

CLIMATE-DRIVEN SERVICE RESILIENCE IN PRESSURISED IRRIGATION SYSTEMS

RÉSISTANCE DES SERVICES FACE AU CLIMAT DANS LES SYSTÈMES D'IRRIGATION SOUS PRESSION

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ABSTRACT

Pressurised collective irrigation systems (CIS) in Mediterranean regions are increasingly exposed to climate-driven stress arising from reduced water availability, higher irrigation demand, and more concentrated peak demand. This work develops a performance-based approach for assessing service-level resilience in reservoir-fed, pressurised CIS, focusing on conveyance and distribution performance, as well as pumping and energy resilience. The framework is applied to the Minutos CIS in southern Portugal under a business-as-usual adaptation pathway, considering RCP4.5 and RCP8.5 for the 2041–2070 and 2071–2100. Climate-driven changes in irrigation demand are translated into hydraulic operating conditions and evaluated through hydraulic modelling of pressure adequacy at hydrants under peak-demand conditions. Service resilience is quantified performance-based indicators, then normalised onto a common 0–1 resilience scale.

Results show that, under current conditions, the system satisfies pressure requirements across most hydrants. However, future increases in irrigation demand become increasingly critical under peak-demand conditions, particularly under late-century RCP8.5. In this scenario, approximately 20% of hydrants experience pressure failures, although the most severe impacts are concentrated in a smaller subset of hydrants. At these critical locations, pressure-failure frequency may exceed 52%, while, in the most constrained cases, failures occur in all simulated hydrant-opening events, with mean pressure deficits reaching 17–20 m. Energy resilience also weakens, with energy use increasing to 1,059 kWh ha⁻¹. Normalised results show a decline in hydraulic service resilience from 0.76 to 0.48, while pumping and energy resilience decreases from 0.71 to 0.57. The integrated conveyance–energy score falls to 0.52, indicating reduced hydraulic and energy safety margins rather than system-wide failure.

Keywords: resilience assessment, pressurised systems, service reliability, water-energy nexus, demand flexibility.

RESUME

Les systèmes d'irrigation collectifs (CIS) sous pression des régions méditerranéennes sont de plus en plus exposés à des contraintes liées au climat, résultant d'une disponibilité en eau réduite, d'une demande d'irrigation plus élevée et d'une demande maximum concentrée. Ce travail développe une approche basée sur la performance pour évaluer la résistance au niveau du service dans les CIS sous pression alimentés par des réservoirs, en mettant l'accent sur les performances de transport et de distribution, ainsi que sur la résistance en matière de pompage et d'énergie. Le cadre est appliqué au CIS de Minutos, au sud du Portugal, selon une trajectoire d'adaptation «activités habituelles», en tenant compte des scénarios RCP4.5 et RCP8.5 pour les périodes 2041–2070 et 2071–2100. Les changements de la demande en irrigation induits par le climat sont traduits en conditions d'exploitation

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hydrauliques et évalués par une modélisation hydraulique de l'adéquation de la pression sur les prises d'eau dans les conditions de demande maximum. La résistance du service est quantifiée à l'aide des indicateurs basés sur les performances, puis normalisée sur une échelle de résistance commune de 0 à 1.

Les résultats montrent que, dans les conditions actuelles, le réseau répond aux exigences de pression pour la plupart des prises d'eau. Cependant, les augmentations futures de la demande d'irrigation deviennent de plus en plus critiques dans la période de demande maximum, en particulier dans le scénario RCP8.5 prévu pour la fin du siècle. Dans le cadre de ce scénario, environ 20% des prises d'eau subissent des défaillances de pression, bien que les impacts les plus graves se concentrent sur un sous-ensemble plus restreint de prises d'eau. À ces emplacements critiques, la fréquence des défaillances de pression peut dépasser 52%, tandis que, dans les cas les plus contraints, des défaillances surviennent lors de toutes les simulations d'ouverture de prises d'eau, avec des déficits de pression moyens atteignant 17 à 20 m. La résistance s'affaiblit également, la consommation d'énergie augmentant à réaliser 1 059 kWh ha⁻¹. Les résultats normalisés indiquent une baisse de la résistance du service hydraulique, qui passe de 0,76 à 0,48, tandis que la résistance du pompage et de l'énergie diminue de 0,71 à 0,57. Le plan intégré «transport-énergie» tombe à 0,52, ce qui indique une réduction des marges de sécurité hydrauliques et énergétiques plutôt qu'une défaillance à l'échelle du système.

Mots-Cles : Evaluation de la Résistance; Systèmes sous pression; Fiabilité du service; Liens entre Eau-Energie; Flexibilité de la demande.

INTRODUCTION

The Mediterranean region is widely recognised as a climate-vulnerable hotspot, where water-dependent sectors are under increasing pressure due to warming and drought intensification (Carreta et al., 2022). Its seasonal mismatch, wet winters with low crop water requirements and hot, dry summers with high atmospheric demand, pushes irrigation demand beyond natural water availability and increases pressure through the water–energy–food–ecosystems nexus (Fader et al., 2016; Jonsson et al., 2024). CIS, are crucial for controlling water availability, maintaining agricultural production and reducing conflicts among users (Cameira et al., 2025). Many CIS are now automated, on-demand pressurised irrigation networks thanks to modernization, which enhances control, flexibility, reliability and volumetric management (Carneiro et al., 2024).

However, it can also produce dynamic and spatially irregular pressure, especially during the peak-demand period (Lamaddalena et al., 2024). Therefore, even in situations where water is available, service failure may occur locally at hydrants or sectors. The water–energy trade-off is further strengthened by modernisation. Higher energy consumption, electricity costs and operational complexity are frequently associated with improved pressure control and delivery flexibility (Fernández García et al., 2017). This has an impact on sustainability mainly in situations where pumping is necessary to maintain pressure (Van De Loo et al., 2025).

Climate change is expected to amplify these constraints. Increased irrigation demand during critical periods and decreased storage margins are likely to result from projected increases in crop water requirements (Fader et al., 2016; Nevermann et al., 2024). The interplay of reservoir operation, demand concentration, network hydraulics and pumping energy in pressurised CIS, transmit climate-driven stress (Cameira et al., 2025; Navarro-González et al., 2023). During peak demand, when pressure deficits and pumping constraints are most likely, systems that perform adequately under average seasonal conditions may become vulnerable. In this context, resilience is understood as the CIS's ability to sustain acceptable irrigation service under pressure, essentially through operational flexibility, energy exposure, delivery reliability and pressure adequacy.

Performance-based assessment of resilience translates the behaviour of the system into measurable indicators compared against defined thresholds (Liu and Mijic, 2025). However, no single indicator at the system-level can represent coherent dynamics of failure and recovery. Therefore, a multi-level

threshold is necessary to distinguish between moderate deterioration, operating stress and critical service failure.

Despite the growing research on hydraulic and energy performance in pressurised irrigation networks, the relationship between climate-driven demand, hydrant-level pressure reliability, and energy-related constraints is still only partially integrated. Earlier work has shown that on-demand systems are affected by spatial and temporal variability in hydrant pressure and discharge, while energy-audit studies confirm the importance of energy use and costs in modernised irrigation districts (Calejo et al., 2008). Applications linking climate-driven demand changes with hydrant-level service risk and energy exposure are still scarce, despite recent modelling techniques combining on-farm demand, hydraulic reliability, and energy efficiency under future scenarios (Cameira et al., 2025).

As a result, there is a disconnect between service-level resilience diagnosis and climate-impact assessment. To address this, this paper operationalises the energy, pumping and conveyance and distribution components of a broader performance-based resilience framework for reservoir-fed pressurised CIS. The goal is to evaluate how service-level resilience under a business-as-usual pathway is impacted by climate-driven demand changes. In particular, the study assesses hydrant-level pressure reliability and pressure-deficit severity, quantifies changes in annual and peak-period irrigation demand, interprets implications for pumping and energy resilience, and identifies locations and circumstances where future service risk becomes concentrated.

MATERIALS AND METHODS

Conceptual framework

The proposed framework conceptualises the CIS as a combined socio-technical system in which water availability, storage, hydraulic supply, energy consumption, demand flexibility and management decisions are collectively shaping the resilience of irrigation-services. Six interacting layers are considered: hydro-climatic supply, storage and allocation, hydraulic supply, pumping and energy consumption, demand adaptive capacity, and the CIS capacity to manage droughts. Together, these layers enable resilience to be assessed as the ability of a system to absorb, redistribute and respond to stress caused by climate change. This document focuses on the conveyance and distribution layer and the pumping and energy layer.

Performance-based resilience indicators

Conveyance and distribution resilience was assessed through indicators that quantify the ability of the pressurised irrigation network to maintain adequate pressure at hydrant level under peak-demand conditions. Hydraulic simulations were performed to identify service failures, defined as simulated conditions in which hydrant pressure fell below $P_{min} = 40$ m, reflecting the requirements of the predominantly sprinkler-based on-farm irrigation systems.

The indicators presented in Table 1 capture both the occurrence and severity of service failures, enabling the assessment of network reliability, pressure-deficit magnitude and the identification of critical hydrants. Hydraulic simulations were performed using SIGOPRAM, following the methodology described by Cameira et al. (2025). Irrigation patterns were derived from monthly gross irrigation requirements for each future scenario. The simulated network extended from the network inlet to the irrigation units supplied by each hydrant.

Hydraulic reliability under peak-demand conditions was assessed through demand-driven simulations, with stochastic outlet openings generated by the Clément probability model. A total of 1,000 simulation runs were carried out, producing corresponding outlet configurations and flow–pressure distributions. Pressures measured at control points were used to adjust pipe roughness and head-loss coefficients, thereby improving the hydraulic representation of the system.

Table 1. Performance-based resilience indicators for conveyance and distribution

Code	Indicator	Equation	Reference
C1	Hydrant pressure reliability	$R_{p,h}^c = 1 - \frac{1}{O} \sum_{s=1}^O f_{h,s}^c$	(Calejo et al., 2008; Cameira et al., 2025; Lamaddalena et al., 2024)
C2	Network pressure reliability	$R_p^c = 1 - \frac{1}{HO} \sum_{h=1}^H \sum_{s=1}^M f_{h,s}^c$	
C3	Relative pressure deficit	$RPD^c = \frac{\sum_{h=1}^H \sum_{s=1}^M P D_{h,s}}{\sum_{h=1}^H \sum_{s=1}^M P_{min,h}}$	
C4	Critical hydrant deficit	$CHD^c = P_{80} \left(\frac{PD_{h,s}}{P_{min,h}} \right)$	Adapted from Mohammedi et al. (2026)
C5	Max hydrant deficit	$PD_{max}^c = \max \left(\frac{PD_{h,s}}{P_{min,h}} \right)$	

$R_{p,h}^c$ –reliability; $f_{h,s}^c$ –failure; O –number of times that the hydrant is open during simulations; R_p^c –network pressure reliability; H –number of hydrants; RPD^c –relative pressure deficit; $PD_{h,s}$ –pressure deficit at hydrant h under simulation condition s ; $P_{min,h}$ –minimum required pressure; CHD^c –critical hydrant pressure deficit; P_{80} –80th percentile, PD_{max}^c –max hydrant pressure deficit.

Pumping and energy resilience was assessed in terms of the energy effort required to sustain hydraulic service. The indicators presented in Table 2 describe energy consumption, energy costs, and their relationship with irrigated area, supplied volume, and abstracted volume. Present-day indicators were calculated from observed electricity use and associated costs. Future values were estimated by applying present-day energy-use and cost ratios to projected irrigation volumes; therefore, they represent scenario-based energy exposure rather than direct forecasts of electricity consumption.

Integrated hydraulic and energy resilience classes and normalization

Resilience classes were defined using proposed thresholds that translate heterogeneous subsystem indicators into four categories, ranging from low to excellent resilience (Table 3). To support comparison across indicators, all metrics were normalised to a common 0–1 scale using continuous threshold-based normalisation. For benefit indicators, scores increase from 0 to 1, whereas for stress indicators, the transformation is reversed. The normalised index was calculated by:

$$S_i = \frac{X_i - X_{min}}{X_{max} - X_{min}} \quad (1)$$

where S_i is the normalised resilience index of indicator i , X_i is the observed or simulated value, and X_{min} and X_{max} are the lower and upper bounds used for normalisation.

Table 2. Performance-based resilience indicators for pumping and energy

Code	Indicator	Equation	Reference
D1	Energy per irrigated area (kWh ha ⁻¹)	$CE/AIR = \frac{CE}{AIR}$	(Cameira et al., 2024)
D2	Energy per supplied volume (kWh m ⁻³)	$CE/VH = \frac{CE}{VH}$	
D3	Energy per abstracted volume (kWh m ⁻³)	$CE/Vo = \frac{CE}{Vo}$	
D4	Energy cost per irrigated area (€ ha ⁻¹)	$CostE/AIR = \frac{CostE}{AIR}$	

Code	Indicator	Equation	Reference
D5	Energy cost per supplied volume (€ m ⁻³)	$CostE/Vo = \frac{CostE}{VH}$	
D6	Energy cost per abstracted volume (€ m ⁻³)	$CostE/VH = \frac{CostE}{Vo}$	
D7	Renewable energy contribution (%)	$REC = \frac{\sum E_{ren,t}}{\sum E_t}$	(Van De Loo et al., 2025)
D8	Pump redundancy (%)	$PR^D = \frac{Q_{installed} - Q_{req}}{Q_{req}}$	(SPU, 2024)

CE -consumed energy, CostE -energy cost, AIR -irrigated area, VH -volume supplied, Vo -abstracted volume, E_{ren,t} -renewable energy, Q-pumping capacity.

Table 3. Hydraulic, pumping and energy resilience classes

Indicators	Class 1- low	Class 2 - moderate	Class 3 - good	Class 4 - excellent
C1	< 0.70	0.70–0.85	0.85–0.95	≥ 0.95
C2–C5	> 0.30	0.15–0.30	0.05–0.15	≤ 0.05
D1–D6	> 1.25	1.00–1.25	0.80–1.00	≤ 0.80
D7	< 0.10	0.10–0.25	0.25–0.50	≥ 0.50
D8	< 0	0–0.25	0.25–0.50	≥ 0.50

Case study: Minutos collective irrigation system

The framework was applied to the Minutos CIS in southern Portugal (Figure 1), a pressurized reservoir-supplied CIS that is representative of Mediterranean conditions. The area is characterized by hot, dry summers and cool, wet winters (Kottek et al., 2006). During 1971–2000, mean annual precipitation at Évora was 609.4 mm, and mean daily air temperature was 15.8 °C, with mean maximum and minimum temperatures of 20.7 °C and 11.0 °C, respectively.

Constructed in 2003 and expanded in 2021, the MCIS currently commands approximately 1,979 ha. Water is abstracted from the main reservoir, pumped to the command reservoir, and then conveyed to the irrigation units by a pressurised gravity network. The area is divided into two sectors: Amoreira (AS) and Foros do Cortiço (FS). In AS, the tertiary network supplies water through a single outlet, whereas in FS, hydrants are commonly shared by one to four outlets. The minimum required pressure head at the outlets is 40 m. The system supplies 97 hydrants, with nominal discharges ranging from 14 to 400 m³ h⁻¹. Each outlet is equipped with a volume meter, a flow limiter and a pressure-control valve. The main network consists mainly of ductile iron (48%), high-density polyethylene (37%), and PVC (15%) with less than 1% reinforced concrete. The Minutos Water Users Association (WUA) is responsible for infrastructure maintenance and water delivery management. The command area has a diverse cropping pattern, dominated by silage, fodder crops, pastures, processing tomato, vineyards, olive groves and almond orchards. Smaller areas are coupled by mix crops. Soil variability was represented using the transferable, irrigation-oriented dataset developed by Ferreira et al. (2026), which supports the estimation of soil-water storage and irrigation requirements.

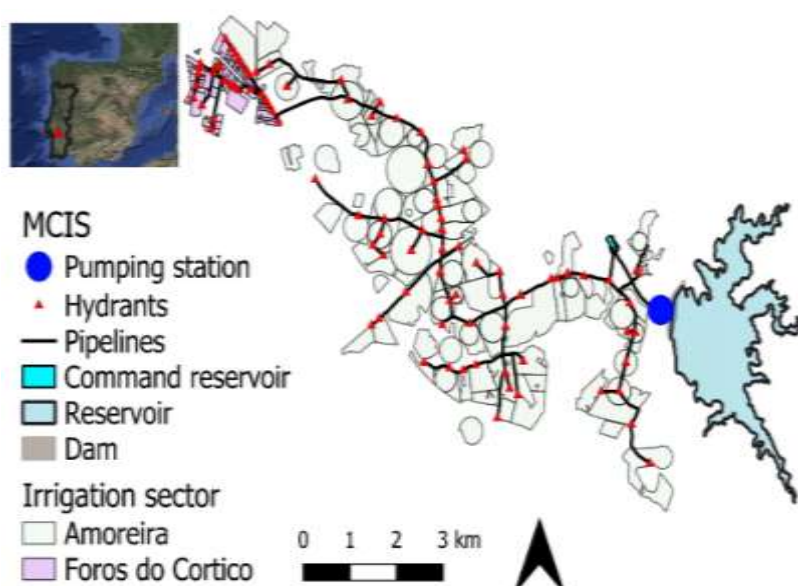


Figure 1. Location of the Minutos CIS and its main infrastructure components.

Future irrigation requirements under climate driven scenarios

Climate forcing was derived from a multi-model ensemble of regional climate simulations, and the ensemble mean was used to represent each scenario and time horizon (Table 4). The assessment followed a business-as-usual scenario, in which the existing infrastructure, operating logic, crop pattern, irrigation technologies were maintained. Accordingly, the future scenarios were designed to isolate the effect of climate forcing on irrigation demand, rather than to represent land-use changes or farmer decision-making in crop management.

Table 4. Multi-model ensemble used for the historical baseline (1971–2000) and future projections under RCP4.5 and RCP8.5 for 2041–2070, and 2071–2100.

Global Climate Model	Regional Climate Models
MOHC-HadGEM2-ES	DMI-HIRHAM5; GERICS-REMO2015; KNMI-RACMO22E
ICHEC-EC-EARTH	KNMI-RACMO22E; SMHI-RCA4
IPSL-CM5A-MR	SMHI-RCA4
MPI-ESM-LR	SMHI-RCA4; MPI-CSC-REMO2009

Reference evapotranspiration was calculated with the locally calibrated Hargreaves–Samani equation (Ferreira et al., 2024). Crop water use was estimated using locally adjusted crop-coefficient curves, defined according to sowing or bud break dates and growth-stage durations. Crop parameters were derived from the observed cropping pattern and refined with official crop information and NDVI time-series evidence. Under future scenarios, these crop data were kept constant, in line with the business-as-usual assumption.

Irrigation demand was simulated with ISAREG for homogeneous units of analysis (HUA), assumed to be internally uniform in terms of soil hydraulic properties, crop parameters, and irrigation system. Net irrigation requirements (NIR) were estimated at field scale and then aggregated to the CIS scale. To account for uncertainty in antecedent soil-moisture, simulations were run under contrasting initial soil-water conditions. NIR was subsequently converted into gross irrigation requirement (GIR) using irrigation efficiency. For each 30-year horizon, the design annual GIR was represented by the 80th

percentile. Peak-month demand was defined as the maximum monthly GIR, typically in July–August. These irrigation requirements were then used as inputs to SIGOPRAM to simulate hydraulic network performance under peak-demand conditions.

RESULTS AND DISCUSSION

Irrigation demand

Future climate scenarios result in an increase in irrigation demand; however, the magnitude and seasonal expression of change vary between annual and peak-month demand (Table 5). Peak demand increases by 9.1 to 13.4% in the mid-century, and by the late century, the increase becomes more noticeable, under RCP8.5 where it reaches 19.0%.

Table 5. Changes in annual and peak-month irrigation demand by scenario.

Horizon	Scenario RCP	Irrigation demand (m ³ . ha. year ⁻¹)		Mean relative change (%)	
		Peak demand	Annual	Peak demand	Annual
2024-2025	Present	1484 ± 225	4546 ± 458	-	-
71-2000	HIS	1484 ± 130	4165 ± 578	-	-
41-2070	RCP4.5	1688 ± 230	4590 ± 559	13.4	10.4
41-2070	RCP8.5	1617 ± 132	4806 ± 660	9.1	15.4
71-2100	RCP4.5	1613 ± 243	4784 ± 737	8.3	14.7
71-2100	RCP8.5	1767 ± 176	5296 ± 752	19.0	27.1

Hydraulic service performance

Current hydraulic service performance, represented by the 2024–2025 operating conditions (Figure 2a), indicates that the conveyance and distribution network satisfies $P_{\min}$ across most of the system. Overall pressure reliability remained very high, and most outlets can therefore be classified as having moderate-to-high hydraulic performance. The critical hydrant deficit, CHD_{P80} , was approximately 11% of $P_{\min}$, whereas the mean pressure deficit during failure events was only 3 m. This suggests that while some hydrants already exhibit reduced pressure margins and increased sensitivity to peak demand, most pressure-deficit events were moderate.

Under future climate-driven demand, overall pressure reliability remains high, but hydraulic service shows gradual deterioration. The number of failed hydrants increases to approximately 20% in future scenarios (Figure 2b), while pressure reliability decreases to 0.96. Severity indicators also worsen modestly: the minimum RPD reaches -50% under late-century RCP8.5, indicating a maximum pressure deficit of 20 m. Although the system remains largely reliable at network scale, increasing CHD_{P80} and maximum deficit values indicate that future demand intensification exposes local hydraulic bottlenecks. The most critical hydrants show pressure-failure frequencies above 52% and mean pressure deficits greater than 7 m.

Although these outlets represent about 7% of the irrigated area, they exert a disproportionate influence on the service-risk profile by concentrating the most frequent and severe failures. This behaviour points to local hydraulic constraints, potentially associated with distal location, higher elevation, and/or high simultaneous demand during peak irrigation periods.

Table 6. Hydraulic service performance under present conditions (2024-2025) and future climate-driven demand scenarios considering high demand conditions

Horizon	RCP	N° of failures	RR_p^C	Min RPD	CHD _{P80}	PD _{max}
2024-25		5.0 ± 3.1	0.98 ± 0.00	-0.09 ± 0.02	4.5 ± 0.4	11.9 ± 0.9
1971-00		6.0 ± 2.3	0.98 ± 0.02	-0.43 ± 0.08	6.7 ± 0.1	16.9 ± 2.8
2041-70	4.5	19 ± 7.1	0.96 ± 0.04	-0.48 ± 0.06	7.0 ± 0.3	18.9 ± 2.4
2041-70	8.5	19 ± 7.8	0.96 ± 0.04	-0.44 ± 0.12	6.9 ± 0.2	17.5 ± 4.6
2071-100	4.5	20 ± 7.8	0.96 ± 0.04	-0.49 ± 0.09	7.0 ± 0.4	19.3 ± 3.4
2071-100	8.5	20 ± 9.2	0.96 ± 0.04	-0.50 ± 0.09	7.1 ± 0.4	19.8 ± 3.4

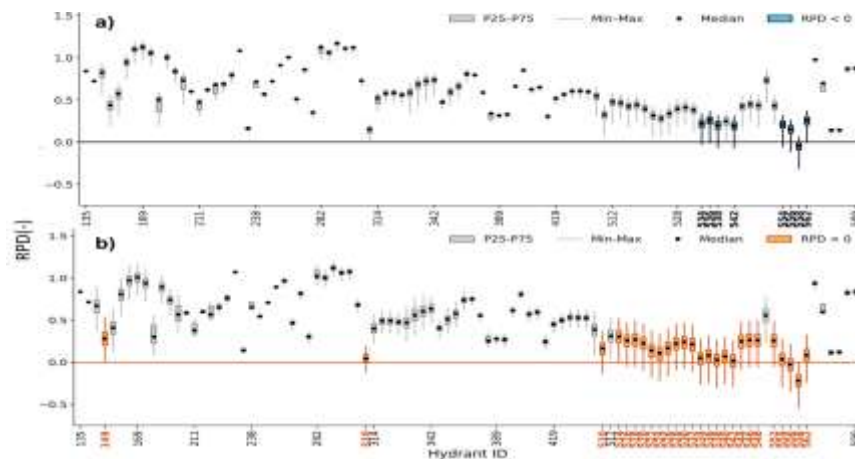


Figure 2. Identification of critical hydrants for: a) present conditions (2025); b) climate-driven demand for 2071–2100 under RCP8.5.

Pumping and energy resilience implications

Under current conditions, maintaining the pressurized irrigation service entails moderate but significant energy costs. Energy use per irrigated area (D1) averaged 832.6 kWh ha⁻¹, while energy cost per irrigated area (D4) averaged 125.0 € ha⁻¹. Average energy consumption (D2) was 0.23 kWh m⁻³ for the supplied volume (D3) and 0.22 kWh m⁻³ for the abstracted volume. The pumping redundancy indicator (D8) was 81%, indicating that the required pumping capacity remained well below the installed capacity. Projected energy exposure indicates that energy consumption per irrigated hectare is expected to increase to 1,058.7 kWh ha⁻¹ under the RCP8.5 by 2071–2100. Concurrently, energy cost (in real terms) per irrigated hectare is projected to rise to 159.0 € ha⁻¹. Pumping redundancy remains positive in all future scenarios, although it declines to 52% under late-century RCP8.5, indicating that the operational safety margin narrows as peak monthly demand increases. This suggests that the pumping system remains structurally adequate, but that future resilience will become increasingly dependent on peak-demand management, scheduling flexibility and energy-aware operation.

The contribution from renewable energy remains a weakness. This suggests a limited ability to separate irrigation service from external energy-market conditions and limited protection against exposure to inflationary spikes in electricity prices. Therefore, a pertinent adaptation pathway for enhancing pumping and energy resilience would be to increase the integration of renewable energy sources along with tariff-sensitive pumping and peak-demand smoothing.

Table 7. Pumping and energy resilience indicators under present conditions and future scenarios.

Horizon	Scenario	D1	D2	D3	D4	D5	D6	D7	D8
1971–2000	HIS	833	0.23	0.22	125	0.03	0.03	9.3	81
2041–2070	RCP4.5	918			138				59
2041–2070	RCP8.5	961			144				66
2071–2100	RCP4.5	956			144				66
2071–2100	RCP8.5	1059			159				52

D1 -consumed energy per irrigated area (kWh ha⁻¹); D2 and D3 -consumed energy per delivered and diverted volume (kWh m⁻³); D4 -energy cost per irrigated area (€ ha⁻¹); D5 and D6 -energy cost per diverted and delivered volume (€ m⁻³); D7 - renewable energy contribution (REC,%); and D7 -pump redundancy (%).

After normalisation, the hydraulic performance service subsystem showed a decline from 0.76 to 0.48 under late-century RCP8.5. This decrease reflects the persistence of high network-scale pressure reliability but also increasing local severity at critical hydrants. Pumping and energy resilience also declined, from 0.71 to 0.57, mainly due to higher area-based energy use and energy cost. The integrated index decreased from 0.74 to 0.52 under late-century RCP8.5, indicating that future climate-driven demand does not imply system-wide failure, but progressively reduces hydraulic and energy safety margins.

CONCLUSIONS

Both annual irrigation requirements and peak demand are predicted to increase due to climate change, with the greatest increase taking place in the late century. High hydraulic service performance is currently maintained by the Minutos system. Future demand concentration, however, gradually lowers service margins. Climate stress is likely to expose local hydraulic bottlenecks rather than cause uniform network degradation, as evidenced by the fact that pressure failures at hydrants increase and become more severe even though overall pressure remains high.

Future demand conditions also result in a decline in pumping and energy resilience. Although the operational safety margin is still structurally adequate, area-based energy use and costs rise with yearly demand, while pump redundancy declines. Exposure to electricity supply and price risks is further increased by the low contribution of renewable energy.

Future conditions do not imply system-wide failure, but the progressively reduce hydraulic and energy safety margins. This is demonstrated by the decline in both hydraulic service and pumping and energy resilience, reaching an integrated score of 0.40 under late-century RCP8.5. Therefore, in addition to pump-operation optimisation, staggered irrigation scheduling, improved telemetry, demand flexibility and greater renewable energy integration, adaptation should prioritise targeted interventions at critical hydrants and constrained branches. To complete the multi-subsystem resilience assessment, future research should link these service-level indicators with reservoir storage dynamics, allocation rules and farmer-level adaptive capacity.

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