

Supplementary Material S1

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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Manuscript EEET-05289-2026-01, revised version R1. This document contains the nightly night-flow records of all campaigns (Figure S1, Table S1), the illustrative campaign-level model (Eq. S1, Table S2), the trend tests with autocorrelation corrections (Table S3), the Monte Carlo uncertainty propagation (Table S4) and the formal spatial clustering tests (Figures S2 and S3). The corresponding data files are provided in Supplementary Material S2 (Excel).

S1. Nightly night-flow records

Night flow was recorded at the outlet of the Atlas distribution reservoir, the single metered inlet of the network during the campaigns (200 m³ bypass, Oulad Zaer reservoir, bulk exports to neighbouring systems and large consumers closed), with clamp-on ultrasonic transit-time flow meters logging at 5-min intervals. The contract required calibration certificates less than one year old for the meters and the delivery of the nightly records as date–time–flow tables with their curves. Each campaign value used in the manuscript (Table 3) is the lowest sustained 5-min reading between 00:00 and 06:00 over the three consecutive nights of the campaign (two nights in August 2025). One isolated 5-min dip of 125.6 m³/h at 01:10 on 2 December 2024, not sustained in the adjacent readings (15-min moving average 138.5 m³/h), was disregarded by the operator and the campaign value was taken as the minimum of the following nights (154.4 m³/h). Four additional nights recorded between campaigns (9 and 11 July, 5 September and 13 November 2024) are also reported.

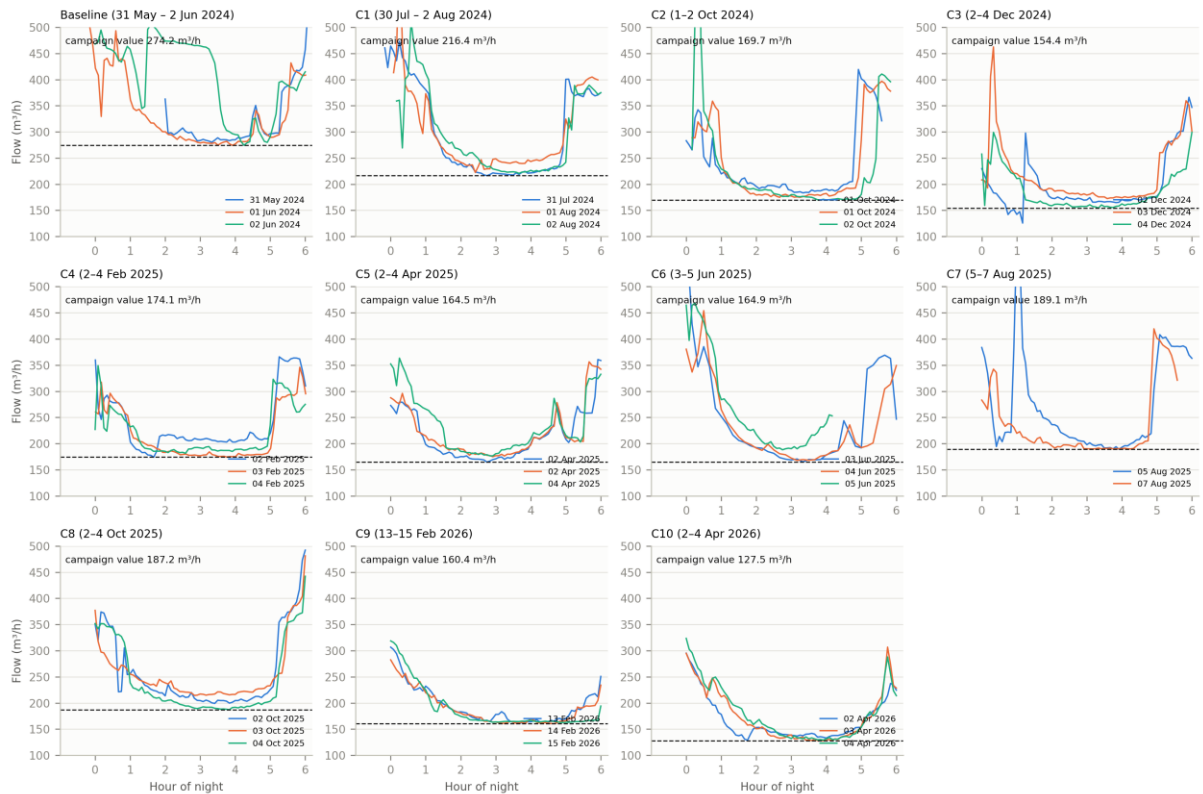


Figure S1. Night-flow curves (5-min readings) of the three nights of each campaign; the dashed line is the campaign value retained by the utility. Hours before midnight are shown as negative.

Table S1. Nightly minima of the 36 recorded nights (flow in m³/h)

Campaign	Night	Record start	Record end	Readings	Minimum	Time of min.	Min. of 15-min mean	Mean of record	Campaign value
Baseline	2024-05-31	05-31 02:00	05-31 06:05	50	280.2	03:20	282.1	321.5	274.2
Baseline	2024-06-01	05-31 23:10	06-01 06:00	83	274.2	03:55	276.1	351.7	274.2
Baseline	2024-06-02	06-02 00:00	06-02 06:00	73	274.5	04:15	278.2	404.9	274.2
between campaigns	2024-07-09	07-09 00:10	07-09 05:15	62	238.0	03:35	238.3	295.0	–
between campaigns	2024-07-11	07-11 00:05	07-11 05:20	64	224.5	03:35	226.2	290.9	–
C1	2024-07-31	07-30 23:50	07-31 06:00	75	216.4	02:45	217.5	299.4	216.4
C1	2024-08-01	08-01 00:05	08-01 05:55	71	222.4	02:25	229.1	298.4	216.4
C1	2024-08-02	08-02 00:10	08-02 06:00	71	220.7	03:40	222.3	294.2	216.4
between campaigns	2024-09-05	09-05 00:40	09-05 04:45	50	205.7	02:00	207.6	276.6	–
C2	2024-10-01	10-01 00:00	10-01 05:35	68	183.3	03:20	184.0	236.3	169.7
C2	2024-10-02	10-02 00:10	10-02 05:50	69	169.7	04:00	170.3	235.4	169.7
C2	2024-10-03	10-01 00:10	10-02 05:50	69	174.9	02:40	175.3	236.4	169.7
between campaigns	2024-11-13	11-13 00:00	11-13 05:00	61	179.8	03:30	180.9	201.3	–
C3	2024-12-02	12-02 00:00	12-02 06:00	73	125.6	01:10	138.5	195.5	154.4
C3	2024-12-03	12-03 00:00	12-03 06:00	73	172.4	03:35	173.3	218.6	154.4
between campaigns	2024-12-24	12-04 00:00	12-04 06:00	73	154.4	03:20	156.2	187.0	–
C4	2025-02-02	02-02 00:00	02-02 06:00	73	174.1	01:40	176.6	239.1	174.1
C4	2025-02-03	02-03 00:00	02-03 06:00	73	174.3	03:45	174.9	216.9	174.1
C4	2025-02-04	02-04 00:00	02-04 06:00	73	181.4	02:35	182.5	220.4	174.1
C5	2025-04-02	04-02 00:00	04-02 06:00	73	164.5	02:45	166.6	214.5	164.5
C5	2025-04-03	04-02 00:00	04-02 06:00	73	174.9	02:55	176.2	220.6	164.5
C5	2025-04-04	04-04 00:00	04-04 06:00	73	176.5	02:50	177.3	235.2	164.5

Campaign	Night	Record start	Record end	Readings	Minimum	Time of min.	Min. of 15-min mean	Mean of record	Campaign value
C6	2025-06-03	06-03 00:00	06-03 06:00	37	164.9	03:20	167.8	249.5	164.9
C6	2025-06-04	06-04 00:00	06-04 06:00	37	167.8	03:10	168.5	235.6	164.9
C6	2025-06-05	06-05 00:00	06-05 04:10	51	188.2	02:45	189.8	267.5	164.9
C7	2025-08-05	08-05 00:00	08-05 06:00	73	189.1	03:55	191.0	271.4	189.1
C7	2025-08-07	08-07 00:00	08-07 05:35	68	189.8	03:10	189.9	236.4	189.1
C8	2025-10-02	10-02 00:00	10-02 06:00	73	199.2	03:25	201.0	258.8	187.2
C8	2025-10-03	10-03 00:00	10-03 06:00	73	214.5	02:50	215.5	255.9	187.2
C8	2025-10-04	10-04 00:00	10-04 06:00	73	187.2	03:50	187.9	243.9	187.2
C9	2026-02-13	02-13 00:00	02-13 06:00	73	161.5	03:40	162.3	194.7	160.4
C9	2026-02-14	02-14 00:00	02-14 06:00	73	160.5	04:40	160.8	189.5	160.4
C9	2026-02-15	02-15 00:00	02-15 06:00	73	162.7	04:55	162.8	188.9	160.4
C10	2026-04-02	04-02 00:00	04-02 06:00	73	128.8	01:45	133.0	167.8	127.5
C10	2026-04-03	04-03 00:00	04-03 06:00	73	127.5	03:55	127.8	175.1	127.5
C10	2026-04-04	04-04 00:00	04-04 06:00	73	129.1	03:55	129.7	180.0	127.5

Note: record start and end as stamped by the logger (month-day hour:minute); in two files (3 October 2024 and 3 April 2025) the logger date stamp repeats the date of the previous night and the "Night" column gives the actual measurement date. Campaign values follow the operator's table reproduced in Table 3 of the manuscript; small differences (≤ 0.1 m³/h) are rounding.

S2. Illustrative campaign-level model

The change in minimum night flow between two consecutive campaigns was expressed as the balance between the flow recovered by the repair of hidden leaks found during the campaign and a linear rise of leakage with time:

$$\Delta Q = -a \cdot N_h + b \cdot t + \varepsilon \quad (\text{S1})$$

where ΔQ is the change in minimum night flow between two campaigns (m³/h), N_h the number of hidden leaks repaired during the campaign, t the campaign duration (d), a the mean flow recovered per repaired hidden leak (m³/h), b the rate of rise of leakage (m³/h/d) and ε the residual. The model was fitted by ordinary least squares without intercept to the ten campaigns of Table 3. As noted by the reviewer, neither coefficient is statistically significant with ten observations; the model is therefore reported for illustration only and no quantitative natural rate of rise of leakage is derived from it in the manuscript.

Table S2. Coefficients of Eq. (S1), ordinary least squares, $n = 10$ campaigns

Coefficient	Estimate	95% confidence interval	p-value
a – flow recovered per hidden leak repaired (m ³ /h)	0.34	–0.13 to 0.81	0.14
b – rate of rise of leakage (m ³ /h per day)	0.05	–0.40 to 0.50	0.81
R^2 (uncentred)	0.45		

Rank correlations between the change in night flow and the effort indicators of the campaigns ($n = 10$): hidden leaks repaired $\rho = -0.52$ ($p = 0.12$); length surveyed $\rho = -0.29$ ($p = 0.41$); survey intensity (km/day) $\rho = -0.30$ ($p = 0.40$). Hidden leaks found versus length surveyed: $\rho = 0.74$ ($p = 0.014$).

S3. Trend tests on monthly repair counts with autocorrelation corrections

The 22 monthly repair counts (June 2024 – March 2026) have a lag-1 autocorrelation of 0.79. The Mann-Kendall test was therefore repeated with the Hamed-Rao and Yue-Wang variance corrections, with trend-free pre-whitening (TFPW) and with simple pre-whitening, and the trend was also estimated with Poisson and negative binomial regressions of the counts on time (Table S3). The negative binomial model was retained because of the strong overdispersion of the Poisson model (dispersion 5.7).

Table S3. Trend of monthly repair counts, June 2024 – March 2026 ($n = 22$ months)

Test / model	Statistic	p-value	Slope
Mann-Kendall, original	$\tau = -0.65$	< 0.001	Sen –4.0 repairs/month

Test / model	Statistic	p-value	Slope
Mann-Kendall, Hamed-Rao variance correction	$\tau = -0.65$	< 0.001	Sen -4.0
Mann-Kendall, Yue-Wang variance correction	$\tau = -0.65$	< 0.001	Sen -4.0
Mann-Kendall, trend-free pre-whitening		< 0.001	Sen -4.0
Mann-Kendall, simple pre-whitening		0.319	(over-corrects when the trend is strong)
Poisson regression on time	dispersion 5.7	< 0.001	-7.0% per month
Negative binomial regression on time ($\alpha = 0.19$)		< 0.001	-6.7% per month (95% CI -9.4 to -3.9)
June–December 2025 vs 2024, negative binomial rate ratio	RR = 0.29	< 0.001	95% CI 0.17–0.50
Hidden-leak yield per 100 km surveyed (Poisson, offset = km)	28.6 per 100 km		95% CI 26.4–31.0
Trend of the yield across campaigns (negative binomial)	+2.4% per campaign	0.260	not significant

Sensitivity to survey effort: the monthly count of hidden leaks depends on the length of mains surveyed, which decreased over the programme (Table 3); the yield model shows that the number of hidden leaks found per km surveyed did not change significantly, so that the decreasing monthly counts reflect both the decreasing survey effort and the decreasing number of visible leaks reported, and are not interpreted in the manuscript as a decrease of the leak occurrence rate.

S4. Monte Carlo propagation of uncertainties

The quantities derived from the night flows were recomputed 20 000 times with the inputs drawn from the distributions of Table S4. The flow-meter error was applied independently to the baseline and final night flows; the legitimate night consumption and the night-day factor were common to both, since the recovered flow is a difference of two night flows measured under the same protocol.

Table S4. Monte Carlo inputs and outputs (20 000 draws; median and 95% interval)

Input	Distribution
Minimum night flow, baseline and end (m ³ /h)	Normal, mean 274.2 and 127.5, standard deviation 2%
Legitimate night consumption (m ³ /h)	Uniform 14–41 (0.6–1.7 L per connection per hour, 24 000 connections)
Night-day factor (h)	Uniform 19.9–21.1 (from the 79 pressure series, N1 = 1 to 1.5)
Distribution input (m ³ /d)	Normal, mean 10 660, standard deviation 5%
Specific energy (kWh/m ³)	Uniform 0.62–0.72 (national coefficient)
Emission factor (kg CO ₂ /kWh)	Uniform 0.57–0.70 (national grid factor)

Output	Median (95% interval)
Recovered volume (10 ⁶ m ³ per year)	1.10 (1.00–1.19)
Avoided energy (GWh per year)	0.73 (0.65–0.82)
Avoided emissions (t CO ₂ per year)	466 (394–548)
Real losses, June 2024 (% of distribution input)	47 (42–54)
Real losses, April 2026 (% of distribution input)	19 (16–23)
Real losses, June 2024 (L per connection per day)	211 (194–228)
Real losses, April 2026 (L per connection per day)	85 (73–98)

Note: the baseline loss share assumes that the distribution input of June 2024 was of the same order as the one measured in April 2026 ($\pm 5\%$); it is indicative. Energy and emissions are model-based estimates using national coefficients, not measured savings.

S5. Formal tests of spatial clustering and bandwidth sensitivity

Ripley's L function of the 1 096 georeferenced repairs was compared with 199 simulations of complete spatial randomness within the convex hull of the repairs buffered by 100 m (Figure S2a): $L(r) - r$ reaches 140.5 m at $r = 50$ m, 267.8 m at 150 m and 526 m at 500 m, against an upper envelope below 4 m, i.e. significant clustering at all scales. On the 200 m grid (638 cells within the study area), Moran's I with

queen contiguity is 0.51 ($z = 25$, pseudo $p = 0.001$ with 999 permutations). The Getis-Ord G_i^* statistic identifies 70 cells significant at $p < 0.01$ (11% of the area) that contain 732 repairs (67%), grouped in the three hotspots of Figure 7 of the manuscript (Figure S3). The kernel density surface was recomputed with bandwidths of 100, 150, 200 and 250 m: the location of the peak is unchanged (within 40 m of the 150 m position) and the 10% of the area with the highest density contains 85, 82, 80, 78% of the repairs respectively (Figure S2b); the Jaccard index of the top-10% area with respect to the 150 m reference surface is 0.88 at 100 m, 0.91 at 200 m and 0.83 at 250 m. The mean nearest-neighbour distance between repairs is 35 m. The grid counts and G_i^* z-scores are provided in Supplementary Material S2.

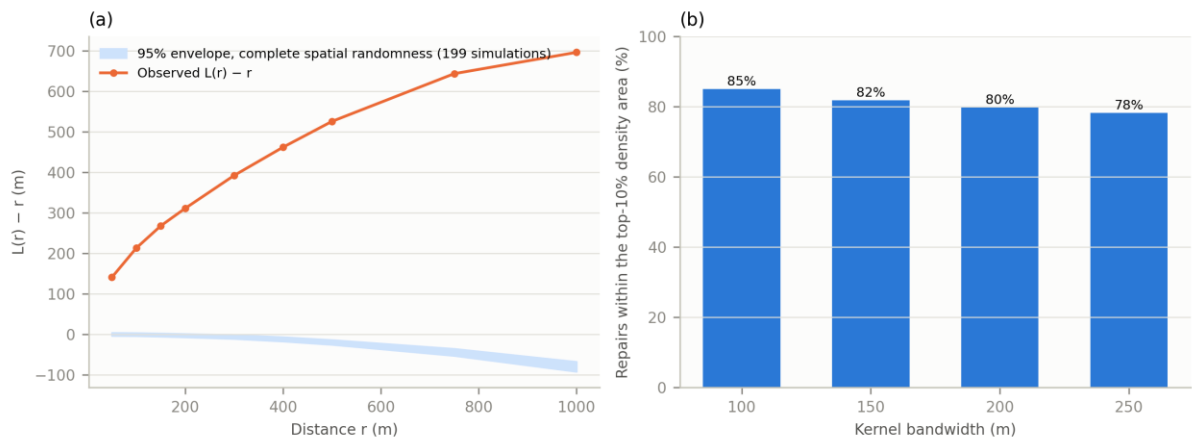


Figure S2. (a) Ripley's L function of the georeferenced repairs ($L(r) - r$) against the 95% envelope of 199 simulations of complete spatial randomness; (b) share of repairs within the 10% of the area with the highest kernel density for bandwidths of 100–250 m.

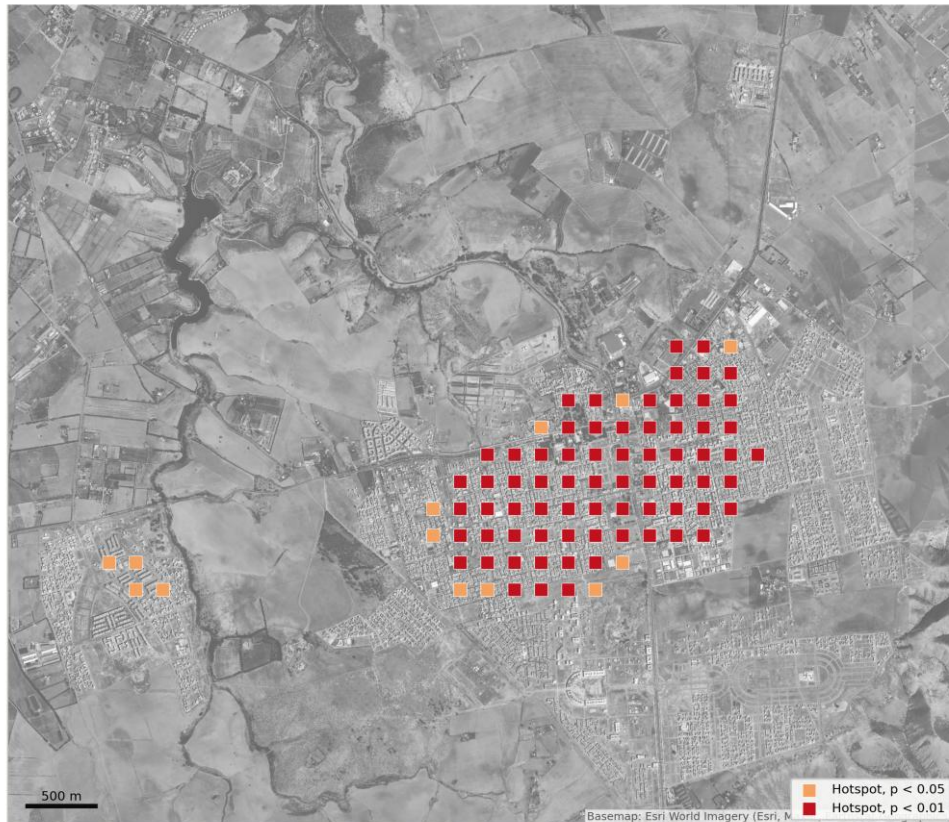


Figure S3. Getis-Ord G_i^* hotspot cells (200 m grid, queen contiguity) of leak repairs, May 2024 – April 2026; background Esri World Imagery.