

Night-flow response to active leakage control in a semi-arid Moroccan town: Evidence from two years of leak repairs and hotspot mapping

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ABSTRACT

Non-revenue water is a major pressure on drinking-water resources in semi-arid regions, where every cubic metre lost has already been abstracted, treated and pumped. This study evaluates a two-year active leakage control programme carried out by the national utility in Aïn Aouda, a Moroccan town of 24 000 service connections, between May 2024 and April 2026. A field register of 1229 interventions (1187 leak repairs, 92% georeferenced) was coded by leak type, failed component, detection mode and service impact, and combined with the survey effort of each campaign (2 070 km of mains surveyed), ten bimonthly minimum night flow campaigns recorded over three consecutive nights with calibrated ultrasonic flow meters under a fixed supply configuration, eight pressure-logging campaigns and continuous flow measurements at the reservoirs. Trends were tested with autocorrelation-corrected Mann-Kendall tests and negative binomial regression, and spatial patterns with kernel density estimation, Ripley's L function, Moran's I and Getis-Ord statistics. Service connections accounted for 60% of repairs, and 66% of them were hidden leaks found only by acoustic survey, against 39% for mains; three components explained 84% of failures. Repairs decreased significantly (−6.7% per month, 95% confidence interval −9.4 to −3.9%) while the minimum night flow fell from 274 to 154 m³/h in six months of intensive search, rose to 189 m³/h when search intensity halved, and reached 127 m³/h (−54%) after a renewed campaign; hidden leaks found per campaign followed the length of mains surveyed ($p = 0.74$). With a measured night-day factor of 20–21 h, real losses are estimated to have decreased from 47% (42–54%) to 19% (16–23%) of the distribution input, an estimated saving of 1.1 million m³ (1.0–1.2), 0.65–0.82 GWh and 390–550 t CO₂ per year (model-based estimates with propagated uncertainty). Leak density concentrated in three persistent hotspots (11% of the urban area holds 67% of repairs, $p < 0.01$), and main failures caused 82% of the 22 494 customer-hours of supply interruption. The results document the response of night flow to a sustained active leakage control effort and its rebound when effort declines, and provide a spatial basis for district metering, pipe renewal and pressure management.

Keywords: non-revenue water, active leakage control, minimum night flow, kernel density estimation, service connections, preventive maintenance, water distribution network, Morocco.

INTRODUCTION

Water losses from distribution networks remain one of the largest inefficiencies of urban water services. Global estimates put non-revenue water at about 126 billion m³ per year, of which

real losses are the dominant component, with the highest specific losses in low- and middle-income countries (Liemberger and Wyatt, 2019). Cross-national analyses show that non-revenue water is driven by network age, pressure, operating practices and institutional capacity rather than by any

single technical factor (van den Berg, 2015). In semi-arid countries, the environmental cost of these losses is particularly high, because the lost water has already been abstracted from stressed aquifers or reservoirs and has consumed energy for treatment and pumping (Molinos-Senante et al., 2016). Morocco is a representative case: recurrent droughts since 2018, declining groundwater levels and a projected reduction of surface water resources have placed water security at the centre of national policy (Hssaisoune et al., 2020; Trambay et al., 2020), and the reduction of network losses is one of the few measures that can deliver additional water within months rather than years.

The International Water Association framework distinguishes four pillars of real-loss management: pressure management, active leakage control, speed and quality of repairs, and asset renewal (Mutikanga et al., 2013; Gupta and Kulat, 2018). Active leakage control, the systematic search for leaks that do not surface, is justified by the fact that hidden leaks run for months before detection, so that their volume is governed by awareness time rather than by flow rate. Its effect is usually monitored through the minimum night flow of a district or system, which is the standard indicator of real losses when legitimate night consumption is small and can be estimated (Alkassseh et al., 2013; Amoatey et al., 2014). Night-flow analysis has been applied in both continuous and intermittent supply contexts and, when combined with a night-day factor derived from pressure records, allows real losses to be expressed as daily volumes and compared with the water balance (AL-Washali et al., 2019; Amoatey et al., 2018). A second, less documented, aspect is the natural rate of rise of leakage once search effort decreases, which determines the economic frequency of intervention (Islam and Babel, 2013; Creaco and Walski, 2017).

Where failures occur is as important as how many occur. Spatial analyses of burst records using geographic information systems, density-based clustering, and kernel density estimation have shown that failures cluster in space and time, and that clusters persist long enough to guide renewal and monitoring priorities (de Oliveira et al., 2011; Martínez García et al., 2019). Spatial clustering of past breaks also improves failure prediction models (Chen and Guikema, 2020; Aslani et al., 2021). Reviews of failure factors consistently point to material, diameter, age, pressure, and soil conditions, with small-diameter plastic and

asbestos-cement pipes and service connections being the most failure-prone assets (Barton et al., 2019; Kabir et al., 2015). Most of this evidence, however, comes from large utilities in Europe and North America with mature asset databases (Snider and McBean, 2021; Robles-Velasco et al., 2020). Small and medium towns in North Africa rarely possess pipe-age records, and published assessments of losses in the region rely mainly on annual water balances (Al-Omari, 2013; Taghlabi et al., 2023), so that decisions on where to search for leaks and which assets to renew are taken with little spatial evidence. Recent regional studies converge on the same point from different angles: the contribution that treated wastewater reuse can make to water security in Morocco (Lemfarak et al., 2025), the performance of traditional clay-based groundwater recharge systems in the Algerian Sahara (Oussama et al., 2026), and the contrast in hydro-physical behaviour between urban and natural soils within a single semi-arid Moroccan basin (Salih et al., 2026). These findings also highlight the importance of site-specific and operationally adaptive approaches to sustainable water management in water-stressed North African environments, where the effectiveness of water-management interventions depends strongly on local conditions and continued monitoring.

Repair registers kept by field crews are an under-used source in this context. When georeferenced and coded, they reveal where the network fails, which components fail, whether failures were visible or hidden, and what each failure costs in supply interruption for customers. Combined with night-flow and pressure measurements, they also allow the effect of active leakage control on real losses to be quantified without a complete billing balance. Published work on leakage in Moroccan networks has so far addressed model-based leak pre-location and smart monitoring pilots in the Casablanca system (Taghlabi et al., 2020; Taghlabi et al., 2023); a search of Scopus and Google Scholar (September 2026, terms: Morocco, leak, night flow, repairs, hotspot) returned no study combining a georeferenced multi-year repair register with night-flow, pressure and spatial hotspot analysis for a Moroccan utility, nor, to our knowledge, for a small North-African town.

The aim of this study is to evaluate a two-year active leakage control programme carried out by the National Office of Electricity and Drinking Water (ONEE) in the town of Aïn Aouda, Morocco, and to derive from it a spatially targeted

preventive maintenance strategy. Four questions are addressed: (i) how did the number of repairs and the minimum night flow of the network respond to the intensity of active search, including the rebound when intensity decreased; (ii) which leak types and components dominate failures, how are they distributed between reported and hidden leaks, and which of them carry the largest service impact; (iii) where do failures concentrate, and are the hotspots persistent over time; and (iv) what water, energy and carbon savings can be attributed to the programme.

MATERIALS AND METHODS

Study area and water supply system

Aïn Aouda (33.80° N, 6.79° W) is a town of the Skhirate-Témara prefecture, about 20 km south of Rabat, in the Rabat-Salé-Kénitra region of Morocco. The climate is semi-arid Mediterranean, with monthly mean maximum temperatures ranging from 21 °C in winter to 35 °C in summer according to the utility's records. Drinking water is supplied by the ONEE Water Branch. Water is pumped from station SP2 through DN 250, DN 400, and DN 500 mains to a 3 000 m³ storage tank, with intermediate offtakes supplying rural settlements along the route; the tank feeds by gravity two 800 m³ distribution reservoirs (Atlas and Oulad Zaer), and a 200 m³ reservoir is supplied by pumping. The distribution network is meshed between the three reservoirs and comprises about 192 km of mains in polyvinyl chloride (PVC, DN 63 to DN 400), high-density polyethylene (HDPE, DN 50 to DN 90) and asbestos cement (DN 60 to DN 250), serving about 24 000 service connections. The network is divided into

pressure zones with ground elevations between 213 and 303 m; no pressure-reducing valves were installed before or during the study period.

Table 1 summarises the utility water balance for 2015–2022, the last years with available billed volumes. Non-revenue water fluctuated between 27% and 32% until 2020 and decreased to 22–24% in 2021–2022, corresponding to 92–98 L per connection per day, a level that places the town in the intermediate performance bands proposed for developing countries (Liemberger & Wyatt, 2019). The distribution input measured at the three reservoir outlets in April 2026 averaged 10 660 m³/d (Figure 11a), i.e. about 3.9 million m³ per year.

Active leakage control programme

The programme was implemented under a performance-based framework contract of the ONEE Water Branch for the search and repair of leaks, with a contractual commitment on the reduction of real losses: after a two-month preparatory phase, the minimum night flow was to be reduced by 25% relative to the baseline within a first 120-day search-and-repair phase, and then kept at least 25% below the baseline with the objective of reaching a 40% reduction over the remaining contract period. The decreasing survey intensity described below therefore reflects the two contractual phases, an intensive reduction phase followed by a maintenance phase. The programme started in June 2024 and combined a systematic acoustic survey of the network (ground microphones and leak-noise correlators on mains and service connections, step testing by valve manoeuvres), repair of the leaks found, and bimonthly night-flow campaigns to track progress. The team comprised a local manager, two leak-detection technicians with about ten years of

Table 1. Water balance indicators of the Aïn Aouda water supply system, 2015–2022 (utility data)

Year	System input (10 ³ m ³)	Billed volume (10 ³ m ³)	Non-revenue water (%)	Mains (km)	Connections	Losses (m ³ / km/d)	Losses (L/ conn./d)
2015	2 005	1 431	28.6	174	12 507	9.0	126
2016	2 331	1 648	29.3	182	13 999	10.3	134
2017	2 654	1 815	31.6	185	15 606	12.4	147
2018	2 520	1 762	30.1	192	16 833	10.8	123
2019	2 800	1 975	29.5	192	18 259	11.8	124
2020	3 018	2 194	27.3	192	19 424	11.8	116
2021	2 970	2 300	22.5	192	20 008	9.6	92
2022	3 342	2 539	24.1	192	22 420	11.5	98

Note: losses = system input – billed volume.

experience assisted by two operators, two crew leaders, four plumbers, four labourers and a store-keeper. The length of mains surveyed was recorded for each campaign: 2 070 km in total over the ten campaigns, i.e. about eleven passes over the 192 km network, with a survey intensity that decreased from 4.6–6.1 km per day during the first four campaigns to 0.9–1.9 km per day from June 2025 onwards (Table 3). Reported leaks (visible at the surface or notified by customers) continued to be repaired by the same crews and were recorded in the same register.

Data sources

Four data sets were used. (1) The repair register kept by the field crews from 14 April 2024 to 5 April 2026, with 1 229 interventions and, for each, the date, the nature of the leak, the designation of the failed part, the address, GPS coordinates recorded by the crew, the duration of the supply cut, the number of customers affected and the detection mode. (2) Ten bimonthly minimum night flow campaigns from June 2024 to April 2026. (3) Pressure records from 23 data-logger deployments between May 2024 and March 2026. (4) Continuous flow measurements with clamp-on ultrasonic flow meters at the three reservoir outlets (4–8 April 2026) and along the transmission main (17–19 February 2026). The annual water balance for 2015–2022 was provided by the utility.

Minimum night flow was measured at the outlet of the Atlas reservoir while the two other supply points (the Oulad Zaer reservoir and the pumped supply of the 200 m³ reservoir) were closed, so that the whole meshed network was fed from a single metered inlet during each campaign, and all bulk exports to neighbouring systems were closed. Large consumers were closed, and no irrigation of public green spaces took place during the measurements. The same protocol was applied in all ten campaigns, which makes the values directly comparable. The baseline night flow before the programme was 274.2 m³/h (76.2 L/s).

Measurement equipment and quality control

Night flow was recorded with clamp-on transit-time ultrasonic flow meters logging at 5-min intervals; the contract required calibration certificates less than one year old for the flow meters, and the certificates are held by the

utility. Each campaign value is the minimum of the 5-min readings recorded between 00:00 and 06:00 over three consecutive nights (two nights in August 2025), as required by the contract, which also required the nightly records to be delivered as date–time–flow tables with the corresponding curves. The nightly records of all campaigns (36 nights, 2 446 readings) were re-examined for this study: the campaign values reported by the utility coincide with the lowest sustained reading of the three nights, and the spread between the nightly minima of a campaign was 0.7–13.6 m³/h in eight campaigns (coefficient of variation 0.2–3.2%), 23 m³/h in June 2025 and 27 m³/h in October 2025; one isolated 5-min dip of 125.6 m³/h on 2 December 2024, not sustained in the adjacent readings, was disregarded by the operator. Four additional nights recorded between campaigns (9 and 11 July, 5 September and 13 November 2024) were used to check the continuity of the series. The nightly records and curves are provided as Supplementary Material (Table S1, Figure S1). Pressure was recorded with data loggers at 5-min intervals; series shorter than one full day were excluded. The continuous flow measurements of April 2026 were made with the same ultrasonic meters at the three reservoir outlets, with signal-quality indicators logged by the instruments (98–99% during the night). For the repair register, quality control consisted of range and consistency checks on dates, the reconciliation of the 40 non-leak interventions, the correction of coordinate formats, the exclusion of points outside the urban perimeter and the cross-check of district names against addresses.

Data cleaning and coding

The register was processed with reproducible rules (Table 2). Forty interventions that were not leak repairs (valve works, meter-box relocation, manhole cleaning, pressure complaints) were excluded, leaving 1 189 leak repairs; two records with implausible dates were excluded from the time series, giving 1 187 repairs for analysis. Leaks were classified into four types (service connection, main, meter box, and fitting). The failed component, and for mains the material and nominal diameter, were extracted from the part designation. The detection mode was recoded as reported (visible) or hidden (found by acoustic survey). Interruption times were converted to minutes and customer-hours of interruption were

computed as the product of customers affected and interruption time. Coordinates were corrected for decimal separators and sign errors, transformed to the national projected system (Merchich / Nord Maroc, EPSG:26191), and eight points falling outside the urban perimeter were discarded, leaving 1 117 georeferenced interventions (91%), of which 1 096 leak repairs. Eighteen district names were harmonised from the free-text addresses.

Statistical analysis

Monthly repair counts over the 22 complete months (June 2024 to March 2026) were tested for trend with the non-parametric Mann-Kendall test and Sen's slope estimator; because monthly counts are serially correlated (lag-1 autocorrelation 0.79), the test was repeated with the Hamed-Rao and Yue-Wang variance corrections and with trend-free pre-whitening, and the trend was also estimated with a negative binomial regression of monthly counts on time, which accounts for overdispersion. The June–December windows of 2024 and 2025 were compared with a negative binomial rate ratio, and seasonal differences with a Kruskal-Wallis test on monthly counts. The yield of the acoustic survey was estimated with a Poisson model of the number of hidden leaks per campaign with the length of mains surveyed as exposure (offset), and its temporal trend with a negative binomial model. The association between leak type and detection mode was tested with a chi-square test and quantified with Cramér's V. Interruption times and numbers of customers affected were compared between leak types with Kruskal-Wallis tests, as their distributions were strongly skewed. The response of the night flow to repairs was described campaign by campaign, with rank correlations between the change in night flow and the survey effort and number of

hidden leaks of each campaign. A simple campaign-level model (Supplementary Material, Equation S1 and Table S2), expressing the change in night flow between two campaigns as the balance between the flow recovered by hidden-leak repairs and a linear rise of leakage with time, was fitted for illustration only; with ten campaigns its coefficients are not statistically significant and it is not used to derive quantitative conclusions. Uncertainty on the derived quantities (recovered volume, real-loss shares, energy and emissions) was propagated by Monte Carlo simulation (20 000 draws) with the following inputs: flow-meter uncertainty $\pm 2\%$ (one standard deviation), night-day factor uniform between 19.9 and 21.1 h, legitimate night consumption uniform between 14 and 41 m³/h, specific energy uniform between 0.62 and 0.72 kWh/m³, emission factor uniform between 0.57 and 0.70 kg CO₂/kWh and distribution input $\pm 5\%$. All analyses were performed in Python 3.11 (pandas, SciPy, pymannkendall, statsmodels) with a significance level of 0.05.

Night-flow analysis, night-day factor and water–energy balance

Real losses were estimated by the night-flow method as the minimum night flow minus an allowance for legitimate night consumption, converted to daily volume with a night-day factor (AL-Washali et al., 2016; Amoatey et al., 2018). Because the flow recovered by the programme is the difference between two night flows measured under the same protocol, it is insensitive to the legitimate-consumption allowance, which was therefore treated as a sensitivity parameter between 0.6 and 1.7 L per connection per hour (Alkassseh et al., 2013). The night-day factor was derived from the pressure records: for each logger series covering at least one full day, the

Table 2. Coding scheme applied to the repair register

Variable	Source field	Classes or units	Records
Leak type	Nature of leak	Service connection; main; meter box; fitting; non-leak (excluded)	1 229
Component	Part designation	Service pipe, main pipe, fitting, stop tap, flange adaptor, angle valve, Gibault joint, gate valve, coupling, tee or elbow, meter box	1 205
Material and diameter of mains	Part designation	PVC, HDPE, asbestos cement, ductile iron; DN 50–500 mm	267
Detection mode	Observation	Reported (visible); hidden (acoustic survey); not recorded	1 173
Interruption time	Cut-off duration	min	933
Customers affected	Subscribers affected	count; customer-hours = count × hours	925
Location	X, Y	WGS84 → EPSG:26191; urban perimeter check	1 117

hourly mean pressure profile was normalised to the 02:00–04:00 night pressure and the factor was computed as the sum over 24 h of the pressure ratio raised to the leakage exponent $N1$, using $N1 = 1$ and $N1 = 1.5$ to bracket the behaviour of rigid and plastic pipes according to the fixed-and-variable-area-discharge concept (van Zyl and Cassa, 2014; Schwaller and van Zyl, 2015). The recovered volume was converted to energy and greenhouse-gas savings with the national specific energy consumption of ONEE water supply, 0.62–0.72 kWh/m³ (African Development Bank, 2014; Plan Bleu, 2011), and a grid emission factor of 0.57–0.70 kg CO₂/kWh for Morocco, following the water–energy nexus approach (Wakeel et al., 2016; Lee et al., 2017). These conversions are model-based estimates: the energy and emission figures were not measured at the plant level and are reported with the uncertainty of the coefficients propagated by the Monte Carlo simulation.

Spatial analysis

Georeferenced repairs were analysed in EPSG:26191. Leak density was estimated by kernel density estimation with a Gaussian kernel, a 150 m bandwidth and a 20 m cell, expressed in repairs per km²; the bandwidth was chosen close to the mean nearest-neighbour distance between repairs and checked for stability between 100 and 250 m. Separate surfaces were computed for all leaks and for hidden leaks, and half-year surfaces on a common colour scale were used to assess the persistence of hotspots, following the rationale of density-based hotspot mapping of pipe failures (de Oliveira et al., 2011; Martínez García et al., 2019). Repairs were also counted on a 200 m grid and aggregated by district. The significance of spatial clustering was tested with Ripley's L function against 199 simulations of complete spatial randomness within the convex hull of the repairs (buffered by 100 m), with Moran's I on the 200 m grid (queen contiguity, 999 permutations) and with the Getis-Ord Gi* statistic to identify cells with significantly high counts; the sensitivity of the density surface to the bandwidth was assessed by comparing, for bandwidths of 100, 150, 200 and 250 m, the location of the peak and the share of repairs falling within the 10% of the area with the highest density (Supplementary Material, Figures S2 and S3). The satellite image used as background is the Esri World Imagery service.

RESULTS

Temporal evolution of repairs and night-flow response

Figure 1 shows the location of the 1 096 georeferenced repairs. The monthly number of repairs decreased markedly over the programme (Figure 2): from 91–109 repairs per month in June–July 2024 to 27–44 per month in the second half of 2025 and 35–47 per month in early 2026. The Mann-Kendall test confirms a significant decreasing trend ($\tau = -0.65$, $p < 0.001$) with a Sen's slope of -4.0 repairs per month; the conclusion is unchanged with the Hamed-Rao and Yue-Wang corrections and with trend-free pre-whitening ($p < 0.001$ in all cases; Supplementary Table S3), and the negative binomial regression gives a decrease of 6.7% per month (95% confidence interval 3.9–9.4%, $p < 0.001$; Poisson dispersion 5.7, negative binomial $\alpha = 0.19$). Between June and December, 600 repairs were carried out in 2024 against 177 in 2025 (rate ratio 0.29, 95% confidence interval 0.17–0.50, negative binomial model). No seasonal signal was detectable once the trend is accounted for (Kruskal-Wallis between seasons, $p = 0.81$). The share of hidden leaks among repairs ranged between 36% and 75% per campaign, with the highest share (75%) in the last campaign.

The minimum night flow decreased rapidly during the first months of the programme (Figure 3, Table 3). The number of hidden leaks found per campaign was closely related to the length of mains surveyed (Spearman $\rho = 0.74$, $p = 0.014$), with an overall yield of 29 hidden leaks per 100 km surveyed (95% confidence interval 26–31; one leak every 3.5 km) and no significant trend of the yield over the campaigns ($p = 0.26$). During the first three campaigns, carried out at 4.6–6.1 km surveyed and 2.4–3.3 repairs per day and including 285 hidden leaks, the night flow fell from 274.2 to 154.4 m³/h, a reduction of 44% in six months. It then rose to 174 m³/h in February 2025 and to 189 m³/h in August 2025 while the survey intensity decreased to 1.6–2.8 km per day and the repair intensity to 1.2–1.3 repairs per day, before decreasing again to 160 m³/h in February 2026. The last campaign, with 57 hidden leaks found on 102 km (56 per 100 km, the highest yield of the programme) and repaired in 59 days, brought the night flow down to 127.5 m³/h, i.e. 53.5% below the baseline and below the final target of the programme (164.5 m³/h). The night-flow values are supported

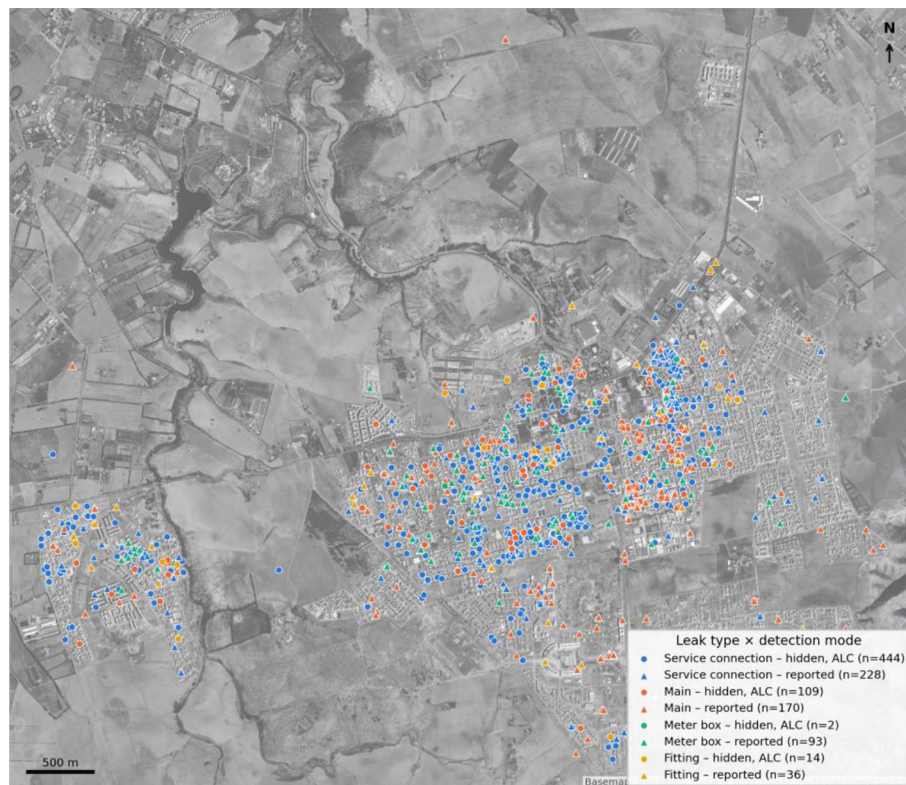


Figure 1. Location of the 1 096 georeferenced leak repairs in Aïn Aouda (May 2024 – April 2026) by leak type and detection mode; projection Merchich / Nord Maroc (EPSG:26191), background Esri World Imagery

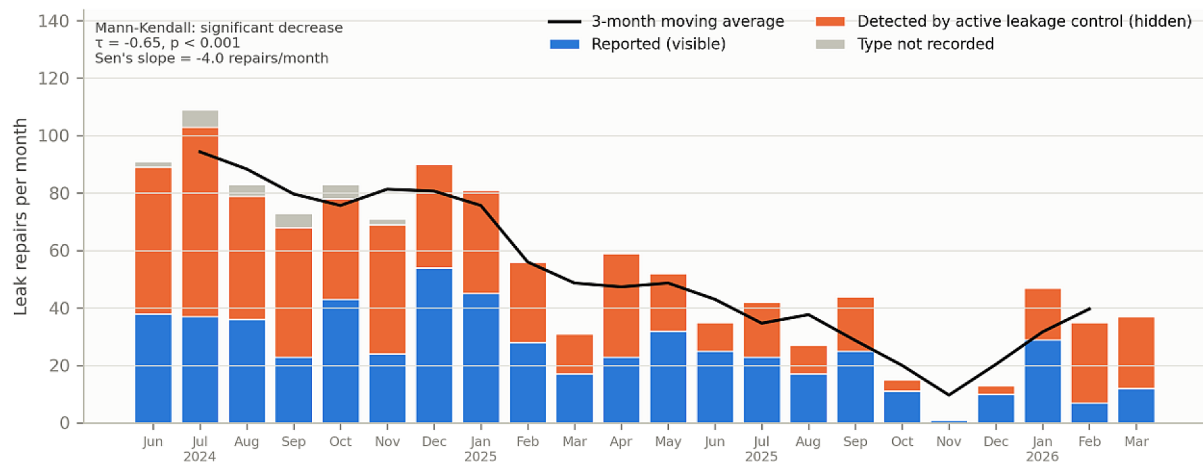


Figure 2. Monthly number of leak repairs by detection mode, June 2024 – March 2026 (n = 1 175), with the 3-month moving average and the Mann-Kendall trend statistics

by the nightly records: within each campaign the three nightly minima differed by 0.7–13.6 m³/h in eight campaigns, by 23 m³/h in June 2025 and by 27 m³/h in October 2025 (Table 3, Supplementary Table S1 and Figure S1), and the four additional nights recorded between campaigns (238 and 225 m³/h in July 2024, 206 m³/h in September 2024, 180 m³/h in November 2024) fall on the same trajectory. The changes in night flow between

consecutive campaigns were negatively but not significantly correlated with the number of hidden leaks repaired (Spearman $\rho = -0.52$, $p = 0.12$) and with the length surveyed ($\rho = -0.29$, $p = 0.41$). The illustrative campaign-level model gives a mean recovered flow of 0.34 m³/h per repaired hidden leak (95% confidence interval -0.13 to 0.81) and a rise of 0.05 m³/h per day (-0.40 to 0.50) with $R^2 = 0.45$; neither coefficient is significant with ten

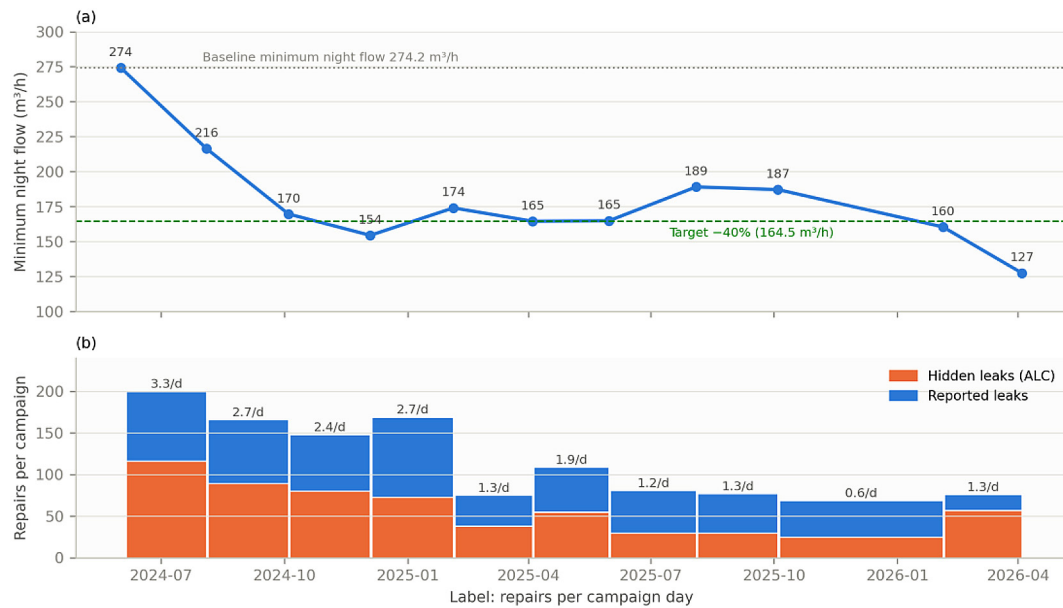


Figure 3. Minimum night flow of the Aïn Aouda network measured at the end of each active leakage control campaign (lowest of three consecutive nights) (a) and number of leak repairs per campaign by detection mode (b), June 2024 – April 2026; labels in (b) give the number of repairs per campaign day

observations (Supplementary Table S2), so that no quantitative rate of rise of leakage is claimed. What the sequence shows descriptively is that the net rise of 35 m³/h between December 2024 and August 2025 occurred while survey intensity fell from 5.7 to 1.6 km per day, and that the night flow decreased again when intensity and hidden-leak yield rose in the last campaign.

Leak typology, detection mode and service impact

Service connections accounted for 713 repairs (60%), mains for 287 (24%), meter boxes for 135 (11%) and fittings for 52 (4%) (Table 4). The detection mode was strongly associated with the leak type ($\chi^2 = 200$, $df = 3$, $p < 0.001$,

Table 3. Survey effort, repairs and minimum night flow per active leakage control campaign

Campaign	Days	Mains surveyed (km)	Survey intensity (km/d)	Repairs	Hidden leaks	Hidden leaks per 100 km	Night flow at end (m³/h)	Nights recorded / spread of nightly minima (m³/h)	Reduction vs baseline (%)
05 Jun–04 Aug 2024	61	370	6.1	200	116	31	216.4	3 / 6.0	21.1
05 Aug–04 Oct 2024	61	278	4.6	166	89	32	169.7	3 / 13.6	38.1
05 Oct–04 Dec 2024	61	347	5.7	148	80	23	154.4	3 / 18.0*	43.7
05 Dec 2024–04 Feb 2025	62	325	5.2	169	73	22	174.1	3 / 7.4	36.5
05 Feb–04 Apr 2025	59	168	2.8	75	38	23	164.5	3 / 12.0	40.0
05 Apr–31 May 2025	57	142	2.5	109	55	39	164.9	3 / 23.3	39.9
01 Jun–04 Aug 2025	65	106	1.6	81	30	28	189.1	2 / 0.7	31.0
05 Aug–04 Oct 2025	61	116	1.9	77	30	26	187.2	3 / 27.3	31.7
05 Oct 2025–04 Feb 2026	123	116	0.9	69	25	22	160.5	3 / 2.3	41.5
05 Feb–04 Apr 2026	59	102	1.7	76	57	56	127.5	3 / 1.7	53.5
Total / overall	669	2 070	3.1	1 170	593	29		29 nights	

Note: baseline minimum night flow before the programme 274.2 m³/h (three nights, 31 May – 2 June 2024, nightly minima 274.2–280.2 m³/h); repairs include reported and hidden leaks recorded in the register during the campaign; mains surveyed is the cumulative length walked by the acoustic survey team; the spread is the difference between the highest and lowest nightly minimum of the campaign; * excluding an isolated 5-min dip of 125.6 m³/h on 2 December 2024.

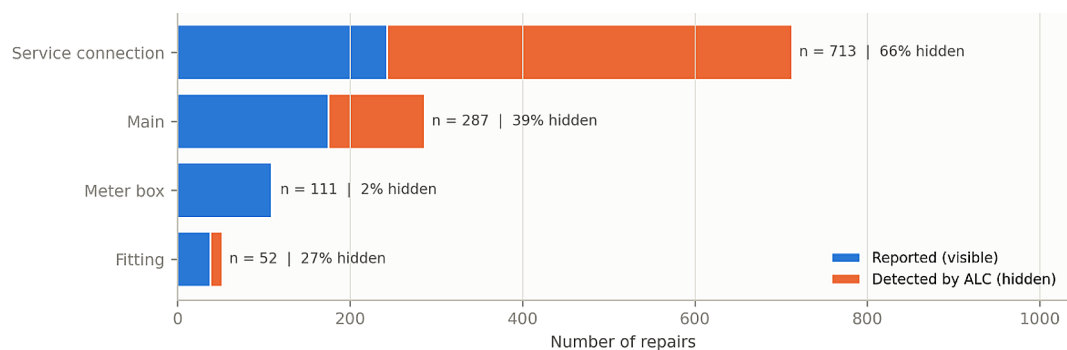


Figure 4. Number of leak repairs by leak type and detection mode; labels give the number of repairs and the share of hidden leaks found by acoustic survey

Cramér's $V = 0.41$): 66% of service-connection leaks were hidden leaks found by acoustic survey, against 39% of main leaks, 27% of fitting leaks and only 2% of meter-box leaks (Figure 4). Three components concentrated 84% of all repairs: the service pipe itself (512 repairs, 43%), the main pipe (268, 23%) and fittings at the connection (223, 19%); stop taps added a further 7% (Figure 5). Among the 267 main repairs with a recorded material, 125 were on PVC, 110 on HDPE and 29 on asbestos-cement pipes; DN 63 mm alone accounted for 100 main failures, followed by DN 50 (49), DN 75 (34) and DN 110 (25).

The service impact of failures was very unequally distributed (Figure 6, Table 4). The median supply interruption was 40 min for mains (inter-quartile range 30–45 min), 35 min for fittings, 25 min for service connections (20–30 min) and 15 min for meter boxes (Kruskal-Wallis $p < 0.001$). The median number of customers affected was 61 for mains and 24 for fittings, against 1.5 for service connections and 1 for meter boxes ($p < 0.001$). In total, the 1 187 repairs caused 24 507 customer-interruptions and 22 494.2 customer-hours without

supply, of which 82.0% (18 437.0 customer-hours) were attributable to the 287 main failures (the calculation, customers affected multiplied by interruption time for each repair and summed by leak type, is reproducible from Table 4 and from the coding scheme of Table 2).

Spatial distribution and persistence of hotspots

The kernel density surface of all repairs (Figure 7) shows three main hotspots. The strongest lies in the north-eastern part of the town (En-nasser district), where three contiguous 200 m cells hold 143 repairs and the density exceeds 700 repairs per km²; a second core covers the central-western sector and a third the central sector, both with densities of 300–400 repairs per km². A separate cluster corresponds to the Al Firdaous district, about 3 km west of the town centre, which is fed by the same network. The density of hidden leaks (Figure 8) reproduces the same three cores and concentrates them further, so that the areas to be prioritised for

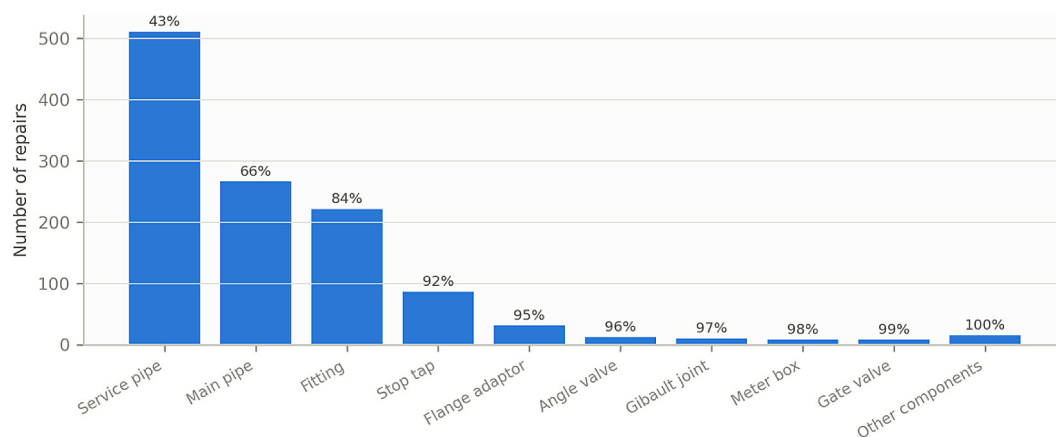


Figure 5. Pareto chart of failed components (n = 1 187 repairs); labels give the cumulative share

Table 4. Leak repairs by type, detection mode and service impact, May 2024 – April 2026

Leak type	Repairs (n)	Share (%)	Hidden leaks (%)	Median interruption (min)	Median customers affected	Customer-hours (sum)
Service connection	713	60.1	65.9	25	1.5	2 631.8
Main	287	24.2	39.0	40	61	18 437.0
Meter box	135	11.4	1.8	15	1	49.8
Fitting	52	4.4	26.9	35	24	1 375.6
All leaks	1 187	100	51.4	30	2	22 494.2

Note: hidden-leak shares computed on repairs with a recorded detection mode ($n = 1\,163$); customer-hours = customers affected $\times$ interruption time. Customer-hours are derived from interruption times recorded in minutes and are therefore reported to one decimal; the column sums exactly to the total.

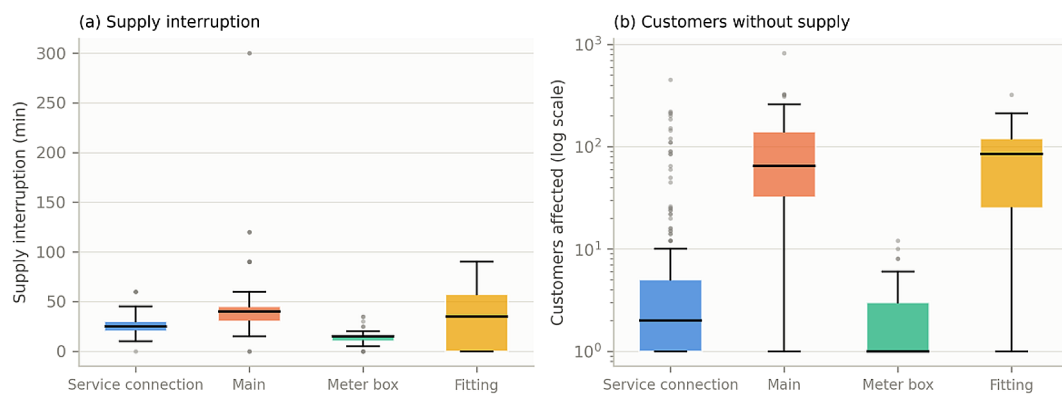


Figure 6. Supply interruption time (a) and number of customers affected (b) per leak repair, by leak type; boxes show the interquartile range and the median, points the outliers

acoustic survey are clearly delimited. The half-year surfaces (Figure 9) show that the north-eastern hotspot is present in all five half-years, while the overall density decreases with time, which indicates a zone where repair alone is insufficient and renewal should be considered. The clustering is statistically significant: Ripley's L function lies far above the 95% envelope of complete spatial randomness at all distances from 50 to 1 000 m ($L(r) - r = 140$ m at $r = 50$ m and 526 m at $r = 500$ m, against an envelope below 3 m; Supplementary Figure S2a), Moran's I of the 200 m grid counts is 0.51 ($z = 25$, permutation $p = 0.001$), and the Getis-Ord G_i^* statistic identifies 70 cells (11% of the study area) as hotspots at $p < 0.01$, which together contain 732 repairs (67%); the hotspot cells form one contiguous block over the north-eastern and central sectors and a small group in Al Firdaous (Supplementary Figure S3). The density surface is insensitive to the bandwidth: for 100, 150, 200 and 250 m the peak remains within 40 m of the same location and the 10% of the area with the highest density contains 85, 82, 80 and 78%

of the repairs respectively (Jaccard overlap of the high-density area with the 150 m reference 0.88 at 100 m, 0.91 at 200 m and 0.83 at 250 m; Supplementary Figure S2b). The mean nearest-neighbour distance between repairs is 35 m.

At district level (Table 5), Ennasser had the largest number of georeferenced repairs (253) with 67% hidden leaks, followed by Oulad Zaer (196), where half of the repairs concerned mains, and Tadamoune (159), where 92% of repairs were on service connections and only 8 on mains. Al Jadid (78) and PAM (47) had the highest shares of hidden leaks (71% and 72%), while Sidi Laarbi combined a low share of hidden leaks (30%) with a high proportion of main failures (30 of 54).

Pressure regime, night-day factor and real-loss balance

The 79 pressure series recorded at about 40 points over eight campaigns show the diurnal regime of a gravity-fed system (Figure 10a): pressure is highest between 01:00 and 06:00, falls to

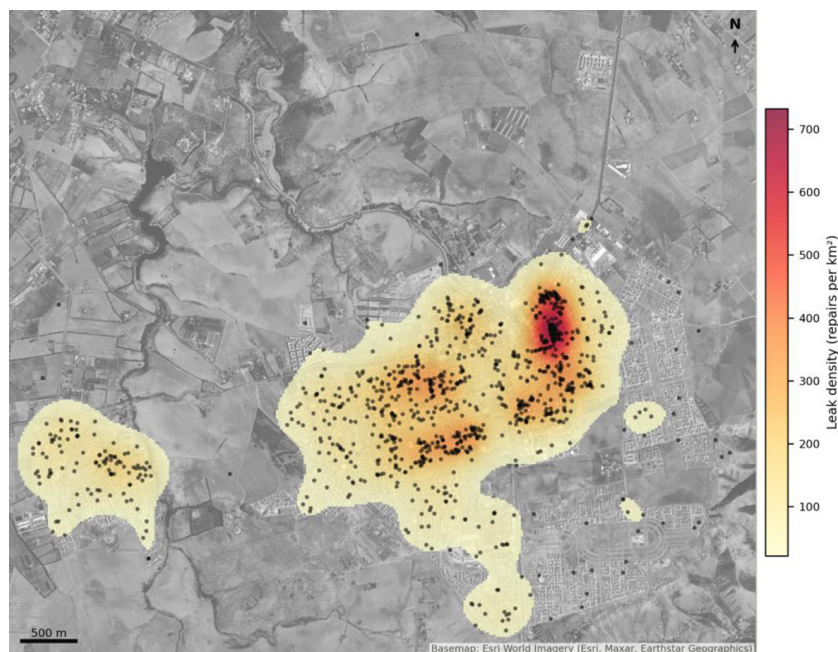


Figure 7. Kernel density of all georeferenced leak repairs ($n = 1\,096$; Gaussian kernel, 150 m bandwidth, 20 m cell); background Esri World Imagery

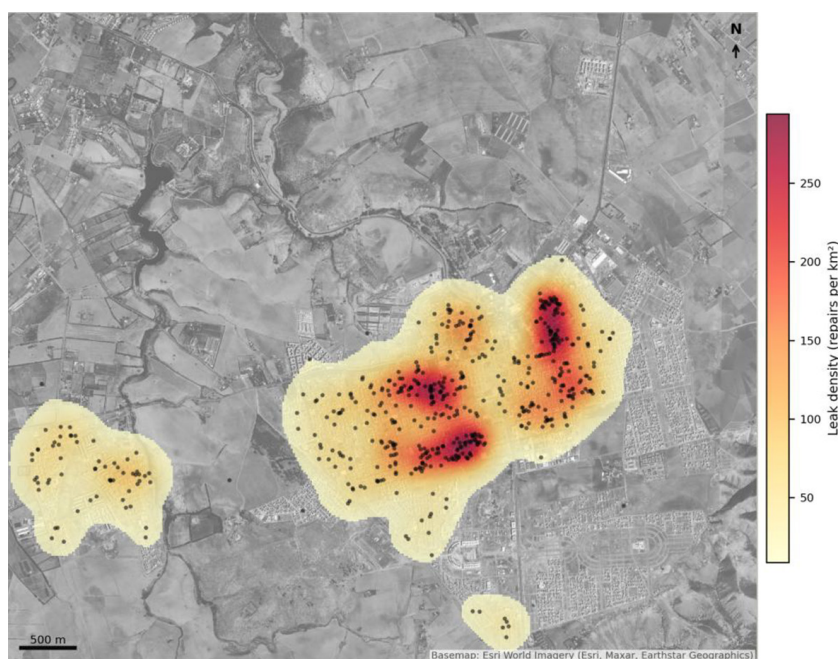


Figure 8. Kernel density of hidden leaks found by acoustic survey ($n = 569$), same parameters as Figure 7

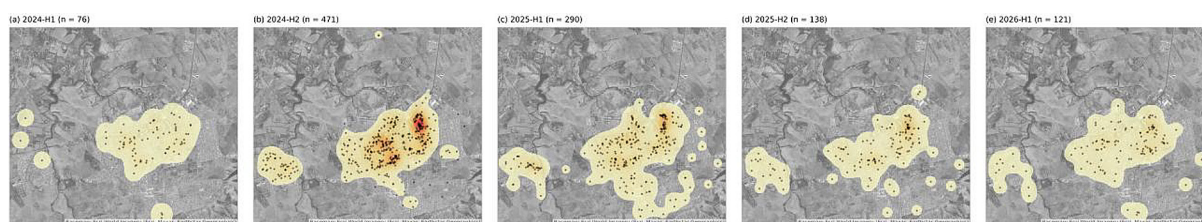


Figure 9. Half-year kernel density surfaces of leak repairs on a common colour scale: (a) 2024-H1, (b) 2024-H2, (c) 2025-H1, (d) 2025-H2, (e) 2026-H1

Table 5. Georeferenced leak repairs by district

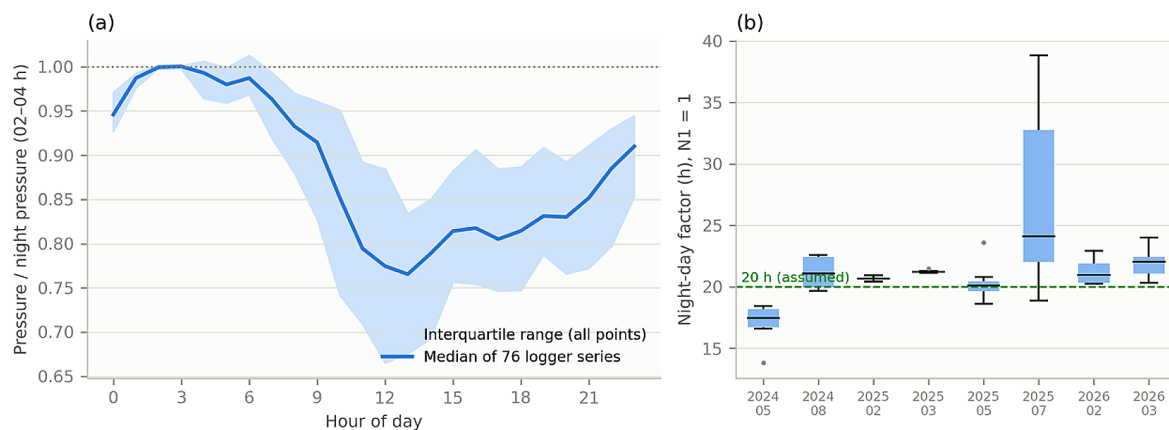
District	Repairs	Hidden leaks (%)	Service connections	Mains
Ennasser	253	67	175	47
Oulad Zaer	196	51	78	99
Tadamoune	159	42	146	8
Al Firdaous	115	54	72	22
Al Jadid	78	71	49	14
Sidi Laarbi	54	30	19	30
PAM	47	72	29	10
Other districts (11)	194	35	104	49
Total	1 096	52	672	279

77% of the night value at 12:00–13:00 and recovers progressively in the evening. The mean pressure was 3.3 bar, the mean night pressure 3.8 bar and the mean daytime pressure 3.2 bar; a few low-lying points (Al Firdaous, PAM, Abouab Zaer) recorded 5–7 bar. The night-day factor had a median of 21.1 h (interquartile range 20.0–22.4 h) for $N1 = 1$ and 19.9 h (18.4–21.6 h) for $N1 = 1.5$ (Figure 10b), so that a value of 20–21 h was used for the volume conversion.

Continuous measurements at the three reservoir outlets in April 2026 (Figure 11a) gave a distribution input of 10 030–11 860 m³/d (mean of the three complete days 10 660 m³/d), a daily minimum of 111–123 m³/h between 03:00 and 04:00, consistent with the 127.5 m³/h of the last campaign, and a ratio of minimum night flow to average daily flow of 0.25. The transmission main profile (Figure 11b) shows the 20 h pumping regime of station SP2 and the inflow to the storage tank (about 10 200 m³/d in February 2026); the differences between the three meters reflect the

rural offtakes upstream of the DN 500 junction and the daily draining and refilling of the DN 500 main during pump stops, not distribution losses.

Applying the night-flow method (Table 6), real losses in April 2026 are estimated at 1 390–2 380 m³/d, i.e. 13–22% of the distribution input and 58–99 L per connection per day, depending on the night flow retained (110.6 or 127.5 m³/h) and on the legitimate night consumption allowance. Under the assumption that the distribution input in June 2024 was of the same order as in April 2026 (it was not measured at the time; the network was supplied from the same reservoirs and the number of connections did not decrease, so that the input is unlikely to have been lower), the baseline night flow of June 2024 corresponds to about 4 700–5 300 m³/d, i.e. about 45% of the input and 195–220 L per connection per day. The flow recovered by the programme, 146.7 m³/h, represents an estimated 1.07–1.12 million m³ per year with the measured night-day factor of 20–21 h, about 30% of the current

**Figure 10.** Diurnal pressure profile normalised to the 02:00–04:00 night pressure, median and interquartile range of 79 logger series (a), and night-day factor per campaign for a leakage exponent of 1 (b)

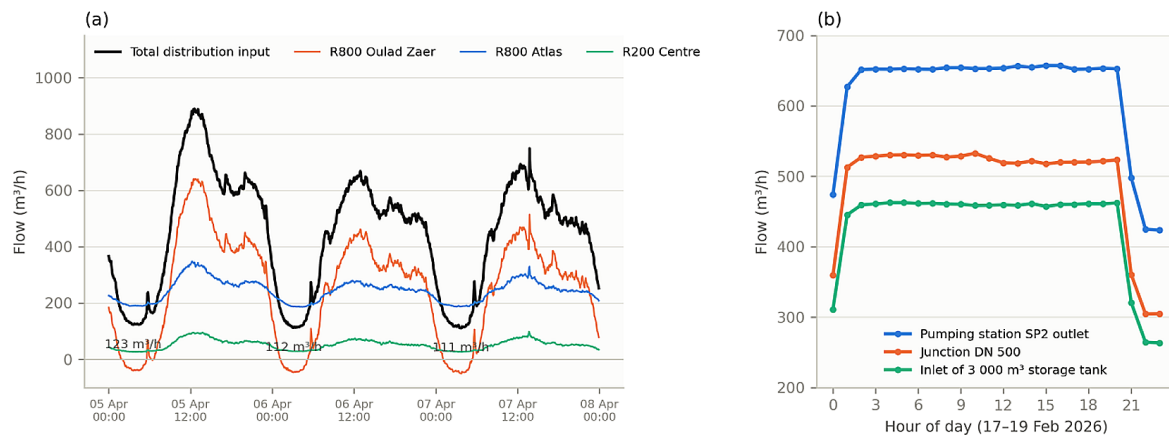


Figure 11. Flow at the three reservoir outlets and total distribution input, 5–7 April 2026 (a), and hourly mean flow along the transmission main from pumping station SP2 to the 3 000 m³ storage tank, 17–19 February 2026 (b)

annual distribution input, and corresponds to an estimated 0.66–0.81 GWh of electricity and 380–560 t CO₂ avoided per year with the national specific energy and emission factors. The Monte Carlo propagation of all input uncertainties gives a recovered volume of 1.10 million m³ per year (95% interval 1.00–1.19), 0.73 GWh (0.65–0.82) and 470 t CO₂ (390–550), and real-loss shares of 47% (42–54%) at the baseline and 19% (16–23%) at the end of the programme, i.e. 211 (194–228) and 85 (73–98) L per connection per day; the baseline share carries the additional, unquantified uncertainty of the distribution input assumption.

DISCUSSION

Attribution of the night-flow reduction

The 54% reduction of the minimum night flow is an observation made during the programme period, not an experimental measurement of the effect of repairs alone, and other factors were examined before relating it to active leakage control. Pressure: the same supply configuration and no pressure management were applied throughout; night pressures measured in the same season were 3.9–4.0 bar in February–April 2025 and 4.2–4.3 bar in February–March 2026, i.e. equal

Table 6. Real-loss balance of the distribution network estimated by the night-flow method (model-based estimates; 95% Monte Carlo intervals in brackets)

Item	June 2024 (baseline)	April 2026 (end of programme)	Assumption
Minimum night flow (m³/h)	274.2	110.6–127.5	Measured, single-inlet protocol, ±2%
Legitimate night consumption (m³/h)	14–41	14–41	0.6–1.7 L/connection/h, 24 000 connections
Night-day factor (h)	20–21	20–21	Measured from 79 pressure series
Real losses (m³/d)	4 700–5 300	1 390–2 380	
Distribution input (m³/d)	≈ 10 700*	10 660	Measured 5–7 April 2026, ±5%
Real losses (% of input)	≈ 45 (42–54)	13–22 (16–23)	
Real losses (L/connection/d)	195–220 (194–228)	58–99 (73–98)	
Recovered flow (m³/h)		146.7	Difference of night flows
Recovered volume (10 ⁶ m³/yr)		1.07–1.12 (1.00–1.19)	146.7 m³/h × 20–21 h × 365 d
Avoided energy (GWh/yr)		0.66–0.81 (0.65–0.82)	0.62–0.72 kWh/m³ (national coefficient, not measured locally)
Avoided emissions (t CO ₂ /yr)		380–560 (390–550)	0.57–0.70 kg CO ₂ /kWh (grid factor, not measured locally)

Note: * the June 2024 distribution input was not measured; the April 2026 value is used, which makes the baseline loss share indicative; Monte Carlo intervals refer to the input uncertainties listed in Methods and do not include this assumption.

or slightly higher at the end of the programme, so that a pressure decrease cannot explain the lower night flow; a sensitivity calculation with the pressure-leakage relationship shows that a $\pm 10\%$ change in night pressure between baseline and end would move the reduction between 48% and 58% ($N1 = 1$) or 46% and 60% ($N1 = 1.5$). Supply regime: the night-flow protocol (single metered inlet, exports and large consumers closed) was identical in all campaigns, and the values are the lowest of three nights recorded at 5-min intervals with calibrated meters, with a spread between nights of a few m^3/h in most campaigns. Consumption and season: legitimate night consumption enters the recovered flow only through its change between campaigns, and the comparison of the same season one year apart ($164.5 \text{ m}^3/\text{h}$ in April 2025, $127.5 \text{ m}^3/\text{h}$ in April 2026, -22%) shows a continued decrease independent of seasonal effects; the summer 2025 values, obtained under a temporary supply deficit, are the only ones that may include a seasonal component of night demand. Effort: the number of hidden leaks found followed the length of mains surveyed closely, and the periods of decreasing night flow coincide with the periods of high survey intensity while the rebound coincides with the low-intensity phase. Taken together, these elements do not prove causality, but they make the sustained active leakage control effort the most parsimonious explanation of the observed reduction and of its rebound, and the quantities derived from it are reported as estimates with their uncertainty rather than as measured savings.

Effectiveness of active leakage control and rebound of leakage

A 54% reduction of the minimum night flow in two years, with real losses estimated to fall from about 45% to 15–20% of the distribution input, is at the upper end of what has been reported for active leakage control programmes in developing-country networks, where reductions of 20–40% of real losses are more typical after the first survey cycle (Mutikanga et al., 2013; Ociepa et al., 2019). Two features of the Aïn Aouda case explain this result. First, the initial level of losses was high, about 200 L per connection per day, so that the marginal return of acoustic survey was large. Second, the search was intensive and sustained during the first six months (4.6–6.1 km of mains surveyed and 2.4–3.3 repairs per day), which is when 44%

of the total reduction was obtained; the number of hidden leaks found followed the survey effort closely, which indicates that detection, not repair capacity, was the limiting factor. The subsequent rise of the night flow from 154 to $189 \text{ m}^3/\text{h}$ when intensity fell to 1.2 repairs per day, and its return to $127 \text{ m}^3/\text{h}$ after a renewed campaign, are consistent with the natural rate of rise of leakage that underlies the economic-intervention-frequency concept (Islam and Babel, 2013; Creaco and Wal-ski, 2017). With ten campaigns the rate of rise could not be estimated with statistical confidence (Supplementary Table S2); the net rise of $35 \text{ m}^3/\text{h}$ in eight months, obtained despite 434 repairs, is reported as an observation, and it suggests that, in this network, active search should be permanent rather than a one-off campaign: on the basis of Table 3, a survey intensity of about 3 km per day, or 60–70 hidden leaks found per two-month campaign, was needed to keep the night flow below the 40% reduction target. The yield of 56 hidden leaks per 100 km in the last campaign, twice the overall average, shows that leaks had accumulated during the low-intensity period and that the network was far from depleted, so that a permanent survey cycle of the whole network every four to six months appears justified.

The night-flow method was applied here without a concurrent billing balance, which is often the situation of small utilities in the region (Al-Omari, 2013; AbuEltayef et al., 2023). Its robustness rests on four elements: the calibrated meters and the three-night protocol, whose nightly records are provided as Supplementary Material; the single-inlet protocol, which removes the compensation between reservoirs observed in normal operation (negative night flows at the Oulad Zaer outlet in Figure 11a); the measured night-day factor, which replaces the default value of 20 h frequently assumed in the literature (Amoatey et al., 2018); and the fact that the recovered flow is a difference between two campaigns, so that the uncertainty on legitimate night consumption affects the level of losses but not the saving. The ratio of minimum night flow to average daily flow of 0.25 measured in April 2026 confirms that the network has moved from a high-loss to an intermediate-loss condition.

Why service connections dominate and what it implies

Six out of ten repairs concerned service connections and two thirds of these were hidden

leaks, a pattern consistent with the literature on background and unreported losses, in which small-diameter pipes, fittings and connections fail more often than mains and their leaks rarely surface (Barton et al., 2019; Kutylowska and Hotłoś, 2014). The Pareto structure of failures (three components for 84% of repairs) and the concentration of main failures on DN 63 PVC and asbestos-cement pipes point to a limited number of asset classes on which preventive action would be most effective. District contrasts add a spatial dimension to this typology: Tadamoune is almost exclusively a service-connection problem, whereas Oulad Zaer and Sidi Laarbi combine connection leaks with a high rate of main failures. These contrasts justify two different strategies, systematic acoustic survey and connection renewal in the first case, main renewal in the second, in line with the multi-criteria prioritisation frameworks proposed for failure management (Pouri and Heidari-mozaffar, 2022; Kabir et al., 2015).

Service impact and persistent hotspots

The register also shows that the failures that lose the most water are not those that affect customers the most. Main failures represented 24% of repairs but 82% of the customer-hours of interruption, whereas service-connection leaks, which dominate the recovered volume, interrupted supply for one or two customers for less than half an hour. Reliability studies of distribution systems have long distinguished hydraulic reliability from the customer-level consequences of failures (Gheisi et al., 2016; Pietrucha-Urbaniak and Tchórzewska-Cieślak, 2018); the customer-hours indicator computed here is a simple way to bring the second dimension into the prioritisation of repairs and renewal. The persistence of the north-eastern hotspot over five half-years, while the overall density decreased, now supported by the formal clustering tests and by the stability of the surface across bandwidths, is the spatial counterpart of this argument: a zone where repairs recur at the same place is a candidate for renewal rather than for repeated repair, as suggested by spatiotemporal analyses of main failures elsewhere (Martínez García et al., 2019; Chen & Guikema, 2020). The density of hidden leaks (Figure 8) delimits directly the sectors in which permanent district metering and acoustic monitoring would be most cost-effective.

Pressure management as a complementary lever

Mean pressures of 3–4 bar leave little room for network-wide pressure reduction, but the 5–7 bar recorded in the low-lying districts (Al Firdaous, PAM, Abouab Zaer), where no pressure-reducing valve exists, represent an untapped lever. According to the pressure-leakage relationship for plastic pipes, reducing pressure from 6 to 4 bar in these zones would reduce background leakage by roughly 45% and, on the basis of published burst-frequency responses, main and connection failures by 30–50% (Schwaller and van Zyl, 2015; Vicente et al., 2016). Pressure management would also slow the natural rate of rise of leakage between survey campaigns and reduce the energy embedded in losses (Gomes et al., 2011; Creaco and Walski, 2017). Al Firdaous, which is both a high-pressure zone and the fourth district in number of repairs, is the obvious pilot area.

Ecological engineering perspective

In a semi-arid basin where the utility faced supply deficits during the summer peak of 2025, the 1.1 million m³ per year recovered by the programme, about 30% of the town's distribution input, is equivalent to the domestic consumption of 10 000–12 000 inhabitants and has been obtained without any new abstraction. The associated energy saving of 0.7–0.8 GWh per year and 400–550 t CO₂ per year is a model-based estimate that follows from the energy intensity of Moroccan water supply and the carbon intensity of the national grid, and is of the same order as the savings reported for leakage reduction in other water–energy nexus assessments (Nair et al., 2014; Plappally & Lienhard V, 2012). These figures place active leakage control among the ecological engineering measures with the shortest lead time and the lowest environmental footprint available to utilities in water-stressed regions (Schilling et al., 2020; Zkhir et al., 2019), and the workflow used here, based on the register kept by field crews, is transferable to the other centres of the utility.

Limitations

The register was kept by field crews and 8% of interventions could not be georeferenced,

while the detection mode was missing for 5% of records; the summer 2025 campaigns were carried out under a temporary supply deficit that may have raised legitimate night consumption; the distribution input was measured only at the end of the programme, so that the baseline loss share is indicative; pipe age was not available, which limits the normalization of failure rates; and the campaign-level model relies on ten observations, so that no quantitative natural rate of rise is derived. The night-flow reduction is an observation under a constant protocol and not a controlled experiment; the energy and carbon savings rest on national coefficients rather than on local measurements; the underlying repair register, coordinates and primary measurement files are operational data of the utility and cannot be released publicly, so that independent reproduction is possible only from the aggregated tables, the nightly night-flow records provided as Supplementary Material and the analysis scripts available on request. None of these limitations affects the measured night-flow values themselves, which are the central result.

Data availability

The nightly night-flow records of all campaigns (date, time, flow at 5-min intervals) and their curves, the per-campaign and per-district tables, the 200 m grid counts with the Getis-Ord statistics, the pressure-series summary and the analysis scripts are provided as Supplementary Material or are available from the corresponding author. The georeferenced repair register, the address-level data and the raw pressure and flow files are operational data of the ONEE Water Branch and are not publicly available; they can be consulted by the editors and reviewers on request under a confidentiality agreement.

CONCLUSIONS

A two-year active leakage control programme in a semi-arid Moroccan town of about 24 000 service connections was evaluated from the repair register of the field crews, ten bi-monthly minimum night flow campaigns measured under a single-inlet protocol, pressure logging and continuous flow measurements at the reservoir outlets. The 1 187 leak repairs were dominated by service connections (60%), two

thirds of which were hidden leaks found only by acoustic survey, and three components, service pipes, main pipes and fittings, accounted for 84% of failures. The minimum night flow, recorded over three nights per campaign with calibrated meters under a constant protocol, decreased from 274 to 154 m³/h during the first six months of intensive search, rose to 189 m³/h when the search intensity halved, and reached 127 m³/h, 54% below the baseline, after a renewed campaign, the number of hidden leaks found following the length of mains surveyed; with a night-day factor of 20–21 h measured from 79 pressure series, the night-flow method indicates that real losses decreased from about 47% (42–54%) to 19% (16–23%) of the distribution input, an estimated saving of about 1.1 million m³ (1.0–1.2), 0.7–0.8 GWh and 400–550 t CO₂ per year, the last two being model-based estimates. Main failures represented one quarter of repairs but 82% of the customer-hours of supply interruption. Leak density concentrated in three statistically significant hotspots, one of which persisted over the whole period, and the density of hidden leaks delimited the sectors where active search is most productive. The pressure regime, with 3–4 bar on average but 5–7 bar in low-lying districts without pressure control, and the district-level contrasts between connection-dominated and main-dominated failure patterns, provide the basis for a differentiated preventive maintenance strategy combining permanent active leakage control, targeted renewal and pressure management.

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