

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = 0$$

$$\frac{\partial Q}{\partial t} + \frac{\partial (Q^2/A)}{\partial x} + gA\frac{\partial H}{\partial x} + gAS_f = 0$$

Where x represents the curvilinear space variable, t the time, A the flow cross-sectional area, Q the flow rate (discharge), H the hydraulic head of the water, S_f indicates the friction slop and g the acceleration of gravity.

The regulations that need to be performed by the gatekeeper in order to ensure the water volumes necessary for the farmers in different canals have been implemented in the hydraulic simulation. For these purposes, the adjustments of the sluice gates have been chosen in a way to ensure, as far as possible, the flow rates predicted by the optimization model, given the difference in physical description of the water passage from one canal to another between the optimization model and the reality-simulating model. Naturally, a perfect correspondence between the flow in the system's entrance obtained from the optimization model and the one in the canal 1 (see Figure 4.1 or 4.2) is guaranteed. This is possible because canal 1 is directly powered by a water source fixed at a given level, therefore it does not undergo upstream level variations (Figure 4.7).

When it comes to following canals powered by the upstream canals, an effort has been made to minimize the difference between the results obtained by the optimization model and the ones obtained for hydraulic model regulation. Changes in upstream flow regulation, gate openings and the starting of irrigations continuously influence the level in the canals, thus making the hydraulic conditions in the river network slightly different from those provided by the optimization model (Figure 4.7). This was expected in the light of the significant simplifications on reproducing the water dynamic into the optimization scheme.

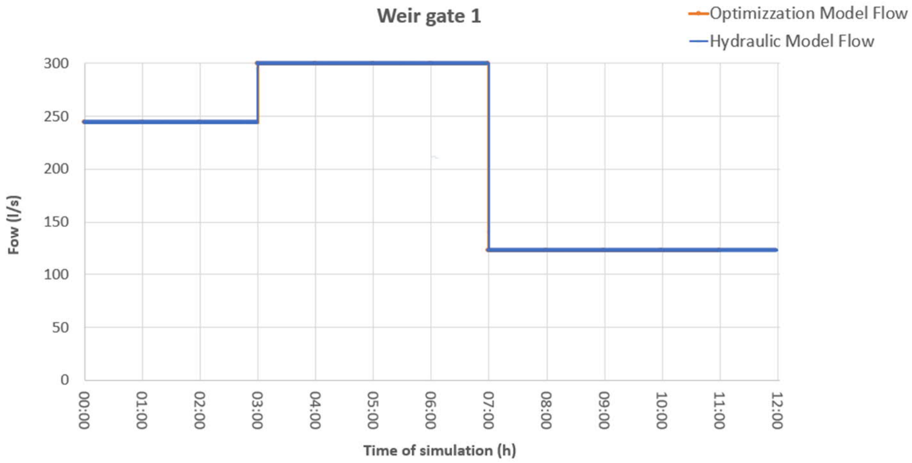

FIGURE 4.7: COMPARISON OF THE FLOW ENTERING INTO THE IRRIGATION DISTRICT FOR THE OPTIMIZZATION AND HYDRAULIC MODEL (CANAL 1 IS DIRECTLY POWERED BY A WATER SOURCE FIXED AT A GIVEN LEVEL, THUS A PERFECT CORRESPONDENCE BETWEEN THE TWO MODELS IS GUARANTEED).

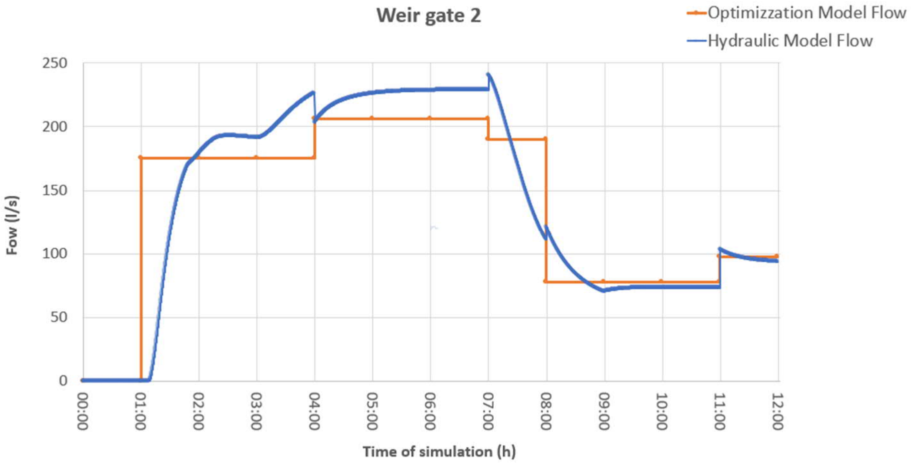

FIGURE 4.8: COMPARISON OF THE FLOW ENTERING INTO THE SECOND CANAL FOR THE OPTIMIZZATION AND HYDRAULIC MODEL.

As depicted in Figure 4.8, despite the differences observed in canal 2, the overall dynamic of the flowing water is properly reproduced by the hydraulic model, which ensures the hydraulic conditions within the canals (i.e. water level, overall volume, retention time, etc.) required to sustain the irrigation requests. Similar results are observed along all other network sections. Following the optimal scheduling provided by the optimization tool with the hydraulic model, all irrigations have been satisfied and no critical conditions (such as canals overtopping) were observed.

These results validate the outcomes of the optimization model that appears reliable in providing a proper irrigation scheduling and operations sequence to WDG called to operate on the network.

5. Real test application – CBEC case study

The Consorzio di Bonifica Emilia Centrale (CBEC) is a reclamation consortium of the Emilia-Romagna Region (Northern Italy) responsible for the irrigation (i.e. Water District Manager, WDM) and water drainage of an area larger of 3,000 km^2, where most of the water required for irrigation is withdrawn from the Po river (major Italian river). The water is allocated to the farms by an intricate irrigation infrastructure composed of more than 3,580 km of canals, six draining plants, 72 pump stations and a number of minor gates and sluices.

The region is located in the Po plain and characterized by a temperate continental climate; it is mainly devoted to agriculture, with a widespread presence of small and medium-sized farms. The irrigation system and the management solutions adopted by CBEC in this region are representative of similar approaches adopted in many parts of Italy, as well as of the South European countries, which make the CBEC a perfect bed-test for the investigation of the scheduling optimization problem.

Actually, the supply and irrigation network consists of a system of open canals on earth. Relevant widths characterize the main canals; therefore, their filling for the irrigation season involves the use of a substantial water volume that is not always recoverable for irrigation purposes. Water losses are due to infiltration through canal banks and bottom, as well as to the management of the irrigation network that requires the filling of long canal stretches and several minor streams to accommodate farmer needs. The complexity of the hydraulic system, together with multiple and interconnected interests and players involved within the irrigation make the scheduling problem a challenging task, which is expected to become even more relevant in case of water scarcity scenarios.

The pilot district covers an area of about 892 ha (320 ha of irrigated area) located between the municipalities of Bagnolo and Correggio, near the city of Reggio Emilia. Figure 5.1 depicts the district, which is named after the two main canals that pass through it: San Michele Canal and Fosdondo Canal.

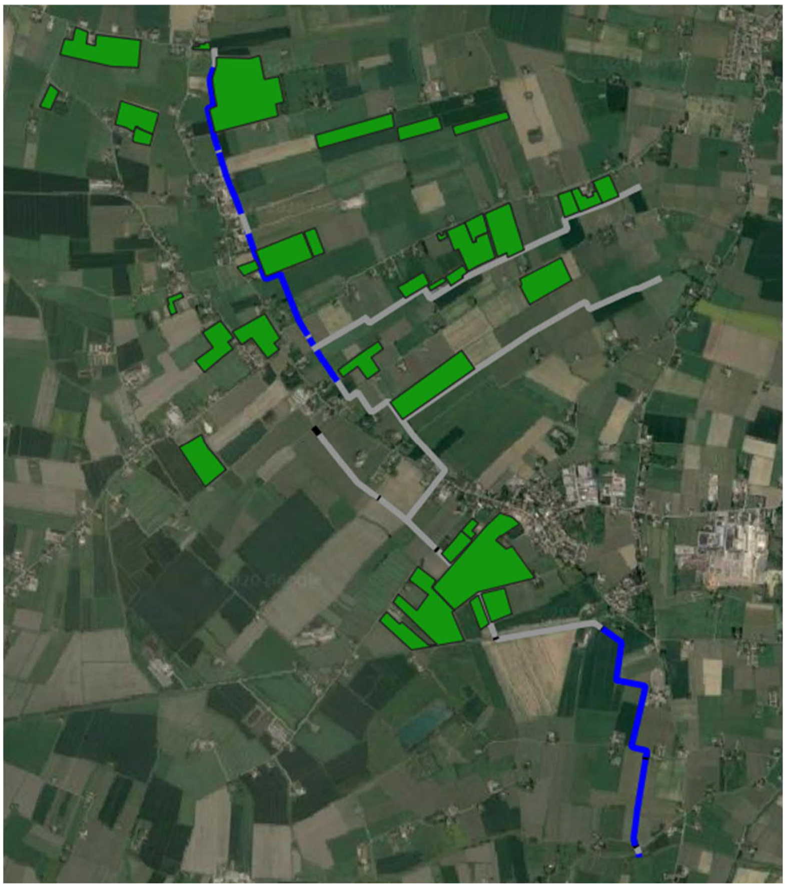

FIGURE 5.1: PILOT IRRIGATION DISTRICT OF CBEC, IN BLUE OPEN CANAL, IN GREY PIPES, IN GREEN IRRIGATED FARMS IN 2019

Figure 5.2 reports a synthetic representation of the irrigation district such as reproduced within the optimization framework earlier specified (the reader can refer to Deliverable “5.01 - Pilot specification” for additional details on district infrastructures, canals geometry and monitoring sensors). The scheme exemplifies the structure of the network as considered within the optimization problem, demanding to sections 3 and 4 for more details.

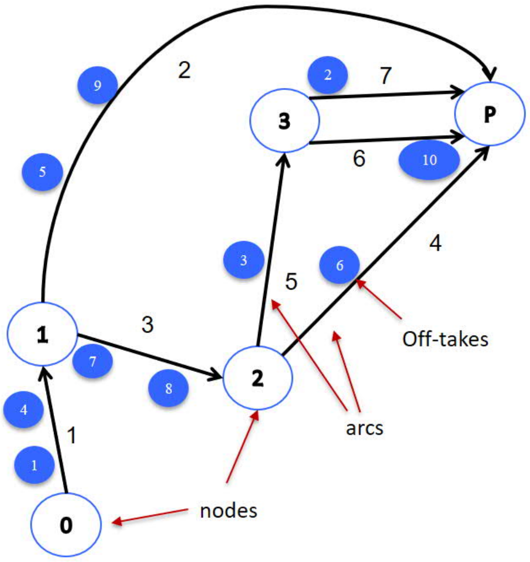

FIGURE 5.2: SYNTHETIC SCHEME OF THE IRRIGATION NETWORK AS REPRODUCED WITHIN THE OPTIMIZATION MODELLING.

5.1. Current irrigation management

Minor canals and pipes reaching the farmers are connected to each other by means of sluice gates that need to be managed by operators (WDG) of the CBEC in relation to water requirements and water availability. This requires a constant presence of operators who survey the proper water allocation by acting on gates, sluice, spillways, etc.

The current procedure to manage the irrigation requests, depicted in Figure 5.3, is based on the initiative of farmers, who have a direct interaction with CBEC administrative office. Farmers contact the CBEC via call centre, or web, and communicate their intention to irrigate. This system is aimed to ensure farmers the access to the water at the time that is more suitable for their interests. In relation to these requests, CBEC plans the service, contacts the farmer and provides the water by operating on the irrigation network. This service is open all working days until 13.00. The gatekeeper responsible of a given irrigation district mediates among the requests and, based on experience and network knowledge, the WDG establishes a plan to supply water in agreement with farmers. The plan is established following conventional rules of practice, which recommend providing water to farms closer to each other, possibly at the same time, avoiding filling the canal unnecessarily. While defining the scheduling the WDG should aspire to reach a compromise between the first-come-first-served basis and the necessity to optimized the irrigation management that impose to irrigate first the farms located closer to the irrigation district intake, and later those more distant.

Apart for the timing, which depends on farmers’ initiatives and habits, the water requirements (i.e., the volume of water used for the irrigation) can vary within a range established by the CBEC in relation to experience, literature indications and water availability. The real amount of water used during each irrigation is thus the results of these concurrent considerations and it is defined by personal agreement reached between WDG and farmers.

Once the scheduling is planned, covering typically a period of 1-3 days in advance, the WDG operates on the irrigation network and assists the farmers during the irrigation, taking notes of the irrigation timing (starting and finishing date and time), as well as of the irrigated volume. All information regarding each irrigation operations is recorded by CBEC. This dataset represents a fundamental element for the application as well as validation of the methodological framework developed in the SWAMP project (see section 6 for additional details).

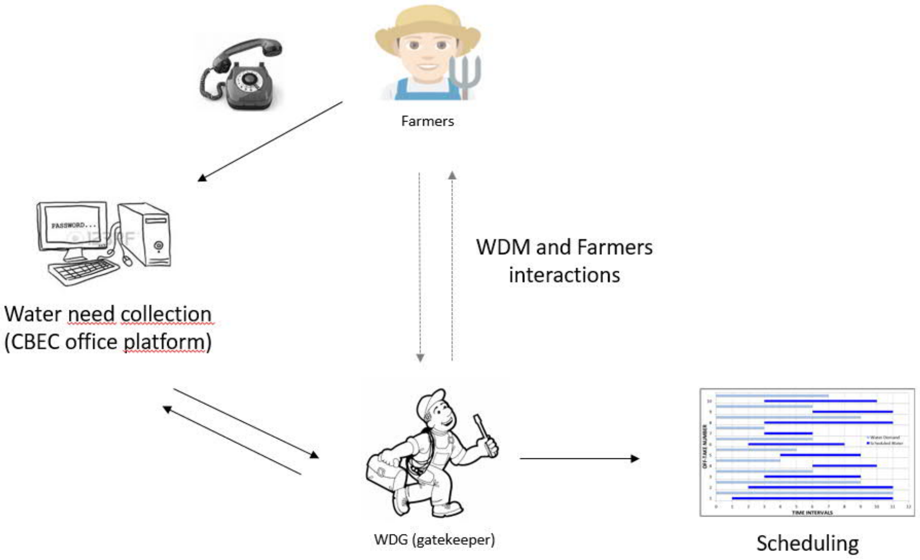

FIGURE 5.3: OPERATIONAL OPTIMIZATION SCHEME THAT CURRENTLY ADOPTED BY THE WDM FOR THE ITALIAN PILOT

5.2. Optimization scheduling integration in the CBEC system

During the final phase of the SWAMP project, a new proposed optimization scheme will be tested in the Italian pilot. Testing the procedure requires the integration of the optimization tool within the existing system adopted by CBEC (WDM) and gatekeeper (WDG) for the management of the irrigation requests (see section 5.1). The pilot serves about 60 farms that need irrigations (this number vary year after year; see Figure 5.1). Water needs estimation will be provided by the SWAMP platform following the water balance method only for 3 of them (see D3.1 and D5.1 for more details on surveyed crops). These requests will be hereafter referred to as SWAMP-based irrigation requests. Remaining farms will still operate following the current practice and their requests pointed out as farmer-based irrigation requests from now on (see also section 5.1).

Thus, the optimization of the scheduling should consider both types of request: SWAMP-based and farmer-based irrigation requests, which have to be satisfied by the same hydraulic infrastructures. Figure 5.4 depicts a schematic representation of the management scheme that will be tested during the next irrigation season in the Italian pilot.

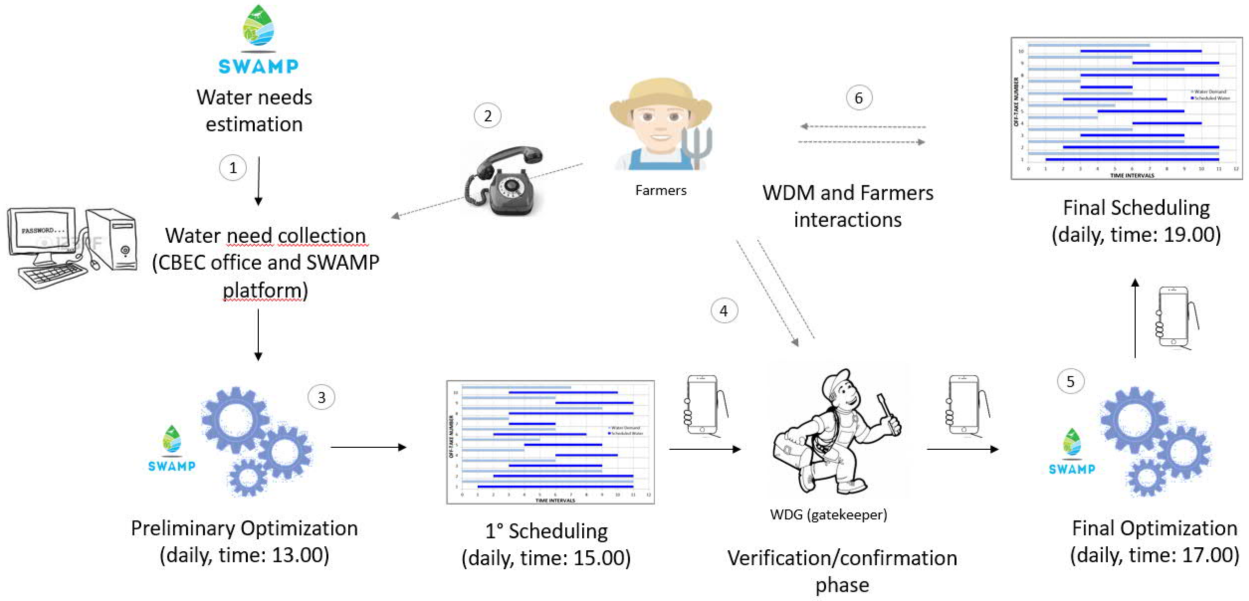

FIGURE 5.4: OPERATIONAL OPTIMIZATION SCHEME THAT WILL BE IMPLEMENTED IN THE ITALIAN PILOT

Starting from the current management approach adopted by the WDM (Figure 5.3), the optimal final scheduling for the coming days will be the outcome of a series of sequential steps as schematized in Figure 5.4:

1) Acquisition of the water needs for the fields considered in the project: Water need for each of the three sites will be estimated by means of the SWAMP platform (water balance method; see D3.1 for additional details) and available for the optimization process through the platform (SWAMP-based requests).
2) Acquisition of farmers' irrigation requests by means of the traditional tool (web or call centre). Farmer-based requests can be collected daily, until 13.00.
3) Preliminary optimization run: At 13.00 all requests are processed within the optimization tool in order to provide a first irrigation scheduling. Although the time required for the optimization depends on a number of variables (see Chapter 3), a reliable and efficient solution will be available in a period of maximum two hours (15.00). The optimization will be performed over a period that covers the coming three days.
4) Verification and confirmation of the 1° scheduling: Results of the first optimization run will be available to the WDG after 15.00 through the WDA (Water Distribution Application; see Deliverable 4.3 for more details). Following the suggested scheduling, the WDG proceeds to get in touch with the farmers whom irrigation requests are settled for the following day. The WDG, in agreement with the farmer, can accept or refuse through the App the irrigation scheduling as indicated by the first optimization run. This step is necessary since each irrigation requires the availability of the farmer, who has to start the pumping system necessary to withdraw the water from the canals.
5) Final optimization run: The second optimization considers those requests that have been preliminary accepted at phase 4. This second optimization step guarantees the achievement of the best scheduling in relation to the availability of the farmers, whose decisions may influence the efficiency of outcomes of the first optimization (step 3). Irrigations refused by farmers at step 4 will be considered for this second scheduling fixing the day after tomorrow as the request timing.
   This final optimization will consider a temporal horizon of two days. This will ensure i) a fast process (final optimization will start at 17.00 and provide the final scheduling maximum at 18.00) and ii) the opportunity to manage the irrigation network in the light of the irrigation foreseen the day after tomorrow.
6) The gatekeeper consults the final irrigation scheduling and communicates to the farmers the final irrigation timing.

This procedure replaces the normal daily interaction among the WDG (gatekeeper) and the farmers, who are continuously in contact to define the actions and agree on irrigation timing and scheduling. The procedure has been defined in agreement with involved stakeholders, namely the WDM (CEBEC), the WDG and the farmers involved within the project. Although it might appear complex, the procedure is believed to simplify the interaction among users (farmers) and the service provider (WDM and WDG), insuring at the same time the most efficient irrigation scheduling.

In addition, the adopted approach will ensure a higher degree of flexibility to the SWAMP platform and the developed applications. In fact, the capability to manage at the same time both farmer- and SWAMP-based irrigation needs offers more operational options and modularity in the future implementation of the solutions developed within the project. To this matter, for the sake of clarity we summarize here three different options concerning as many levels of implementation:

i) SWAMP platform full application: This condition represents the optimal case in which the overall set of modules of the SWAMP platform is applied to all farms within the pilot, as well as to other irrigation districts. In this case, irrigation needs will be estimated by the platform (Task 3.1) and the irrigation scheduled following the optimal approach. The optimal procedure will manage SWAMP-based irrigation requests, exclusively.

ii) Partial or limited SWAMP platform application: This condition represents the case in which only few, or a portion, of farms located within an irrigation district benefit of the SWAMP solution for the estimation of the irrigation needs. In such condition, the optimal scheduling module is still applicable. This might also be representative of the transition period that goes from the current situation to the one depicted at scenario i). The Italian case study is supposed to be at this stage at the end of the of the project.

iii) Irrigation scheduling only: In this case, the optimization module is called to manage farmer-based requests exclusively. Although representing the worst-case scenario in terms of project achievements, this ensures the possibility to immediately enlarge the application of the scheduling procedure to other irrigation districts. Even if irrigation requests will remain based on farmers experience only (farmer-based irrigation, exclusively), the scheduling will be optimized following the procedure proposed here (see section 3).

To evaluate the efficiency of the system and identify its weaknesses, gaps or elements of improvements, a trial test of few weeks during the upcoming irrigation season is planned. During this period, the overall system (see Figure 5.4) will be tested under operational conditions. This option, although significant and necessary, requires the availability and interoperability, of multiples data sources and tools (SWAMP platform, WDM app, water need estimation module, etc.). Despite the advanced degree of readiness of each individual element and module, their interoperability is not ready yet, and the recent constrains and restrictions to field operations and people mobility due to Covid-19 pose additional challenges. In such condition, the target is to be able to test the system at least by the end of the upcoming irrigation season (i.e., late summer 2020).

6. Performance assessment plan

The impact assessment of the optimization scheduling in the Italian pilot represents a challenging task. The pilot infrastructure and the current irrigation practice present some peculiarities that are similar to those of the analogous irrigation districts in the Po valley and in other regions; nevertheless, these characteristics challenge the performance assessment and the evaluation of targets achievement.

Such peculiarities are:

- Impossibility to identify two similar pilots for comparison purposes. The irrigation district adopted as pilot represents a unique element, with irrigation canals, pipes and geometries that cannot be identified in another irrigation district. This makes impossible evaluating the performance of the irrigation district by means of a one-to-one comparison with a twin pilot not managed following SWAMP rules.

- The pilot considers more than 60 irrigated farms, while only for 3 of them the water need requirements will be estimated by the project (previously indicated as SWAMP-based requests). This means that during the same irrigation season there will be the coexistence of SWAMP-based and farmer-based irrigations (i.e. requests estimated based on their personal experience), both served by means of the same irrigation network. This prevents the possibility to manage the irrigation network to accomplish SWAMP-based requests only.

- Intra-annual comparison of the district performance is difficult due to the variability of the weather conditions, crop types and their movements within the district. Thus, each year appears unique in terms of water requirements, water distribution and district efficiency.

Following these considerations, the assessment of the scheduling optimization cannot be inferred by looking at different districts, but rather it can only be achieved by referring to a digital twin of the irrigation network. This consists of a hydraulic model of the irrigation network developed to mimic its hydraulic behaviour under the hypothesis of an optimal management practice.

Figure 6.1 reports a schematic representation of the plan conceived to assess the performance of the optimization scheduling. In the light of the complexities and peculiarities listed above, the assessment plan will benefit of two key elements: 1) a detailed database of irrigation records collected during past irrigation seasons; 2) a digital twin (hydraulic model) of the irrigation district.

Concerning the former, the CBEC collects all details regarding each irrigation request. Among these data, the database records the request date, the irrigation date, hours of irrigations, amount of volume used, location of the irrigation, etc. (such requests are represented as red vertical lines in Figure 6.1). This information enables the identification of the irrigation performed during a given period of time (black vertical lines in Figure 6.1), in response to farmers' requests. It is worth noting that red lines are equal in length since the farmers do not require a specific amount of water, but rather the access to it. On the contrary, the length of the black lines indicates the variability of the irrigated volume, which vary from different crops and in relation to water availability, crop type and irrigation method.

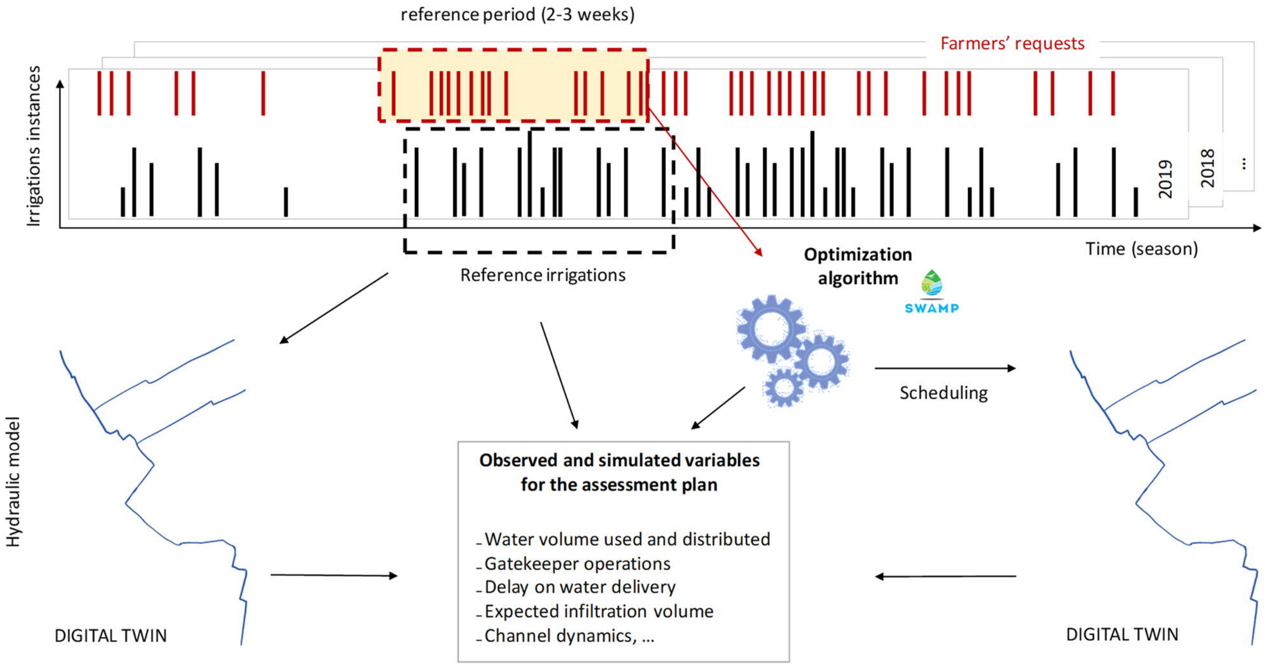

FIGURE 6.1: SCHEMATIC REPRESENTATION OF THE PERFORMANCE ASSESSMENT PLAN.

Starting from this dataset, the performance assessment plan will refer to a period of few weeks assumed as reference period. Real operations performed in this timeframe (black lines) will be analysed by means of a digital twin (i.e., hydraulic model) in order to assess the performance of the network under past real conditions. As previously shown for the synthetic test application (section 4), the digital twin duplicates the realistic behaviour of the irrigation network by means of a hydraulic model (developed using the software SWMM), which is capable to simulate the delay on water delivery, the water volume needed to fill in the canals, etc. The digital twin will enable the estimation of all hydraulic variables that cannot be measured in the field (e.g., water losses due to infiltrations) or that were not collected during the irrigation season (e.g., overall water volume in time within the canals, etc.). The simulation of past irrigation sequences, together with the recorded dataset, will provide us all the information necessary to evaluate the performance of the irrigation district while traditionally managed.

Afterwards, farmers' requests that generated the irrigations during the same reference period (red lines highlighted in Figure 6.1) will be managed by means of the optimization procedure developed and presented in this document. The scheduling resulting from the optimization process represents the optimal sequence of the irrigations adopted as input for the digital twin. Following this approach, the digital twin assumes the role of mimicking the real irrigation network, thus providing all hydraulic variables and indexes previously measured, or estimated, with reference to the real irrigation sequence.

The comparison of these results will support the evaluation of the benefits expected from the use of the optimization procedure. In particular, with reference to the chosen reference period, the assessment plan will enable the comparison of key variables, such as:

- the overall volume of water allocated to the irrigation district to satisfy the requests;
- the estimation of the water losses due to infiltration within the irrigation system as a function of the water volume (and retention time) within the canals;
- the amount of gate operations needed to accomplish the scheduling (in both cases: real and optimized scheduling);
- the water delivering delay in time (days) between the request and its satisfaction.

Those findings will be used as reference for the evaluation of the final assessment plan at the end of the project (see D5.4). In particular, for what regard the irrigation network, the assessment of water consumption reduction will be evaluated in terms of efficiency of the water allocation system (i.e., the ratio between the overall water volume distributed to the field and the volume allocated to the district), which in end will be estimated based on the outcomes of the presents assessment plan. Similarly, the impact in terms of energy consumption will be evaluated as a function of the reduction of the water volume distributed within the district, while the reduction of water losses due to infiltration would be a direct output of the assessment plan.

Finally, the outcomes and feedbacks of the real test application planned with the CBEC (see Section 5) will serve to evaluate the impact of the optimization framework in terms of sustainability, efficiency and flexibility of the overall irrigation system (e.g., efforts of the gatekeeper, improvement on farmers and gatekeeper interactions thanks to the use of web applications).

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