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Rethinking the modernization of pressurized networks: Lessons from a case study in the Gharb (Morocco)

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A B S T R A C T

Irrigation modernization aims to improve water efficiency and reduce energy costs while ensuring the long-term sustainability of irrigation systems. However, restricted investments, and standardized management often create technical and economic constraints that limit farmers' ability to adapt irrigation methods to their needs. This study examines the 2012 collective drip irrigation project in the Gharb irrigation scheme (Morocco), adaptation of a previous existing network, which sought to replace sprinkler irrigation with drip irrigation to improve water and energy use. Despite initial adoption, 48 % of farmers reverted to sprinkler irrigation due to pressure deficiencies, soil constraints, and financial barriers. By means of an original methodology supported by hydraulic modeling and design tools (Gestar®) and field data collection, we evaluated alternative network operational conditions and infrastructure modifications to improve system reliability. The findings show that allowing farmers to combine drip and low-pressure sprinkler irrigation enhances flexibility while restraining water and energy use. Improving network performance requires resizing bottleneck pipes and adjusting head at pumping station, ensuring sufficient pressure at outlets for nominal conditions. These modifications must be economically viable, requiring cost-benefit analyses to balance infrastructure investments with long-term affordability. Beyond technical adjustments, the study highlights the importance of negotiation and participatory governance in irrigation modernization. While this case focuses on the Gharb region, the research approach, the challenges of infrastructure limits, adaptation strategies, and governance gaps are relevant to irrigation modernization worldwide. Ultimately, modernization should support farmer-centered irrigation systems, ensuring economic feasibility, resource efficiency, and adaptability to future challenges.

1. Introduction

In the face of increasing water scarcity and rising energy costs, the modernization of collective pressurized irrigation networks has become a key strategy to improve water and energy use efficiency (Belaud et al., 2020). However, modernization efforts also present technical, economic, and institutional challenges that can affect their long-term effectiveness.

Many studies have focused on reducing water demand and energy consumption and their associated costs, particularly since the increase in the price of electricity. Some studies emphasize infrastructure changes, such as the transition from sprinkler to drip irrigation (Bowen et al., 2012). Others propose the implementation of low-pressure sprinkler irrigation systems (Oniward et al., 2010; Robles et al., 2017; Yan et al., 2020). Additionally, some studies recommended installing variable speed pumps to optimize energy use at the network level (Moreno et al., 2007; Lamaddalena, et Khila, 2012; Delfan Azari et al., 2021).

Beyond infrastructure, new management strategies have also been assessed to reduce energy consumption at the network level. For example, reducing the total head at the central pumping station can lower energy costs but may cause a drop in pressure at hydrants, ultimately affecting water application efficiency (Córcoles et al., 2016). Other strategies involve irrigation sectorization, optimizing irrigation turns based on farmers' energy requirements (Rodríguez Díaz et al., 2009; Carrillo Cobo et al., 2011; Navajas et al., 2012; García et al., 2014). Additional measures include semi-arranged demand

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management (Garcia et *al.* 2017) and arranged demand to minimize energy cost (Aliod et al., 2015; Córcoles et al., 2015). These approaches have been shown to save up to 30 % of energy cost (Navarro et *al.* 2012; Aliod et al., 2015) and even an additional 10 % if pumping station operating point is optimized in real time (Faci et al., 2016).

To further improve pressurized irrigation systems, mathematical models and optimization frameworks have become essential tools for optimizing irrigation infrastructures design and/or their management. Nowadays, most computational tools designed to simulate pressurized water distribution networks are based on the EPANET numerical kernel (Rossman, 2000), initially developed in the drinking water context, to compute their performances under different operating conditions. Professional software with original hydraulic modeling specifically conceived for pressurized irrigation networks can be found ready to use in COPAM (Lamaddalena, et Sagardoy, 2000), developed at CIHEAM-Bari, and GESTAR (Estrada et al., 2009) developed at University of Zaragoza. They both integrate hydraulic simulation computational routines, as well as network sizing optimization algorithms and performance characterization tools to enhance network design and management. COPAM capabilities related to performance assessment have been recently updated by means of MASSPRES (Lamaddalena et al., 2024).

A wide range of optimization techniques, from innovative evolutionary algorithms (Ikudayisi and Adeyemo, 2015) to classic linear programming (DIOPRAM, 1989), have been studied and applied to minimize infrastructure and energy cost and to improve water allocation efficiency while minimizing energy consumption and operational costs (Aliod et al., 2015; Loureiro et al., 2024; Xu, Chen, 2024). More recently, machine learning and real-time decision support systems have further advanced irrigation management by incorporating weather forecasts, soil moisture levels, and crop water needs to optimize irrigation scheduling dynamically (Abioye et al., 2022; Umutoni, Samadi, 2024). These modeling approaches contribute to the development of more resource-efficient and resilient irrigation systems, aligning modernization efforts with economic and environmental sustainability goals.

However, irrigation modernization of collective irrigation schemes is increasingly understood as a holistic process. It extends beyond energy and water demand savings aiming to enhance water productivity, ensure sustainable rural livelihoods, and improve the resilience of irrigation systems. This involves a range of stakeholders, including farmers, water users associations, state technical services, and policy makers (Tarjuelo et al., 2015; Playán et al., 2024). Moving beyond the optimization of isolated parameters, the focus is shifting towards enhancing the robustness of irrigation systems, meaning understanding how individual decisions interact with diverse contextual variables (Janssen and Anderies, 2013). As farmers have different objectives and means, poorly adapted or overly rigid designs often create practical difficulties in operating the irrigation system. For example, in Valencia (Spain), the modernization of the Jucar irrigation system introduced collective fertigation, where fertilizers were dissolved in irrigation water and applied collectively. However, this approach conflicted with the needs of certain farmers, particularly those practicing organic farming or growing early and late-season fruit varieties (Poblador et al., 2021).

Indeed, while the overall goals of irrigation modernization are generally shared among stakeholders, the specific design choices in infrastructure and management that are made — whether at the collective network or on-farm equipment—have generally far-reaching, and sometimes unintended consequences on farmers' daily irrigation practices and the overall performance of irrigation schemes (Ortega-Reig et al., 2017). The interplay between collective network management and on-farm irrigation methods and practices is, therefore, increasingly considered a crucial issue (Zapata et al., 2023). For instance, in free-access pressurized irrigation systems, hydrants are in general deliberately oversized compared to the fictitious continuous flow needed to meet total water demand. This flexibility allows farmers greater freedom in deciding when and how much water to apply (Sawassi et al., 2021). This approach, known as "degrees of freedom", seeks to strike a balance between providing farmers with irrigation scheduling flexibility while preventing investment and energy waste. However, in some cases, designers or stakeholders favor uppermost economic solutions that restrict farmers' choices regarding water use or irrigation technique. These designs aim to achieve theoretical water demand savings, when no effective volume demand control exits, or cost reductions, but may not align with farmers' practical needs and future irrigation evolution (Rodríguez-Díaz et al., 2011).

A similar divergence between expectations and reality has been observed in Morocco's Gharb irrigation scheme, one of the country's largest state-managed irrigation networks. The C3 district, originally designed for sprinkler irrigation in 1976 and readapted in 2012 to promote drip irrigation, serves as a relevant case study for examining the real impacts of irrigation modernization. The 2012 project aimed to reduce water demand and energy consumption, improve irrigation service through a centralized pumping station, and provide individual billing and flexible water supply rates. However, despite these efforts, field observations revealed discrepancies between expected and actual farmer adoption of drip irrigation. Throughout the process, farmers actively voiced concerns regarding large pressure variations, irrigation scheduling constraints, and system adaptability (Kettani et al., 2022). Their feedback played a key role in identifying necessary adjustments, including resizing key pipelines and optimizing water distribution strategies to enhance system performance and reliability.

This study aims to identify the challenges and impacts of irrigation modernization projects, emphasizing the need for a more flexible and participatory approach that aligns with farmers' needs and ensures the long-term success of irrigation modernization initiatives.

It also seeks to assess the actual performance of the pressurized irrigation network after the 2012 modernization project, and to evaluate several alternative infrastructure solutions proposed to overcome the disfunctions found, including network redesign, in order to improve system efficiency and dysfunction challenges related to water distribution and proper pressure level at hydrants.

2. Materials and methods

The general approach followed in this study involves a comprehensive analysis of the pressurized irrigation network in the C3 district part of the state-managed Gharb irrigation scheme. Originally established in 1976 and historically reliant on sprinkler irrigation, the district was refurbished in 2012 through the implementation of a collective drip irrigation project, as part of Morocco's national water-saving strategy.

The study evaluated the performance of the existing system, and several other feasible modifications, after a field data collection, by means of hydraulic modeling, and scenario simulations.

The study required various alternative network scenarios to be tested, and the assessment of the impact of different irrigation methods, drip and sprinkler systems. The evaluation and assessment of each scenario is performed by means of two main statistical parameters related to individual outlets operational quality (reliability, and relative pressure deficit, defined in 2.4) under different flow regimes, and also by means of synthetic network characteristic curves (see the analysis parameter definitions in 2.4) that show the overall pressure head requirements at network inlet for each flow regime.

To perform all the involved computational tasks, including the optimum network resizing in required scenarios, GESTAR version 2016 software package (Estrada et al.; 2009; GESTAR®, 2016) was used. This package is specifically dedicated to design, simulate and analyze performance of pressurized irrigation networks and their pumping stations, containing a complete collection of generalized tools that support all the required procedures, modules and data bases, in a single user friendly graphical interactive environment. It has been extensively exploited and validated, since 1998, as a reference advanced engineering tool for design and management of pressurized irrigation networks, among others countries, in the intensive irrigation modernization programs deployed in Spain from 2000 until now. A larger irrigation project, (15.000 ha) now developed in Agadir, Morrocco, is also being engineered with GESTAR.

By comparing these scenarios, the study aims to identify optimal strategies for managing or refurbishing the irrigation network, while considering both functional and financial aspects.

2.1. Case study: C3 district

The 2012 project aimed to reduce water and energy consumption through a renewed pumping station and drip irrigation introduction. It also addressed some issues in the previous system, such as the difficulty of sharing hydrants, high water bills, and the inconvenience of mobile sprinkler equipment (Kettani et al., 2022).

- ***Challenges of Drip Irrigation Adoption***

  Farmers were first consulted through interviews and meetings to understand their willingness to switch from sprinkler to drip irrigation. Before starting the project, the irrigation administration asked for their approval, and about 70 % agreed to adopt the new system. They were motivated by the hope that drip irrigation would help solve major issues with sprinkler systems, such as high-water costs, difficult equipment management, and uneven water distribution.

  Despite this initial optimism, many farmers encountered major challenges that hindered the full adoption of drip irrigation or led them to revert to sprinkler systems. These difficulties stemmed from a combination of technical, economic, and agronomic factors, making the new system less practical or financially viable for some farmers. This shift was partly influenced by soil characteristics, which caused infiltration and cracking issues under drip irrigation, as well as equipment-related constraints, including filter clogging and rodent damage, leading to dissatisfaction among farmers. The transition also increased labor demands, requiring more frequent handling of drip lines. Furthermore, sprinkler irrigation remained better suited for certain crops, such as sugar beet and alfalfa, which require uniform soil moisture and easier equipment management. Finally, financial constraints, land tenure issues, and individual farmer preferences further contributed to the uneven adoption of drip irrigation. As a result, 48 % of farmers who initially adopted drip irrigation partially or entirely reverted to sprinkler irrigation, while 20 % never installed the system.

- ***C3 Irrigation Network Overview***

The C3 irrigation district spans 3443 ha and is supplied by the SMPC3 pumping station, which operates with variable speed drivers that can modulate supplied flow rate and pressure head efficiently. The network design allows free access at collective hydrants, while plot-level irrigation follows a rotational schedule, preventing farmers from irrigating entire plots simultaneously.

Each collective hydrant, covering an average of 12 ha, serves multiple farms with outlets (individual hydrants) that supports a range of crops, including cereals, sugar cane, sugar beet, sunflower, and forage crops. Individual outlets were sized to supply a maximum flow rate of 1 L s^{-1} ha^{-1}, and the minimum required pressure upstream the outlet is 28 m.

The hydraulic network (Fig. 1) is now composed of: (i) a main pumping station (SPC3) drawing water from the Sebou river; (ii) an open canal conveying water to the pressure station; (iii) the pressure pumping station (SMPC3) with variable speed drivers, a collective filtration station and regulating pressure-surge protecting tanks; and (iv) main, secondary, tertiary and connection (connecting the tertiary pipes

Fig. 1. Map of the C3 irrigation district.

to outlets) pipes.

Water distribution is organized into three main branches (A, B, and C), with SMPC3 as the central inlet node (Fig. 1).

- ***Focus on Branch C***

Branch C (Fig. 1, Table 1) was chosen as the focus of this study due to its high conversion rate to drip irrigation, making it a valuable case for assessing the long-term impact of modernization efforts. Additionally, as the first section to undergo modernization, it provides the longest historical record, allowing for a thorough evaluation of system performance and farmer adaptation. The availability of complete data for this branch further strengthens its suitability for in-depth modeling and hydraulic analysis.

2.2. Analysis Methodology

To address the weaknesses identified in the 2014 modified irrigation network, we opted initially for minimal interventions on existing infrastructure while ensuring cost-effective solutions. First, we analyzed the network's actual operation after the 2014 modifications (base scenario, S0) (Fig. 2). To assess the feasibility of different irrigation methods with minimal structural changes, we generated two scenarios: one with exclusive drip irrigation (S1) and another with low-pressure sprinkler irrigation (S2). This evaluation helped determine which system best suited field conditions and farmer needs while maintaining economic viability.

To resolve water pressure and availability constraints, we tested two corrective actions: 1) modifying the total head at the Branch C inlet within the discrete range possible, that is limited by present pumping station capabilities and requirements of rest of branches, and 2) resizing some pipes in the network or the whole network (a major modification in this case) to reduce pressure losses (Fig. 2). Given the financial implications of any modification, a comparative analysis of the functional and economic performance of these solutions was conducted to identify the most viable option. This approach ensured that improvements remained technically feasible, financially sustainable, and aligned with system constraints and farmer preferences.

2.3. Software tools

For this study, several Gestar® computational modules were used to analyze the pressurized irrigation system, and to simulate or design alternative infrastructure and management scenarios.

- Design flow Rates computation and Network Sizing optimization in Gestar®

  Design flow rates in branched networks can be defined for each pipe using either the Clément formula, in the case of on-demand irrigation networks, or by upstream flow accumulation of open hydrants in irrigation networks operating on predefined turns. Gestar also permits user-defined flow rates values at each pipe.

  Once the design flow rates are stablished, Gestar® provides sizing tools for branched networks that includes economic optimization criteria. They can identify the combination of pipes and pumping head needed to meet the set of pressure requirements at design flow rates, with a minimum overall cost (accounting for both investment and energy consumption). Optimization routines are adapted depending if the system is going to operate on-demand or with predetermined turns. The network sizing optimization modules introduce a quick two-step combined algorithm that begins with a Lagrange Multipliers type method (González and Aliod, 2003), formulated in terms of continuous diameter to estimate a first guess of the pipe's inner diameters along the series of conduits. In a second iteration the initial pipes selection is refined fitting the theoretical continuous diameter to normalized discrete diameter by means a simplified Labye's type discontinuous method (Labye et al., 1988).
- Hydraulic Performance Assessment in Gestar®

  Simulation for quasi steady hydraulic analysis is provided in a generalized matrix Nodal Analysis Method enhanced with a predictor-corrector relaxation numerical technique, equivalent to the final algorithm called Gradient Method (Todini and Pilati, 1987) used in EPANET. It confers rapid unconditional convergence, as well as superior stability when multiple interacting regulating vales are present. It also allows to introduce a flexible combination of known at unknows parameter at each node, useful for inverse analysis. Details can be found in Estrada et al. (2009). The computational kernel is complemented with a wide range of operational and configuration tools for irrigation networks, that generate deterministic (instant or time dependent) demand configuration or random (single or multiple) flow configuration for any complex network, either branched or looped, including arbitrary characteristic pumping stations, regulating valves, etc. A general hybrid modeling for hydrants, that combines a flow driven demand node; when pressure is above minimum required, with a pressure-dependent node, when the pressure is below, can be used when overdemand conditions detailed modeling is seek. Further modules related to general modeling, design and regulation of pumping stations are included (Paño et al.; 2012). Results are directly offered in detail, for every node and element at every flow configuration considered, or condensed as and average and extreme values (GESTAR®, 2016).

  The hydraulic modeling in this study was used to identify the potential and actual network performance and variations under rather different operational conditions. This network assessment allowed us to identify the inherent dysfunctions, the most effective infrastructure modifications and overall management strategies, but it is not meant to plan the daily operations. Therefore, calibration of computed pressure against observed pressure for flow data in order to replicate detailed field data has not been considered, for the sake of simplicity of presentation of essential objectives and results. Reference FAO tools, including COPAM and MASS PRESS, that include or focus on pressurized irrigation network assessment do not address pressure calibration either. Furthermore, the network collapse found in practice above certain demand regimes is predicted as well by hydraulic simulations, indicating that the cause is not any high hidden local head losses or erroneous data acquisition, but a straightforward overdemand on the system.
- Creation of an input file and database

To implement the irrigation networks in the Gestar® software package, we had to obtain information concerning the irrigation network such as pipe internal diameters and roughness, and the layout of the network. Topography and hydraulic data were obtained from the network design document (ORMVAG, 2012) and by checking the physical condition of the network in the field.

Field measurements were taken on 20 farms. The actual flow rate was recorded at each individual outlet to determine irrigation volumes. Additionally, pressure was measured at the outlets located downstream network to confirm the almost perennial pressure deficit at peak season.

The irrigation network is modeled as a set of pipes, nodes (i.e. pipe junctions) and individual flow driven outlets. The input file was created using GIS software (ArcMap®) then exported to AutoCAD® and finally imported into Gestar®. The input data required to create the model were, in the first place, the pipes data, the internal diameter, the

Table 1
Characteristics of Branch C.

	Branch C	Total C3 District
Cultivable area (ha)	658	3443
Collective hydrants	62	314
Individual outlets	364	1616

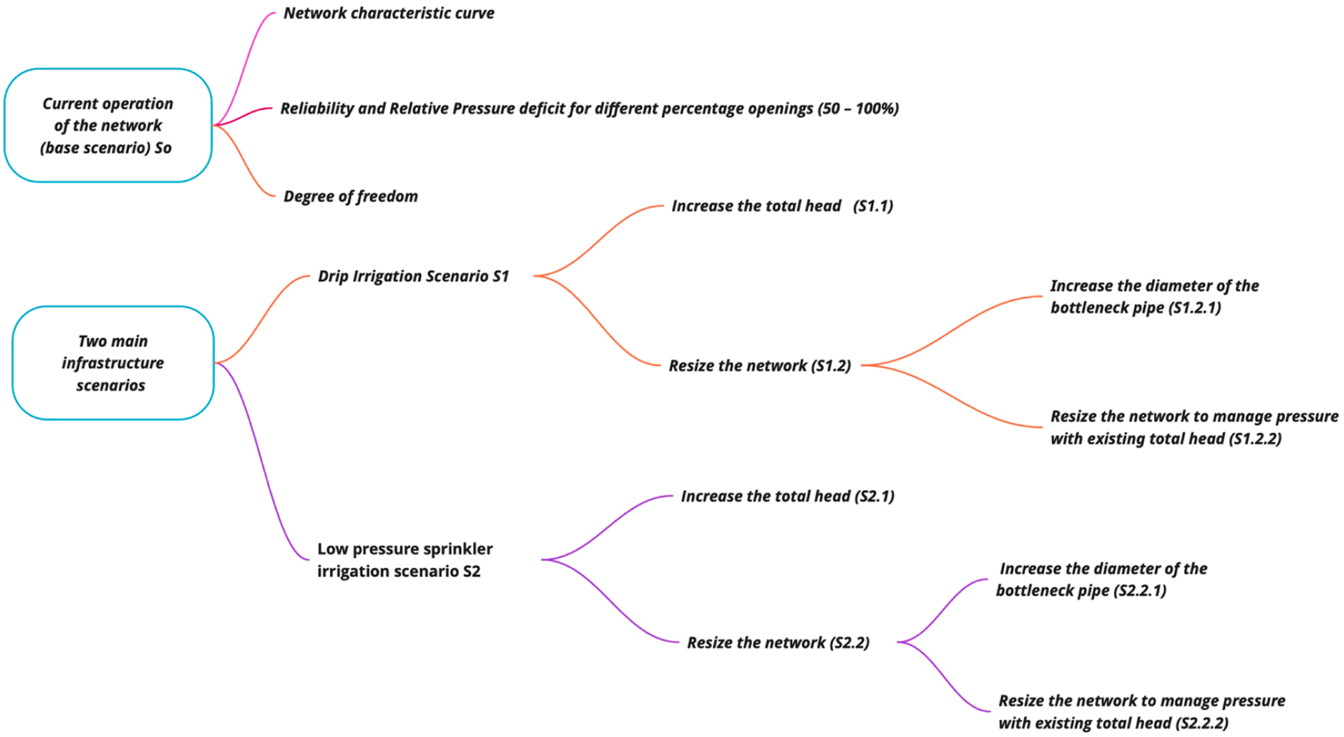

Fig. 2. Upper: Analysis parameters and techniques used in the scenarios (listed here for the base scenario). Lower: Methodology strategy, and description of alternative scenarios studied apart from the base scenario.

roughness attributed depending on the pipe material (as indicated in Table 6 pipes with heavy aging were considered) and length. In the second place, the topology and topography of the network with 364 individual hydrants (outlets) were mapped. Finally, individual outlet data were introduced: irrigated area, the continuous fictitious flow, the network availability ratio, the minimum required pressure upstream outlet (MRP, hereafter denoted Hmin) and the maximum allowed demand (i.e. the maximum flow rate that can be extracted from an outlet).

2.4. Network analysis and diagnose parameters

To assess the performance of pressurized irrigation system scenarios, different statistical parameters and indicators were computed, including the networḱs characteristic curves for the entire C3 network, and outlets individual performances, where every single outlet is modeled and open independently. These variables, along with their compact representation, help evaluate the whole system and the single individual outlet's ability to meet irrigation demands while maintaining adequate pressure at outlets in a simple and comprehensive manner. The following nomenclature and definitions will be used in the network hydraulic analysis, equivalent to the ones found in Lamaddalena, et Sagardoy (2000).

- Flow regime

  A flow regime is defined as the percentage of individual outlets that are open simultaneously. In the case that all hydrants have approximate the same flow rate (which is the case when similar areas are irrigated from every hydrant), the flow regime will correspond to a % of the maximum theoretical flow rate (all outlets open) found at the inlet pipe of the irrigation sector (C3 branch in this case).
- Demand configuration

  Demand configuration for a given flow regime (%), is any of the possible specific combination of outlets open that satisfy the % corresponding flow regime. For example, in a network of 100 hydrants, for a 60 % flow regime, any combination of 60 hydrants open, while the rest are closed, will be a demand configuration for a flow regime of 60 %. As the number of combinations of possible demand configurations is quite huge when the number of outlets increase, calculation of average values or distributions for all possible demand configuration is not practical. Instead, an ensemble of demand configurations, each one randomly generated, according to the outlet probability of opening is used.
- Reliability of an outlet for a given flow regime

  According to Lamaddalena, et Sagardoy (2000), outlet reliability *(1)* is defined as the probability that a given outlet provides the required pressure (Hmin,i) under a specific flow regime. It is computed by evaluating multiple random outlet demand configurations and determining how often the outlet upstream pressure remains above the required threshold. The reliability of outlet i is given by:

$$R_i = \frac{\sum_{r=1}^{C} S_{i,r} \times P_{i,r}}{\sum_{r=1}^{C} S_{i,r}} \tag{1}$$

where:

C is the number of demand configurations simulated for a given flow regime of the network.

- $r \in [1, \mathrm{C}]$ denotes a demand configuration,
- R_i is the reliability of outlet i,
- $S_{i,r}$= 1, if hydrant i is open in the outlet configuration r;
- $S_{i,r}$= 0, if hydrant i is closed in the outlet configuration r;
- $P_{i,r}$= 1, if the pressure of the outlet i that is open in configuration r is higher than Hmin,i at the outlet;
- $P_{i,r}$= 0, if the pressure of the outlet i that is open in configuration r is lower than Hmin,i at the outlet.

In (1) the denominator is the total number of random configurations where outlet i was open among the total random generated C configurations (for a flow regime), whereas the numerator computes the number of demand configurations where the outlet not only was open but also reached a pressure head above Hmin,i. When the number of demand configurations is high enough (usually about 3 x number of outlets) the corresponding averaged values tend to stabilize and the number of demand configurations, C, used for computations, barely modify the average values. In this study it was established that C= 1000.

- ***Relative pressure deficit of an outlet***

Following Lamaddalena, et Sagardoy (2000), the relative pressure deficit just upstream of an outlet i ($\Delta H_{i,r}$) at a particular demand configuration r, evaluates how much pressure deviates from Hmin,i *(2)*:

$$\Delta H_{i,r} = \frac{H_{i,r} - H_{\min,i}}{H_{\min,i}} \tag{2}$$

where:

- $H_{i,r}$: pressure at the outlet i in demand configuration r (m),
- $H_{\min,\ i}$: minimum pressure required (m) at the outlet i

If $\Delta H_{i,r}$< **0** the outlet is in a relative pressure deficit, meaning the network fails to supply sufficient pressure in that demand configuration.

When $\Delta H_{i,r}$ is averaged over a subset of random demand configurations where the outlet was open, the average pressure deficit for outlet i is computed and denoted *(3)*:

$$RPD_i = \frac{\sum_{r=1}^{C} S_{i,r} \times \Delta H_{i,r}}{\sum_{r=1}^{C} S_{i,r}} \tag{3}$$

(3) Indicates the average relative pressure deficit, conditioned to found the outlet open.

A common minimum required pressure was set for upstream individual outlets, with 28.0 m for drip irrigation and 33.0 m for low-pressure sprinkler irrigation, accounting for all head losses between the outlet upstream section and the irrigation emitters.

- ***The characteristic curve of the network***

The indexed X% characteristic curve (Lamaddalena, et Sagardoy, 2000), of the irrigation network or subnetwork at its inlet node (i.e. the node where the network begins), describes the relation between the percentage of open outlets (flow regime) and the upper required pressure head at the inlet to guarantee a minimum pressure, Hmin, at all open outlets, for X % of the C demand configurations. In GESTAR, this curve is generated by default with X = 95 % of random demand configurations for each flow regime. X% values above 95 % generate upper envelopes with extreme pressure head requirement at the inlet, due to singular combination of outlets demands seldom occurring. As in the case of outlets reliability and RPD computation, C= 1000.

2.5. *Irrigation Infrastructure Design: from original design (sprinkler) to drip oriented design*

The irrigation system designs of 1976 and 2012 were carried out by specialized engineering firms. The 1976 sprinkler irrigation project was designed for on-demand irrigation with rotational water turns within plots, considering the water needs of the dominant crops and operational constraints. Similarly, the 2012 drip irrigation conversion project involved a reassessment of operational criteria, including a reduction in the sugarcane area and an increase in overall irrigation efficiency. These studies established flow rates, water requirements, and hydraulic parameters based on theoretical approaches and calculations using available data, without necessarily incorporating practical adjustments related to evolving agricultural conditions and farmers' irrigation practices.

2.5.1. *Design criteria and crop water requirements for the 1976 sprinkler irrigation project*

The sprinkler irrigation project was designed in 1976 (and implemented in 1984) for on-demand irrigation with a water sequential rotation inside the plots.

The crop rotation, which is factored into the calculation of crop water requirements, consisted of 75 % sugar cane area and 25 % quadrennial rotation area (cereals, fodder, legumes, etc.). The efficiencies considered were 85 % for application at plot level, and 95 % for the distribution network (Table 2). An overall efficiency of 81 % was expected, and as a consequence the gross peak water requirement was close to 1 L s^{-1} ha^{-1}, expressed in terms of the Fictitious continuous flow rate (Fcf). The network availability for irrigation was set to 24 h a day.

As the assigned flow rate at the collective hydrants was the result of multiplying the peak Fcf (1 L s^{-1} ha^{-1}) by the irrigated area, in practice, it failed to give any degree of freedom to the irrigator at peak season. It gave some limited degree of freedom off-season, but not enough to be considered a fully functional on-demand system, contradicting the on-demand initial formulation in those conditions.

To make it worse, the pipes design flow rates for on-demand service were computed taking the crops average water requirements, not the peak requirements (Table 2). As a consequence, the head pumping station design flow rate was 2730 l/s for 3443 ha, equivalent to an 80 % flow regime. That corresponds about 550 L s^{-1} for 658 ha irrigated at Branch C, what implies that, even with continuous irrigation 24 hours a day, at peak season water requirements would not be achieved by the network.

2.5.2. *Operational criteria and crop water requirements for the 2012 drip irrigation project*

Two main changes were introduced in the drip irrigation project (Table 3) designed in 2012 (and implemented in 2014), compared to the initial design of 1976 (Table 2). First, a reduction was operated in the area under sugar cane from 75 % to 50 %. This reduction is associated with the objectives outlined in Morocco's Green Plan (MAPM, 2008). Second, an increase in the overall efficiency of the project was assumed from 0.81 to 0.86, by considering an application efficiency of 90 % for drip irrigation (ORMVAG, 2012). It should be noted that during the process, it was decided to keep the existing network unchanged (the only pipes that were installed are those connecting the collective hydrants to the individual outlets) and some outlets nominal flow rates slightly increased, ascending to 748 L s^{-1} the total C branch flow rate with 100 % of the outlets open.

Compared to the initial design scenario, the peak water demand was decreased, due to the reduced area in sugar cane and increased efficiency. Taking into account the estimated monthly gross water requirement for peak demand (2495 m^3/ha) and 90 % of peak requirements (2,24 m^3/ha), the corresponding Fcf, the average Degree of freedom (Dof) at outlets, the on-demand flow rate at Sector C inlet (according to on-demand Clement formulation (Clément and Galand, 1979), for a Quality Operation factor U (95 %) and network availability coefficient r = 1), and the associated % Flow regime (Fr), are shown in Table 4.

As indicated in Table 4, on demand flow rates for peak season still cannot be realistically accommodated in the existing network. Nevertheless, assuming an 80 % flow regime as the original project did, equivalent to 0,6 m^3/s at Branch C inlet in 2014 year, up to the 90 % of peak water requirements can be serviced on demand, although with low flexibility. In a tightly arranged irrigation demand (not to overshoot the 600 L/s limit), up to 94.8 % of peak season water requirements could be also supplied. Therefore, a network capable to work at 80 % flow regimen (reference demand) is selected as the minimum goal desired to be achieved.

Table 2
Crop water requirements (BRL, 1976).

Sprinkler irrigation system (1976)

Crop	Water requirements in the peak month (mm)					Efficiency	
	Net		Gross				
	Average rotation	Peak	Average rotation	Peak	Percentage	Global	0.81
Sugar cane	163	228	202	282	75 %	Distribution network	0.95
Quadrennial rotation	95	198	118	245	25 %	Application at plot level	0.85

Table 3
Crop water requirements (ORMVAG, 2012).

Drip irrigation system (2012)

Crop	Water requirements in the peak month (mm)					Efficiency	
	Net		Gross				
	Average rotation	Peak	Average rotation	Peak	Percentage	Global	0.86
Sugar cane	163	228	191	267	50 %	Distribution network	0.95
Quadrennial rotation	95	198	111	232	50 %	Application at plot level	0.9

Table 4
Network operational parameters at Peak and reference conditions.

Water requirement condition	Water requirement (m^3/ha)	Fcf (L/s/ha)	Dof	Clément Flow rate at C Branch inlet (m^3/s)	Fr (%)
Peak demand	2495	0,96	1,18	0650	88
90 % of Peak demand	2245	0,87	1,30	0600	80

3. Results

3.1. Analysis of current network operation (S0)

3.1.1. Saving energy: but what are the constraints?

The modernization project aimed to achieve significant energy savings by upgrading the pumping station with variable speed pumps and reducing the total head from 75 m to 55 m (Kettani et al., 2022). The irrigation authority determined the total head based on the shift from sprinkler to drip irrigation, extrapolating a reduction in upstream collective hydrant pressure from 55 m to 35 m. However, the feasibility study had originally recommended a total head of 65 m to satisfy an 80 % of flow regime, 10 m more than what was actually provided (ORMVAG, 2012) (Fig. 3).

Taking into account localized head losses at the collective head station (12 m), mainly due to the collective filtration station, the actual pressure available at the inlet node of Branch C (SMPC3) is only 43 m (55 m – 12 m). According to the computed network characteristic curve for Branch C (Fig. 4), this pressure can only maintain the upstream pressure at individual outlets above Hmin (28 m) up to a flow regime 53 % (0.4 m^3/s). Therefore, this pressure (43 m) is only adequate for irrigation in off peak periods.

- **Scenario S0 (blue):** Pressure head required at node SMP C3 to ensure a minimum pressure of 28 m at the outlets, as a function of the flow rate in branch C.
- **Scenario S1.2.1 (orange):** Existing network after increasing the internal diameter of one pipeline from 450 mm to 700 mm.
- **Scenario S1.2.2 (gray):** Resized network, with a fixed inlet pressure of 43 m at the branch head.

3.1.2. Reliability and relative pressure deficit of the existing C branch network

A minimum required pressure of 28.0 m was set for upstream individual outlets, accounting for all head losses between the outlet and the drippers. Reliability for various flow regimes were evaluated, with 50 %, 60 %, 70 %, 80 %, 90 %, and 100 % of individual outlets operating simultaneously. Results are shown in (Fig. 5), where outlets number ordering corresponds from minimum to maximum reliability in the most unfavorable condition. In concordance with the network characteristic curve (Fig. 4), it is found that the network provides pressure enough to hydrants when less than 50 % of outlets are open (Fig. 5); however, reliability decreases significantly when more outlets operate simultaneously.

A critical bottleneck was identified in a 450-mm pipe on the main line distributing water to Branch C (Fig. 6). This pipe causes a pressure drop of up to 11 m over 876 m length, significantly affecting downstream outlets. Increasing its diameter to the same value of the pipe located upstream, 700 mm, reduces required inlet pressure by 5 m for 80 % flow configuration (Fig. 4), improving system performances

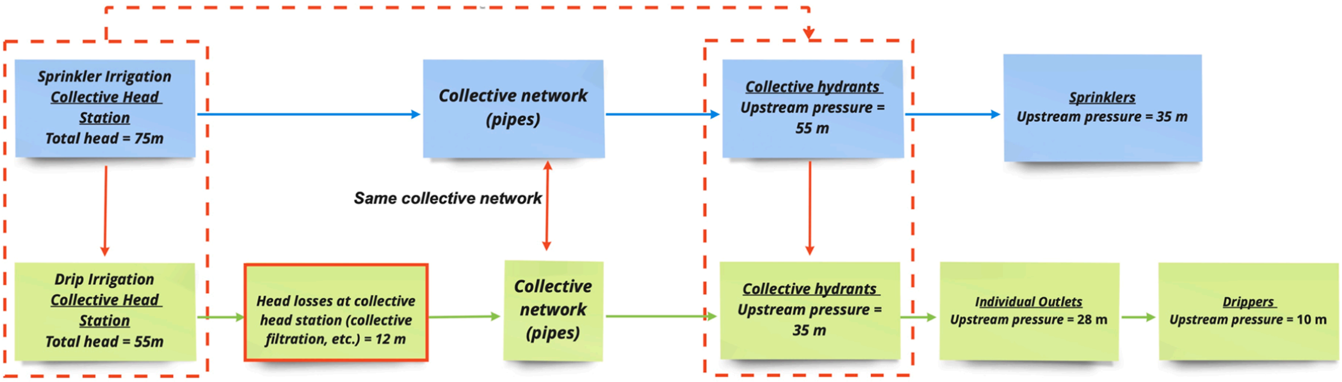

Fig. 3. Comparison in pressure requirements between the original project (1976), in blue, and the modified project (2012), in green.

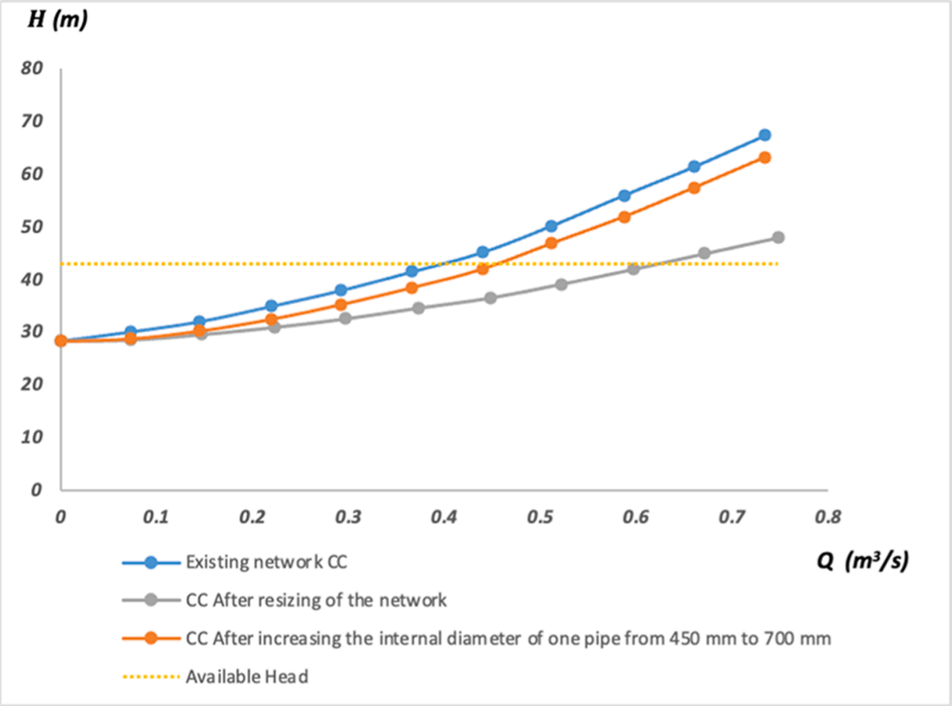

Fig. 4. Characteristic curves of the C3 branch network for three different scenarios.

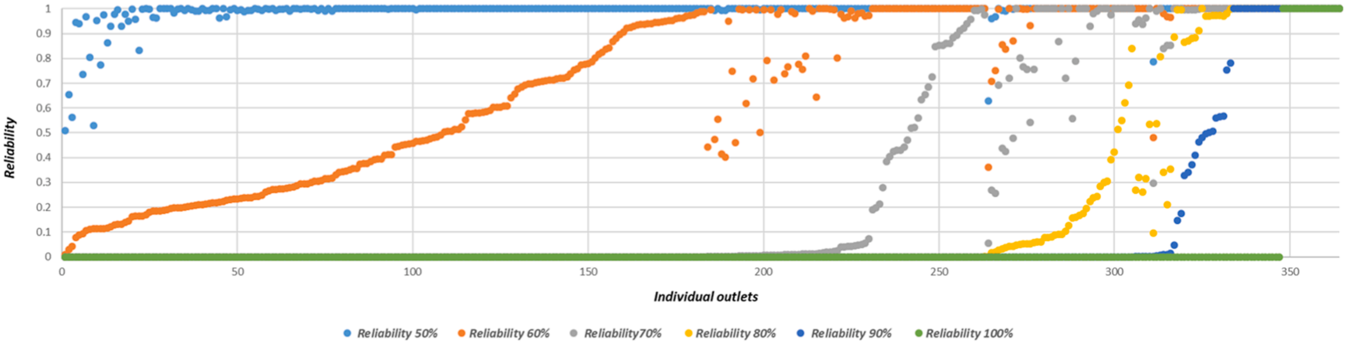

Fig. 5. Scenario S0. Reliability of individual outlets under different flow regimes, percentage of open outlets (50 – 100 %).

downstream. At the time of writing, the cost of resizing this pipe was calculated to be about 2.3 million dirhams (US$ 230,000) (Table 5).

3.1.3. How do farmers adapt to low pressure?

Some farmers, using the new individual outlets, were faced with insufficient pressure at the outlets. These farmers were generally located downstream in the network or at the last position after the collective hydrant. The affected farmers removed the cartridges from their filters and let the water flow through to the drip lines without being filtered, or they manipulated the flow limiter and the pressure regulator to increase extracted flow rate. As a consequence, they were able to withdraw water at a flow rate that can exceed the flow rate authorized by the flow limiter by 300 % (Fig. 7). Other farmers reverted for this reason to sprinkler irrigation, which they were able to operate, even at lower pressure, by reducing the number of sprinklers operating simultaneously.

3.1.4. Available degrees of freedom

The project 2012 feasibility study had already indicated that, despite the modifications introduced, the outlet flow rates were insufficient to meet farmers' needs, particularly regarding irrigation flexibility (ORMVAG, 2012). Indeed, the present outlets Dof still ranges from 1 to 1.4, restricting farmers' ability to adjust irrigation schedules to match crop requirements or any management strategy around maximum irrigation period.

The consequences of this insufficient degree of freedom for irrigators are multiple. First, it limits farmers' ability to manage their water resources effectively, which can lead to periods of water scarcity or surplus, negatively impacting crop yields. Additionally, the lack of flexibility may compromise the optimal timing of irrigation with the actual needs of the crops, hindering their growth and development.

The insufficient degree of freedom leads to an overload of the network, especially during peak demand periods, making the system less resilient to climatic variations or fluctuating irrigation needs. Moreover, it may lead to conflicts among farmers due to poor collective water management, where some may be disadvantaged compared to others.

When irrigation is needed to be applied al around the clock, it prevents the option to reduce or suppress irrigation in electricity tariff peak hours. Moreover, it prohibits to vary pumping station pressure head according to negotiated shifts for hydrants with different pressure requirements, i.e. sprinkler and drip irrigated parcels, that could produce significative energy savings, or any other water demand management strategy

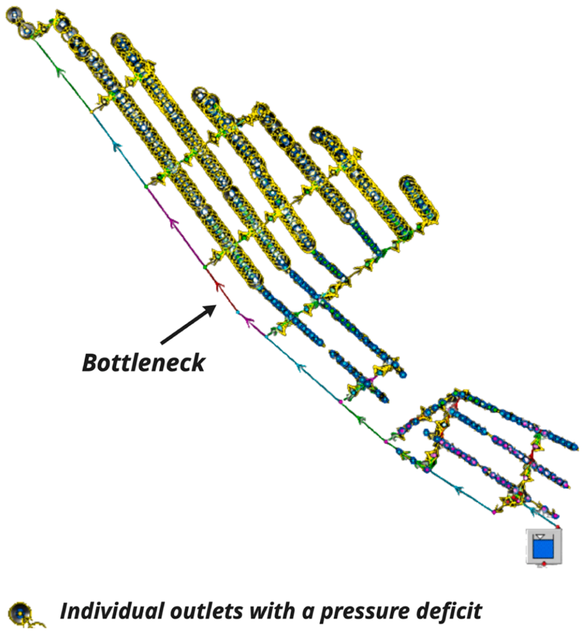

Fig. 6. Location of the 450-mm pipe acting as a bottleneck; affected outlets are highlighted (in yellow) in Gestar® graphical interface.

Finally, the inefficiency of the system can result in higher operational costs, as irrigators may need to resort to alternative solutions or request frequent adjustments to the system to meet their needs.

3.2. Alternative scenarios: drip irrigation (S1)

Through the analysis of the current network operation, simulations indicate that the supplied head at C sector inlet (43 m) is insufficient to meet the required pressures at desired flow rates. Consequently, adaptations are proposed. We examined in the first stage scenarios involving only drip irrigation (S1) as in the reference scenario (S0), where the pressure requirement is generally lower than for sprinkler irrigation. The current network performance (i.e. reliability and the relative pressure deficit) can be improved by increasing the total head upstream of the network (S1.1) or by reducing the head losses at the network level by increasing the diameters of some pipes (S1.2.1 and S 1.2.2).

3.2.1. Increasing the total head (S1.1)

We simulated the network operating under the reference 80 % flow regime, with three different total heads upstream of the branch C (SMPC3 downstream). The first total head (43 m) corresponds to the total head currently supplied to the network, the second (53 m) corresponds to the total head recommended in the drip irrigation project study in 2012, and the third (56 m) corresponds to the total head found that would prevent too serious pressure deficit at most of individual outlets (Fig. 8).

3.2.2. Resizing the network (S1.2)

3.2.2.1. Increasing the diameter of the bottleneck pipe (S1.2.1). As mentioned above, the total head at the inlet to subsector C can be reduced by at least 5 m (and consequently in the pumping station) by increasing the diameter of the 450 mm pipe situated at the main line in Branch C, where the bottleneck is located. When the bottleneck pipe is increased to 700 mm the network can operate effectively with 80 % of the outlets open of d by ensuring a total head of 51 m upstream of Branch C (Fig. 11).

3.2.2.2. Resizing the network to manage pressure with existing total head, 43 m (S1.2.2). The network could perform satisfactorily with the existing total head provided at the inlet to Branch C (43 m) in the present operational conditions, if the overall head losses in the network were reduced. The network head losses can be reduced by increasing the diameter of several pipes, modifications that are simulated by means of a redesign by Gestar® optimum sizing modules. Even though the optimization module options can define, altogether with the network pipes sizing, the optimum head at the Branch C inlet that will minimize the sum of investment and energy cost, the present operational minimum pressure, 43 m supplied at the subsector C inlet, has been adopted as an external constrain for the network optimum resizing. The pipes design flow rates were assigned by Clément approach, without modifying hydrants outlets parameters, taking network efficiency parameter r = 1, and establishing Quality Operation factor U 95 %. This solution involves replacing 50 pipes over a distance of 15.5 km, at a cost of 24.9 million dirhams (US$ 2490,000) (Table 4). It also will offer the advantage of inducing the rehabilitation of most of the network, as the current infrastructure suffers from frequent leaks due to the aging pipes, which have been in place since 1984. The resulting network design has the characteristic curve in Fig. 11and is fully reliable (Fig. 9) as it corresponds to a new properly executed design.

Table 5
Techno-economic comparison of network improvement scenarios.

			Investment (Dh)	*Investment/ year (Dh)*	*Pumping head (m)*	*Energy cost/ year (Dh)*	*Total cost /year (Dh)*	*Quality of service*
Base scenario	***Current network operation***	***S0***	0	0	55	1150,000	1150,000	
Drip irrigation (S1)	***Increasing the total head***	***S1.1***	0	0	68	1422,000	1422,000	Improved network reliability at cost of higher operational expenses
	Increasing the diameter of the bottleneck pipe and total head	***S1.2.1***	2300,000	147,000	63	1318,000	1465,000	Reduced pressure losses, slightly improved reliability, stable operational costs, but does not solve the pressure deficits
	Resizing the network	***S1.2.2***	24,900,000	1594,000	55	1150,000	2744,000	Improved network reliability with high investment
Low pressure sprinklers (S2)	***Increasing the total head***	***S2.1***	0	0	73	1527,000	1527,000	Improved network reliability at cost of higher operational expenses
	Increasing the diameter of the bottleneck pipe and total head	***S2.2.1***	2300,000	147,000	68	1422,000	1569,000	Balance between cost and performance, better return on investment
	Resizing the network	***S2.2.2***	31,900,000	2042,000	55	1150,000	3192,000	Greater flexibility for farmers with high investment

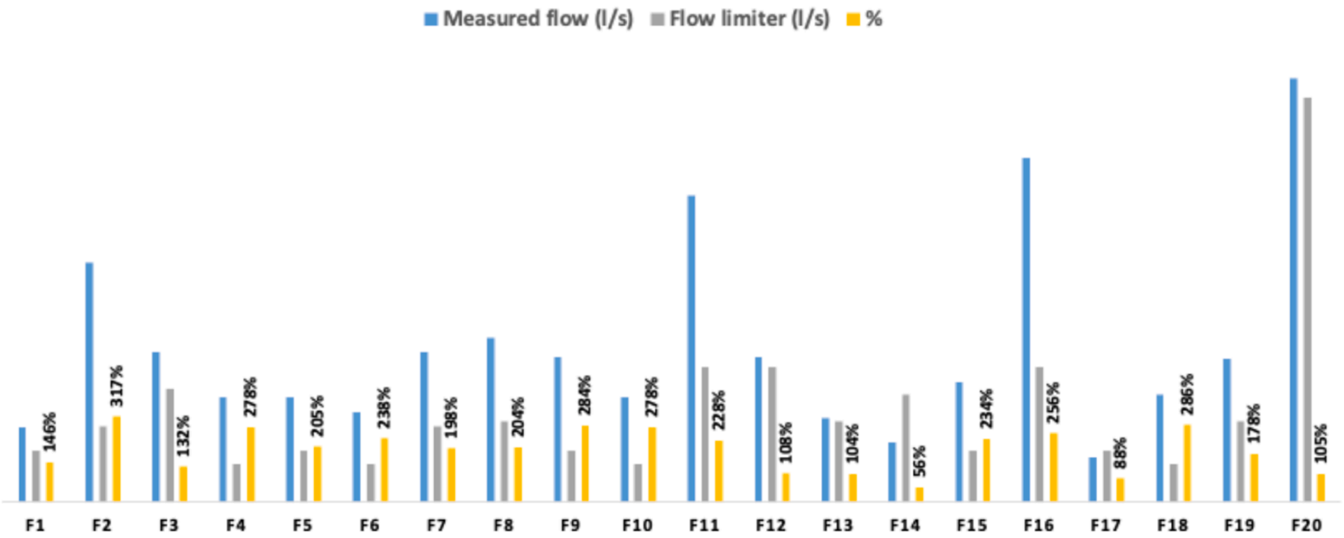

Fig. 7. Comparison between measured flow rate and the flow rate authorized by the flow limiter at 20 plots.

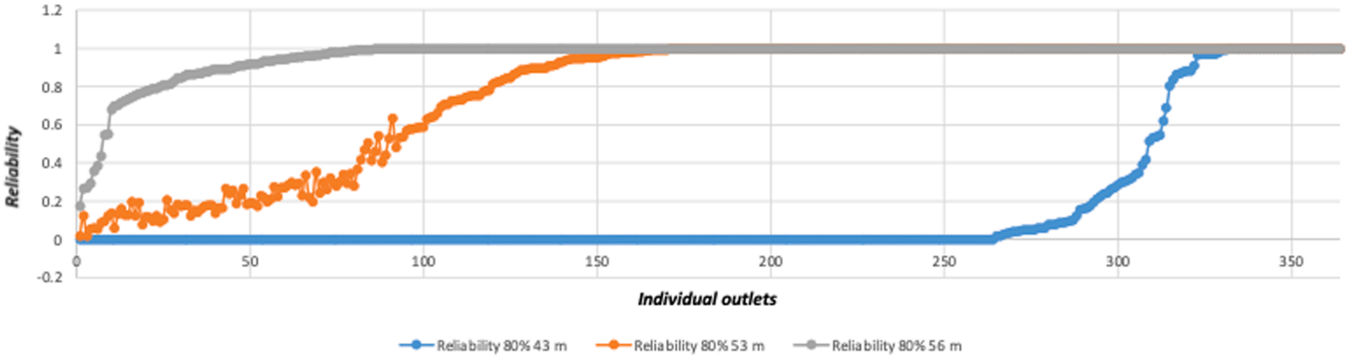

Fig. 8. Scenario S1.1. Reliability under a flow regime of 80 % open outlets, for three different total heads upstream of Branch C (43 m, 53 m and 56 m).

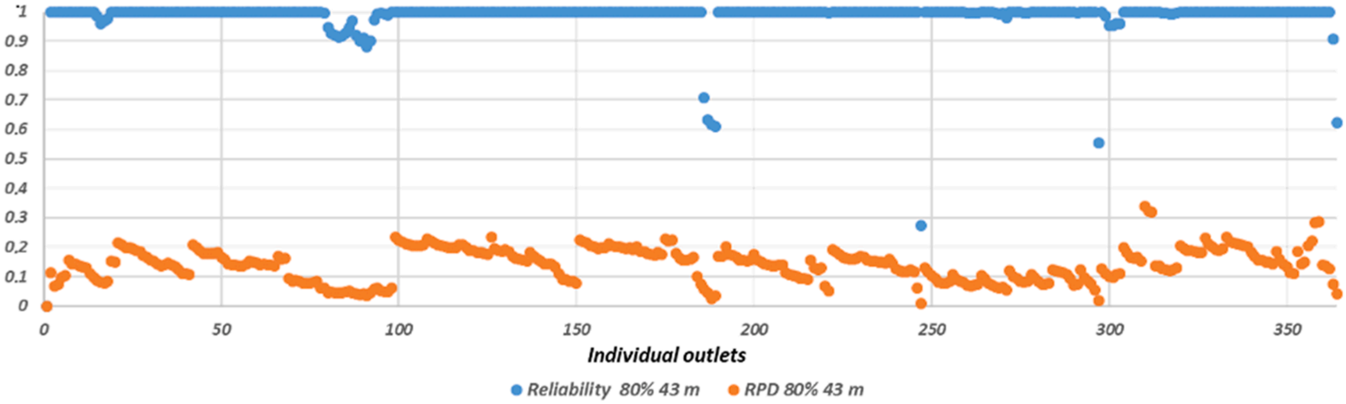

Fig. 9. Scenario S1.2.2. High reliability and absence of a relative pressure deficit with a flow regime of 80 % of open outlets, after resizing of the network (43 m).

3.3. *Scenario: low pressure sprinklers (S2)*

Field observations showed that 48 % of farmers, having installed drip irrigation, have partially or completely reverted to sprinkler irrigation systems which they consider is better suited to their soils (cracked clay soils) and crops. However, it is difficult to provide sufficient pressure, after the modernization project, for full-fledged sprinkler irrigation. Thus, in this scenario, the operation of the network under low pressure sprinkler irrigation was simulated with sprinklers operating at 1.5 bar, which requires a minimum head (Hmin) of 33 m upstream of the individual outlets. This value affects both the performance analysis and pipe sizing. This scenario gives farmers more flexibility in their choice of irrigation system. Solid-set low pressure sprinklers are recommended to overcome the soil problems in the study area (impracticable heavy soil after watering).

3.3.1. *Enhance the total head (S2.1)*

The performance of the network was analyzed for the reference flow regime of 80 % open individual outlets, considering five different heads upstream of Branch C. The first total head (43 m) corresponds to the head currently supplied to the Branch C network, the second (53 m) corresponds to the total head recommended in the drip irrigation project study in 2012, and three more values: 56 m, 59 m and 61 m, still below the 1976 project pressure (Fig. 10). The results indicate that a minimum of 61 m head will be needed to ensure no RPD occur at any of the individual outlets, although 11 % of outlets still experiment reliability below 0,9.

3.3.2. *Resizing the network (S2.2)*

As was the case in the drip irrigation scenario S1, the performance of the network can be improved, even with the existing head provided upstream Branch C (43 m), by resizing the network (S2.2.2). Alternatively (S2.2.1), the diameter of the bottleneck pipe referred to in Section 3.2.2 can be increased thereby reducing the head required in respect scenario (S2.1).

3.3.2.1. Increasing the diameter of the bottleneck pipe (S2.2.1). As shown in scenario S2.1 (Fig. 10), 61 m of pressure is required at the upstream end of Branch C to enable the network to perform satisfactorily under a flow regime of 80 % of open individual outlets. This l head can be reduced by 5 m by changing the diameter of the bottleneck pipe along a length of 876 m, as deduced from the characteristic curve of Branch C (Fig. 11). In this way, good reliability and absence of any RPD can be guaranteed (Fig. 12 and Fig. 13) while at the same time enabling energy savings and giving farmers more flexibility to operate the irrigation system in the way they want.

- **Scenario S2 (Orange):** Pressure head required at node SMP C3 to ensure a minimum pressure of 33 m at the outlets, as a function of the flow rate in branch C.
- **Scenario S2.2.1 (gray):** Existing network after increasing the internal diameter of one pipeline from 450 mm to 700 mm.
- **Scenario 2.2.2 (Bleu):** Resized network, with a fixed inlet pressure of 43 m at the branch head.

3.3.2.2. Resizing the network to manage pressure with existing total head, 43 m (S2.2.2). By resizing the network with Gestar® while keeping the existing total head of 43 m, head losses in the system can be reduced, leading to energy savings (Fig. 11). A value of 33.0 m for Hmin (minimum required pressure upstream of the outlet) was considered that accounts for all head losses from each individual outlet to the low-pressure sprinklers. The same design flow rates as in Scenario S1.2 have been considered. This option consists in replacing 53 pipes over 15.8 km, with an estimated cost of 31.9 million dirhams (US$ 3190,000) (Table 5). It also provides the added benefit of rehabilitating a large portion of the existing network.

3.4. *Techno-economic evaluation of improvement scenarios*

A total of seven scenarios were analyzed, including the current situation (S0) and six alternatives combining different levels of intervention. For each one, the total annual cost was estimated as the sum of energy consumption—based on the nominal pressure head at the pumping station—and the annual amortization of investments (Table 5).

The system's annual water requirement was estimated at 7000 m^3 / ha, assuming a pumping efficiency of 0.6 and an electricity price of 1 Dh/kWh. Infrastructure upgrades were limited to pipe replacement, with amortization calculated over 25 years at a 4 % net interest rate. Fixed costs such as electricity contracts were not considered, as their differences between scenarios were negligible.

Increasing the inlet pressure alone (Scenario S1.1) addresses the network's poor pressure reliability but results in a 24 % increase in energy costs compared to the current situation (S0). However, this increase remains moderate—only 6 % higher than the energy consumption projected in the 2012 drip irrigation project study.

In Scenarios S1.2.2 and S2.2.2, the proposed resizing of main and secondary pipes targets infrastructure that has not been upgraded since 1984 and suffers from frequent leaks. These leaks likely contribute to the pressure drops experienced by farmers. Despite the potential hydraulic benefits, the investment required for this large-scale network refurbishment is considerable. In the case of adopting low-pressure sprinkler irrigation, for instance, it would lead to an approximate 200 % increase in total annual costs compared to the base case (S0), while maintaining a low average Degree of freedom (Dof) of 1.3. If such a high investment can be justified, increasing the Dof should also be prioritized to improve system usability and flexibility, further increasing the upgraded network cost.

The SX.2.1 scenarios, which combine an increase in pumping head with the elimination of the identified bottleneck, result in only a modest increase in total cost—about 3 % higher than S.X.1—due to the installation of a 700 mm pipe. As it provides a relieve on head and energy required that benefits the components, and improves the system resilience respect uncertainties in energy cost increases, these scenarios will be a preferred option.

The cost difference between Scenario S1.2.1 (drip irrigation) and S2.2.1 (drip + low-pressure sprinkler) is only 7 %. Yet, S2.2.1 offers farmers the flexibility to choose the irrigation method that best fits their needs and cropping systems.

The transition to a hybrid irrigation system, combining drip and low-pressure sprinkler techniques, would allow for a more precise adaptation to crop requirements and soil conditions, ultimately minimizing water waste. By addressing existing system constraints, the proposed corrective measures would help mitigate water losses resulting from farmer-induced modifications, such as the removal of flow limiters or unauthorized system adjustments, thereby improving the overall

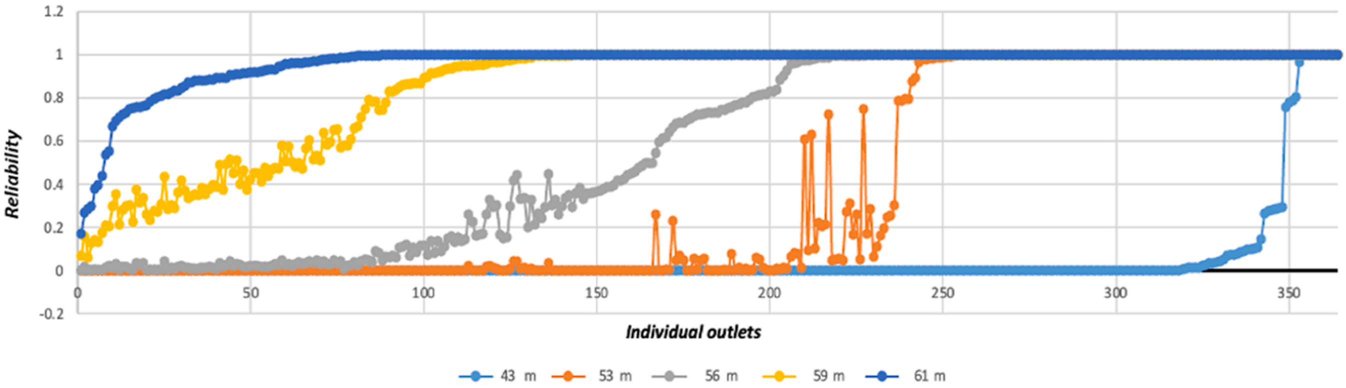

Fig. 10. S.2.1 scenario Reliability under a regime of 80 % of open outlets, for five different total head values at the upstream of Branch C (43 m, 53 m, 56 m, 59 m and 61 m) when low pressure sprinklers are used.

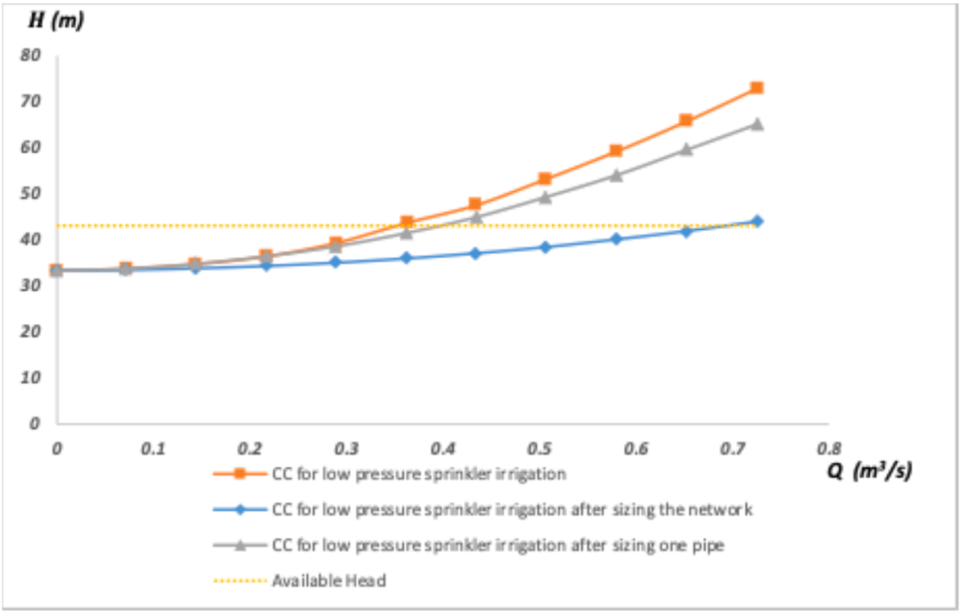

Fig. 11. Characteristic curves of the Branch C network under low-pressure sprinkler irrigation for three scenarios.

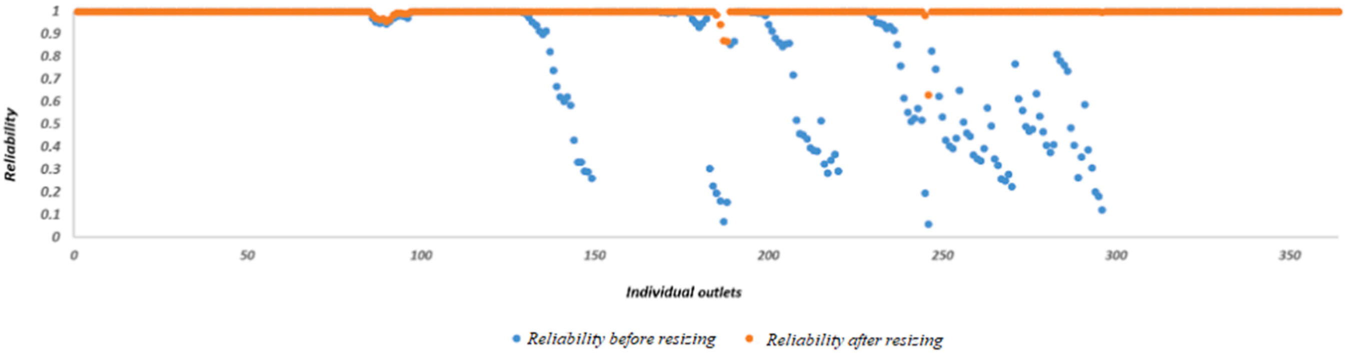

Fig. 12. Reliability under a flow regime of 80 %, before and after resizing of the bottleneck pipe 450 mm to 700 mm (Total head at branch C inlet 56 m).

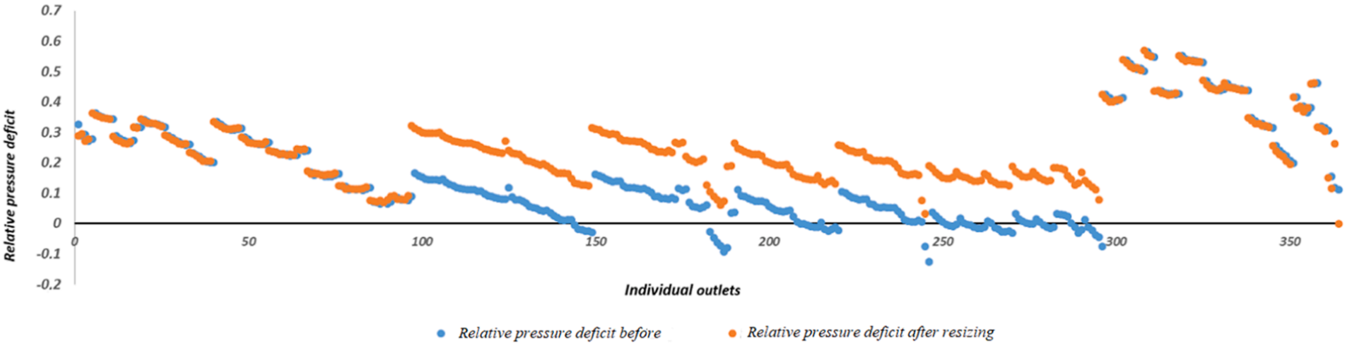

Fig. 13. Relative pressure deficit for flow regime 80 % before and after resizing the bottleneck pipe 450 mm to 700 mm (Total head at Branch C inlet 56 m).

efficiency of the network.

Considering all the advantages and drawbacks exposed, the alternative (S2.2.1) which combines an increase in inlet pressure with the elimination of the main bottleneck, emerges as the most balanced option, offering a reasonable compromise between annual cost increase and gains in operational flexibility.

3.5. Head losses sensitivity analysis

To establish the range of variability in the model's predictions for the selected solution, a sensitivity analysis was performed, evaluating the variation in calculated pressures based on the parameter with the greatest cumulative impact, that is, the linear and singular head losses, the one with the greatest uncertainty. Other parameters, such as outlets flow rate, exhibit fluctuations that tend to cancel out as a whole, or present a fixed value, such as elevations or lengths, which, once verified, are subject to very low uncertainty.

Pipe roughness exhibits, on the one hand, increases with time from the manufacturing values and, on the other hand, cannot be accurately characterized. Singular losses, distributed throughout the network, rarely can be accurately characterized, so they are approximated by increasing some dimensional (length) or physical (roughness) parameter. In this case, they are integrated in terms of increased roughness, which will thus retain both the deterioration of the pipe walls and individual distributed losses. Table 6 shows the roughness values considered for each of the three types of pipes installed in the network, from the lowest possible value, which corresponds to new pipes, according to manufacturing values, to the highest values (C) attributed to extremely aged pipes (roughness 1000, 20 and 8 times the new values depending on the pipes' material). The intermediate values include option "Ref", which was used as the reference value in the study for all model simulation and sizing calculations. This value is the roughness upper range, considering the degradation that has occurred since 1984.

For the selected compromise scenario S2.2.1—which ensures full reliability under the 80 % flow regime—Fig. 14 presents, for each hydrant, the average pressure head difference (calculated over $C = 1000$ demand configurations) between the roughness cases New, A, B, and C, and the reference case (Ref). This illustrates the sensitivity of the results to roughness under the most extreme possible flow conditions, generating the largest possible differences, as head loses depends dramatically to squared flow rate. As expected, variability depends largely on the location of the hydrant, being higher in those located at the end of branches, due to their longer trajectory that water needs to cover and the final smaller diameters that supply water to them.

Although the sensitivity of the results is not uniform across the entire network—making global indicators less meaningful—it can nonetheless be stated that, under maximum flow conditions, the pressure variability resulting from roughness uncertainty ranges between $+3.4$ m in the most optimistic case (A) to -2.7 m in the most unfavorable case (C), relative to the reference scenario.

4. Discussion

4.1. Modernization of irrigation infrastructure: The need for farmer involvement

Water and energy conservation have become critical in modern agriculture, requiring irrigation systems to be both efficient and adaptable to changing environmental and economic conditions. This case study illustrates the challenges of modernizing a pressurized irrigation system originally designed under too tight constraints; high pressure requirements- and no capability of practical on-demand operation, while it had been announced as an on-demand system, with negative effects on flexibility in irrigation. Many recent irrigation modernization projects emphasize energy cost reduction in addition to water productivity (Belaud, Mateos et al., 2020; Playán et al., 2024; Cameira et al., 2024). However, our study highlights how energy-saving strategies, particularly those associated with collective filtration for drip irrigation, have introduced significant hydraulic constraints for farmers. Inadequate pressure has discouraged farmers from using even drip irrigation, resulting in inefficiencies in water use and unintended system modifications by frustrated users, such as removing flow limiters (Rodríguez-Díaz et al., 2011; Kettani et al., 2022).

Table 6
Roughness values considered for the three types of pipes in the network, ranging from the lowest values (new pipes based on manufacturing data) to the highest values (C), corresponding to severely deteriorated pipes.

	New (mm)	A (mm)	B (mm)	Ref (mm)	C (mm)
PEHD	0004	0,05	0,1	0,2	0,4
Asbestos cement	0025	0,05	0,1	0,2	0,5
Reinforced concrete	0,25	0,3	0,6	1,2	2

The rigidity of the pre-defined project parameters, which only permitted a single irrigation practice, continuous irrigation at peak period and restricted crop choices, conflicted with current agricultural trends that require flexibility to adapt to fluctuating market conditions, crop rotations, and climate variability (FAO, 2017). When irrigation system designs do not account for farmers' actual needs, technical issues escalate into broader trust and governance challenges. Previous studies emphasize that collective irrigation projects must integrate individual on-farm practices and preferences (Sawassi et al., 2021; Zapata et al., 2023).

Throughout the modernization process, farmers consistently raised concerns about inadequate pressure, restricted irrigation flexibility, and unpredictable water availability. These issues were systematically recorded through field surveys and direct consultations. Rather than being considered only after implementation, farmer feedback could play a central role in evaluating alternative management scenarios and infrastructure adjustments during modernization projects. Bypassing such negotiations during the design and implementation phases—either due to time constraints or the perception that users lack technical expertise—often leads to operational inefficiencies, infrastructure failures, and dissatisfaction among both farmers and system managers, as documented in this case study.

In this modeling study, two key modifications that did not imply large infrastructures changes were explored, in response to demands of farmers: resizing the bottleneck pipe in Branch C to minimize pressure losses and therefore increasing pressure available downstream, and increasing the total head at the network inlet to enhance reliability, particularly for downstream users. Farmers also expressed concerns regarding the increased energy costs and labor demands of the new system. Although full on-demand irrigation was not feasible, their feedback underscored the necessity for a more adaptable framework, enabling the coexistence of drip and low-pressure sprinkler irrigation to accommodate diverse farming needs. By increasing network flexibility and allowing the coexistence of drip and low-pressure sprinkler irrigation, these adjustments reduce farmers' operational costs while improving their capacity to adapt to climatic and market fluctuations. In other words, modernization projects should shift towards the enhancement of the robustness of irrigation systems, accounting for the way individual irrigation-related decisions interact and evolve with diverse contextual variables (Janssen and Anderies, 2013).

While these infrastructure adaptations address immediate technical issues, long-term sustainability requires a stronger policy framework that promotes governance models aligned with real-world agricultural practices. In Portugal, participatory approaches such as farmer-led maintenance committees and regular consultation meetings have proven effective in improving water and energy efficiency (Cameira et al., 2024). Similarly, broader participatory approaches, such as farmer-led maintenance committees or regular consultation meetings, can foster trust and align the objectives of different stakeholders (Jackson, 2023). However, engagement must go beyond periodic consultations; it should be embedded in the initial design phases to ensure that solutions align with local socio-economic and hydrological realities (Kettani et al., 2022).

4.2. Re-thinking irrigation management for Cost-Effective solutions

Providing flexibility in irrigation systems is crucial, but it comes with financial trade-offs. System design and operation costs increase with greater flexibility, raising expenses for end users (Sawassi, 2021). Water access principles can be classified in 3 types (Wahlin and Zimbelman, 2014), which strongly influence the required capacity of the infrastructure: (i) centralized scheduling (e.g. fixed water turns); (ii) arranged schedule; (iii) on-demand (also called "limited rate demand"). While (iii) offers the maximum flexibility, it requires enough storage and

Fig. 14. Sensitivity of pressure computed at hydrants, in respect pipes roughness uncertainty. Values shown are average pressures computed at hydrants in cases New, A, B, and C minus computed average pressure in Ref case.

pressure control so that the demand is fulfilled. Oversizing networks to provide this flexibility increases expenses, which is often a limitation for investment and operation costs.

In this study case, the infrastructure was undersized to meet demand, regardless of the irrigation equipment used. Compared to on-demand distribution, arranged scheduling offers the advantage of reducing infrastructure requirements while improving operational efficiency through better water allocation strategies (see review of methods in Walhin and Zimbelman 2014). Advances in digital communication tools may allow farmers to submit irrigation requests in advance (typically one or two days), enabling more effective water access management through centralized optimization (Hong et al., 2014, Fan et al., 2023; Mai et al., 2024). Such strategies have been successfully applied in the modernization of traditional irrigation systems in Spain, where infrastructure constraints required smarter water management (Playán et al., 2024). However, our case study shows that when the infrastructure is undersized, and when this is not compensated by management tools required in a constrained collective irrigation scheme, the system is bound to fail.

The integration of a structured economic approach is essential to ensuring the success of irrigation modernization projects. A combination of public subsidies, participatory financing, and tailored economic models can help balance investment and operational costs while enhancing the long-term sustainability of infrastructure. Therefore, it is crucial to adopt a long-term vision that incorporates financial viability, resource conservation, and adaptability to farmers' needs.

The proposed solutions in this study focus on improving hydraulic performance through a combination of increasing the total head at the Branch C inlet and resizing key pipelines, particularly the bottleneck pipe. These measures come with economic implications that must be carefully evaluated.

Increasing the total head from 43 m to 56 m would enhance network reliability but would also lead to a 24 % increase in operating costs compared to the current system, raising concerns about long-term energy expenses and sustainability. While energy cost reduction is often a key goal of irrigation modernization projects, the technical constraints observed in this case required trade-offs between pressure reliability and energy consumption. These trade-offs are particularly relevant in semi-arid contexts where ensuring reliable access to water can outweigh energy savings in the short term.

Conversely, the combined scenario (S2.2.1), which involves both resizing the bottleneck pipe (2.3 million dirhams or ~US$230,000) and increasing the pumping head, results in an annual cost of 1.57 million dirhams or ~US$157,000 — only 3 % more than increasing the head alone (S2.1). This slight additional investment yields substantial gains in hydraulic performance and energy efficiency. Compared to the current configuration (S0), it raises the annual cost by just 36 %, while allowing for both drip and low-pressure sprinkler irrigation. The scenario significantly improves system reliability and flexibility. Additionally, maintaining a low-pressure sprinkler irrigation option ensures flexibility for farmers, reducing the likelihood of them reverting to inadequate irrigation methods for some crops. Moreover, during peak periods, the practical absence of freedom degree at hydrants, makes it impossible to organize demand sectorized in time by irrigation system,

However, the economic feasibility of these solutions depends on their acceptability to farmers, who may struggle with increased costs associated with higher energy consumption. Previous studies emphasize the importance of developing adaptive pricing mechanisms to mitigate these financial burdens and ensure farmer adoption. By integrating economic considerations into modernization strategies, irrigation systems can be designed to be financially sustainable, minimizing the risks of unintended consequences and maximizing long-term benefits for both farmers and water managers.

5. Conclusion

This study demonstrates that irrigation modernization is a complex process requiring both technical and institutional adjustments. While transitioning from sprinkler to drip irrigation can enhance water application and energy efficiency, rigid undersized infrastructure and inadequate management frameworks can create unforeseen challenges. Our findings highlight the importance of integrating flexibility into irrigation systems to better align with farmers' needs and field realities.

To enhance modernization efforts, policymakers and irrigation managers should promote hybrid irrigation solutions, allowing farmers to alternate between drip and low-pressure sprinkler systems based on crop and soil requirements. Addressing pressure losses and technical constraints requires carefully evaluated investments, such as resizing key pipelines and increasing total head. While hybrid irrigation models and participatory governance offer promising solutions, they also involve trade-offs. Hybrid systems may require higher initial investments for infrastructure modifications and careful coordination to manage water allocation efficiently. A thorough cost-benefit analysis is necessary to balance infrastructure costs with long-term water and energy savings.

Beyond technical and economic solutions, farmer participation is crucial to ensure that irrigation systems match real-world agricultural practices. In this study, farmers' feedback allowed the development of the proposed adjustments that could then be modeled for their efficacy in obtaining the required pressure and discharge at the outlets. A progressive modernization strategy should be prioritized, ensuring that technical upgrades are introduced in phases, in concertation with farmers, to decide on the technical design choices, while accounting for the financial implications, both in terms of investment and operational costs.

While this study is centered on the Gharb region, the challenges it addresses—pressure instability, adaptation strategies, and governance issues—are widely relevant to irrigation modernization in other semi-arid areas.

CRediT authorship contribution statement

Taky Abdelilah: Writing – review & editing, Methodology, Conceptualization. **Bouarfa Sami:** Resources, Methodology, Conceptualization. **Hammani Ali:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Kettani Abla:** Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Data curation, Conceptualization. **Aliod Ricardo:** Writing – review & editing, Software, Resources, Conceptualization. **Kuper Marcel:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Resources, Methodology, Funding acquisition, Conceptualization.

Declaration of Competing Interest

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

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Data availability

Data will be made available on request.

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