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Article

Pressure-Dependent Leakage Modelling and District-Metered-Area Zoning for Non-Revenue Water Reduction in Aging Water Distribution Networks: A FAVAD/N_1 Framework

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Abstract: Non-revenue water (NRW) is the single most important indicator of the technical condition of a water distribution network, and in aging systems its physical (real-loss) component is dominated by pressure-dependent leakage. This paper presents an integrated framework for characterizing that leakage and reducing it through district-metered-area (DMA) zoning and active pressure management. The framework rests on the Fixed and Variable Area Discharge (FAVAD) concept, in which leakage is proportional to pressure raised to an exponent N_1 that reflects whether the leak paths are rigid or expanding. We show how N_1 is inferred from minimum-night-flow (MNF) analysis within a DMA, how the resulting pressure-dependent relationship is embedded in a hydraulic model so that leakage responds automatically to pressure changes, and how the network is partitioned into pressure zones on the basis of elevation and hydraulic structure. Applied to a representative model of the Karshi network in arid southern Uzbekistan, the method delineates three elevation-driven DMAs, isolates a large pressure-driven leakage component in the night flow, and predicts leakage reductions as an explicit function of pressure reduction and N_1. For the case network, N_1 values in the range 1.0-1.6 imply that a realistic 20 % reduction of average zone pressure lowers real losses by roughly 20-30 %. The paper provides a transparent, data-modest workflow that regional utilities can apply to quantify and reduce NRW where input data are incomplete and capital is limited.

Keywords: non-revenue water; real losses; FAVAD; N_1 exponent; pressure management; district metered area; minimum night flow; leakage; arid region.

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1. Introduction

The efficiency of a water distribution network is most commonly summarized by its non-revenue water (NRW): the volume supplied to the network that is not billed to consumers, expressed as a percentage of system input. NRW captures the gap between what a utility produces and what it recovers, and it is the primary yardstick for assessing the technical state of a network and the scope for improvement [1,2]. In many cities of Central Asia, NRW is high-frequently well above the levels achieved by well-run utilities-because the networks are old, corroded and operated at excessive pressure.

According to the methodology of the International Water Association (IWA), water losses divide into two broad categories. Apparent (commercial) losses arise from meter under-registration, unauthorized consumption and data-handling errors; they represent water that is delivered but not correctly accounted for. Real (physical) losses arise from leaks, bursts and overflows; they represent water that never reaches a consumer. Real losses are directly governed by pressure and are therefore the component most amenable to control through hydraulic-regime management [3,4]. This paper focuses on the real-loss component and on the practical tools-pressure-dependent leakage modelling and DMA zoning-by which it can be quantified and reduced.

The relationship between pressure and leakage is the theoretical core of leakage management. Classical hydraulics treats flow through an orifice as proportional to the square root of pressure, implying a pressure exponent of 0.5. Field studies, however, repeatedly found that real networks are far more sensitive to pressure than this suggests. The FAVAD concept resolved the discrepancy by recognizing that some leak openings are effectively rigid (fixed area) while others-longitudinal cracks, joints in plastic pipe-expand as pressure rises (variable area) [5,6]. The combined behaviour is captured by a power law in which leakage is proportional to pressure raised to an exponent N_1, typically between 0.5 and 2.5, with a value near 1.0 common for mixed networks [6,7]. A practical consequence is that in many systems a given percentage reduction in pressure produces at least the same percentage reduction in leakage-and often more.

The contribution of this paper is to assemble these elements into a coherent, transparent workflow tailored to aging networks in arid regions with limited data, and to demonstrate it on a representative model of the Karshi network. Specifically, the paper situates real losses within the IWA water balance; explains and quantifies the FAVAD/N_1 relationship and how N_1 is obtained from MNF; presents a criteria-based methodology for delineating pressure zones driven by elevation and hydraulic structure; and predicts the leakage reduction achievable as a function of pressure reduction and N_1[8].

2. Materials and Methods

2.1. Structure of non-revenue water

The IWA standard water balance decomposes the system input volume into authorized consumption and water losses, and further into billed and unbilled, apparent and real components (Figure 1). Revenue water is the billed authorized consumption-the only portion for which the utility is paid. Everything else is non-revenue water: unbilled authorized consumption, apparent losses and real losses. This structure is important because the appropriate intervention differs by component: apparent losses call for metering and commercial measures, whereas real losses call for pressure management, active leakage control and asset renewal. Table 1 lists the components and the typical intervention associated with each[9].

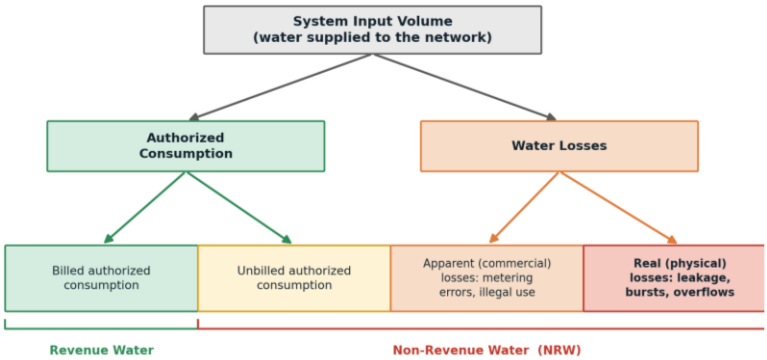


Figure 1. The IWA standard water balance. System input volume divides into authorized consumption and water losses; non-revenue water comprises unbilled authorized consumption together with apparent and real losses. Real (physical) losses-the pressure-driven leakage that is the focus of this study-are highlighted[10].

Table 1. Components of the IWA water balance and their primary control measures.

Component	Nature	Typical share of NRW	Primary control measure
Unbilled authorized	legitimate, unbilled	low	billing / policy
Apparent (commercial) losses	metering & theft	moderate	metering, enforcement
Real (physical) losses	leakage & bursts	high	pressure management, ALC

ALC = active leakage control (step-testing, acoustic surveys, rapid repair).

2.2. The FAVAD concept and the N_1 exponent

Why is leakage more sensitive to pressure than the classical orifice theory predicts? The FAVAD concept provides the answer. A leak in a rigid material-for example, a small hole at a corroded metal joint-behaves as a fixed-area orifice: its discharge grows only with the square root of pressure ($N_1 \approx 0.5$). A leak in a deformable path-a longitudinal split in a plastic pipe, or an opening at a flexible joint-enlarges as pressure rises, so both the discharge velocity and the leak area increase together, producing a much stronger dependence (N_1 up to about 1.5-2.5). Real networks contain a mixture of both, so the effective exponent lies somewhere between these limits (Figure 2)[11].

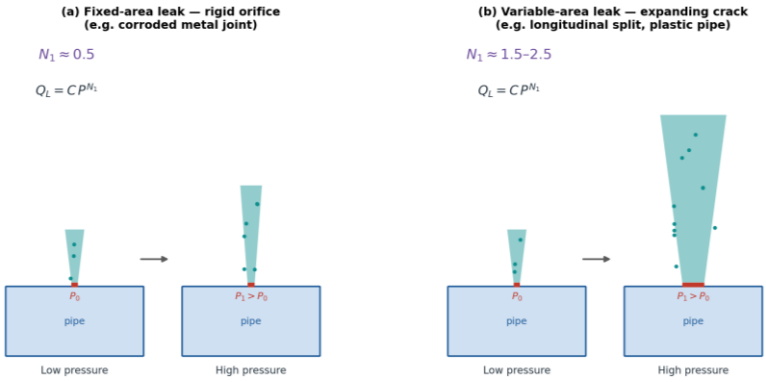


Figure 2. The FAVAD concept. (a) A rigid, fixed-area leak: the opening does not change with pressure, so discharge rises only as the square root of pressure ($N_1 \approx 0.5$). (b) A variable-area leak: the crack widens as pressure rises, so discharge increases far more steeply ($N_1 \approx 1.5$-2.5). The effective N_1 of a real network reflects the mix of both leak types.

Formally, the leakage discharge Q_l is written as a power function of pressure P,

$$Q_L = C P^{N_1} \tag{1}$$

where C is a leakage coefficient (proportional to the number and area of leak paths) and N_1 is the pressure-leakage exponent. For practical work it is convenient to express the effect of a pressure change as a ratio. If the average pressure changes from P_0 to P_1, the leakage changes in the ratio[12].

$$\frac{L_1}{L_0} = \left(\frac{P_1}{P_0}\right)^{N_1} \tag{2}$$

where L_0 and L_1 are the leakage rates before and after the change. Equation (2) is the workhorse of pressure-management planning: once N_1 is known for a zone, the leakage reduction produced by any pressure reduction can be predicted directly. For example, a 20 % reduction of average pressure ($P_1/P_0 = 0.8$) reduces leakage by about 11 % when $N_1 = 0.5$, about 20 % when $N_1 = 1.0$, and about 29 % when $N_1 = 1.5$. Figure 3 shows these relationships across the practical range of N_1 and makes clear that the returns to pressure reduction rise sharply with N_1-so aged networks with many expanding cracks, which have the highest N_1, benefit the most[13].

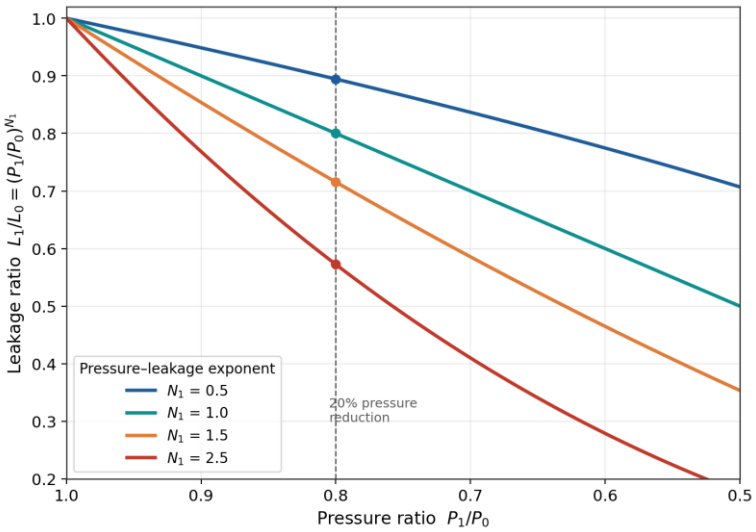


Figure 3. Leakage response to pressure reduction for different values of the pressure-leakage exponent N_1. The markers indicate the leakage remaining after a 20 % pressure reduction; higher N_1 yields a larger leakage reduction for the same pressure change.

Because N_1 is decisive, its representative values are worth tabulating. Table 2 summarizes the ranges associated with different pipe materials and leak morphologies reported in the leakage-management literature and used to guide the interpretation of the case-study measurements[14].

Table 2. Indicative pressure-leakage exponent N_1 by leak type and pipe material.

Leak / pipe type	Area behaviour	Typical N_1	Sensitivity
Round holes, rigid metal	fixed	0.5	low
Corrosion clusters, metal	near-fixed	0.5-0.8	low-moderate
Mixed network (system average)	mixed	0.9-1.3	moderate
Joints / detached fittings	variable	1.3-1.8	high
Longitudinal splits, plastic	variable	1.5-2.5	very high

2.3. Embedding pressure-dependent leakage in the hydraulic model

To evaluate the effect of pressure control, the leakage relationship must be incorporated into the network hydraulic model so that leakage recalculates automatically as pressures change. Conventional models treat nodal demand as fixed and pressure-independent, which cannot represent leakage correctly. Instead, the outflow at each node i is split into the genuine consumer demand $Q_{e,i}$ and a pressure-dependent leakage term:

$$Q_i = Q_{e,i} + C_i P_i^{N_1} \tag{3}$$

Substituting (3) into the nodal continuity equations converts the model into a pressure-dependent (pressure-driven) formulation, solved with the standard global-gradient method. The total real loss of the network is then the sum of the nodal leakage terms,

$$W_L = \sum C_i P_i^{N_1} \tag{4}$$

so that any pressure-control action-achieved through pressure-reducing valves or variable-frequency pumping-propagates directly into the computed loss. This is the mechanism that links the zoning and pressure-control decisions described below to a quantifiable leakage reduction[15].

2.4. Estimating N_1 and the leakage baseline from minimum night flow

The leakage coefficient C and the exponent N_1 must be determined from measurements rather than assumed. The most reliable field method is minimum-night-flow (MNF) analysis applied within a DMA. During the early-morning hours (typically 02:00-04:00), legitimate consumption falls to its

minimum, so the inflow to a zone is dominated by leakage. Decomposing the measured night inflow into a small legitimate-use component and a residual leakage component yields the leakage baseline (Figure 6). Repeating the measurement at two or more controlled pressure levels-by throttling the inlet valve and recording the corresponding night flows-provides paired values of pressure and leakage, from which N_1 is obtained directly by rearranging equation (2):

$$N_1 = \frac{\ln(L_1/L_0)}{\ln(P_1/P_0)} \tag{5}$$

This step-test procedure gives a zone-specific N_1 that reflects the actual mix of leak types in that part of the network, which is far more accurate than adopting a single textbook value for the whole system.

2.5. Delineating district-metered areas

DMA delineation converts an undifferentiated network into a set of manageable pressure zones. The objective is to divide the network into hydraulically discrete areas, each supplied through a single metered inlet, so that the water balance, pressure and leakage of every zone can be monitored and controlled independently. The delineation follows a criteria-based procedure (Figure 4): the topology, elevation and demand distribution are analysed; hydraulically separable candidate zones are identified; each zone is sized to a manageable number of connections; boundary valves and a single metered inlet are defined; and the pressure feasibility of the zone is checked against the service window before valves and meters are installed and the MNF of each DMA is monitored.

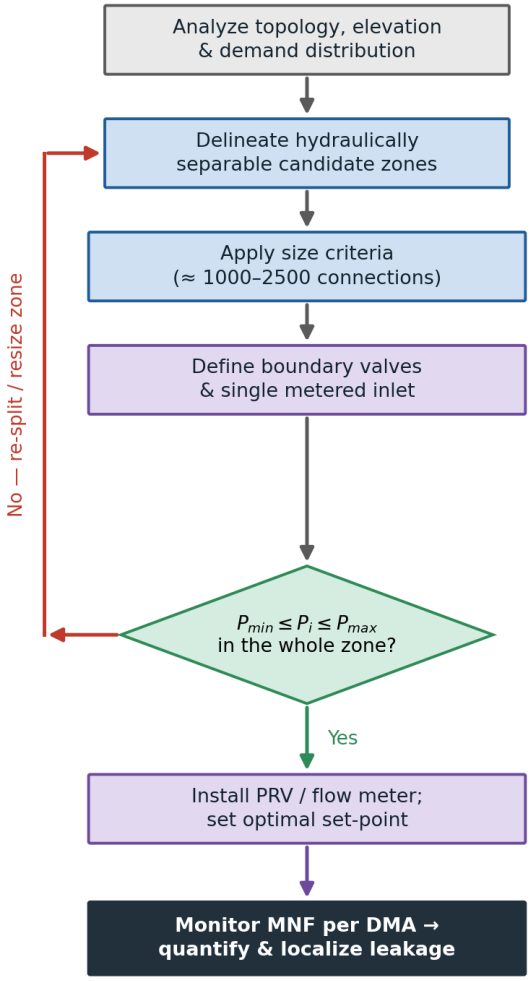


Figure 4. Methodology for delineating district-metered areas. If any part of a candidate zone falls outside the allowable pressure window, the zone is re-split or resized before installation; the feedback loop guarantees that every finalized DMA satisfies the service constraint.

Among the delineation criteria, ground elevation is the most influential in cities with pronounced relief, because differences in elevation translate directly into differences in pressure: low-lying districts experience the highest pressures and therefore the highest leakage, and must be isolated so that their pressure can be reduced without starving higher ground. The mathematical criterion for an acceptable zone is that the pressure at every node remains within the service window,

$$P_{\min} \leq P_i \leq P_{\max} \tag{6}$$

where P_{min} is the minimum pressure needed to satisfy consumers and P_{max} is the maximum permitted in order to limit leakage and burst frequency. The narrower the spread of pressure within a zone, the better the zone has been delineated. Figure 5 illustrates how the case-study network is partitioned into three elevation-driven DMAs.

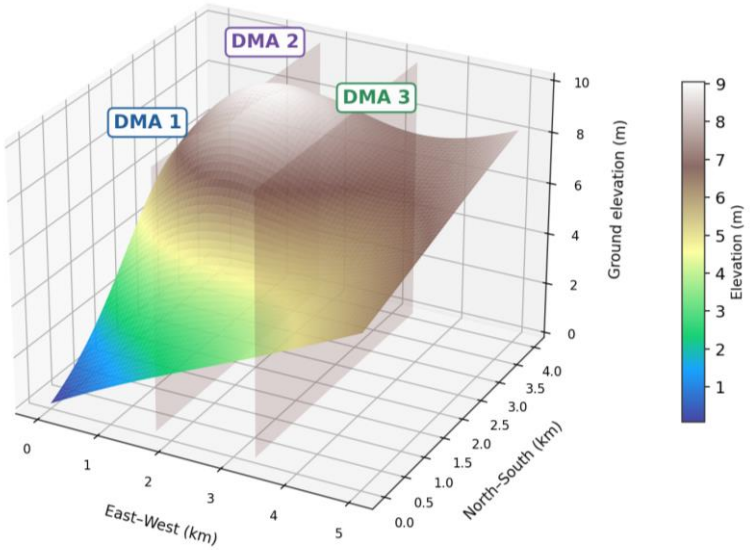


Figure 5. Elevation-driven partitioning of the representative network into three district-metered areas. Because pressure tracks ground elevation, the low-lying zone (DMA 1) carries the highest baseline pressure and leakage and is isolated so its pressure can be reduced independently of the higher zones.

3. Results

3.1. Night-flow decomposition and leakage baseline

Applying MNF analysis to the representative Karshi model reveals a large pressure-driven leakage component. During the 02:00-04:00 window, legitimate consumption collapses to a small residual while the zone inflow remains substantial; the difference is leakage. For the modelled network, leakage accounts for roughly two-thirds of the minimum night inflow (Figure 6), a signature of an aged, over-pressurized system. Because the night pressure is also the highest of the day (demand, and hence head loss, is lowest at night), the leakage rate peaks exactly when legitimate demand is lowest-underlining the value of suppressing night-time pressure[16].

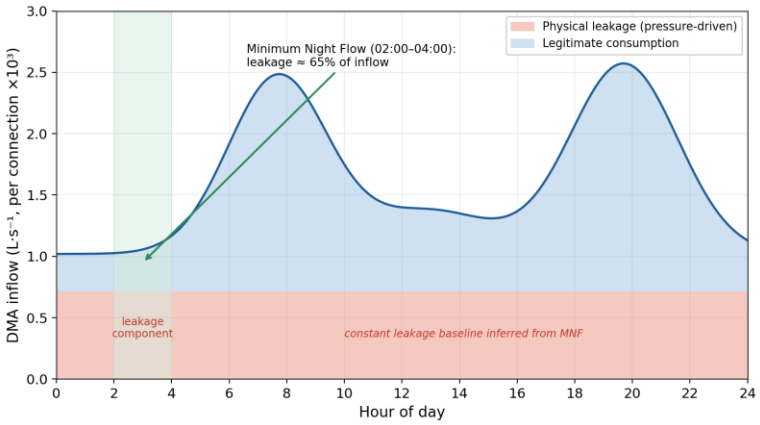


Figure 6. Minimum-night-flow decomposition of DMA inflow. In the 02:00-04:00 window, legitimate consumption is minimal and leakage constitutes about two-thirds of the inflow; the leakage baseline inferred here anchors the estimation of N_1 and of the achievable savings.

3.2. Delineated zones and their characteristics

The delineation procedure produced three DMAs whose modelled characteristics are summarized in Table 3. DMA 1, occupying the low-lying district, carries the highest baseline pressure and the largest leakage share and is therefore the priority for pressure reduction; DMA 3, on higher ground, has the lowest baseline pressure and the least scope for reduction. The estimated N_1 values, obtained by the step-test procedure of Section 2.4, lie between 1.0 and 1.6, consistent with an aged mixed network containing a significant proportion of expanding leak paths[17].

Table 3. Delineated DMAs and their modelled characteristics (representative values).

Zone	Connections	Mean elevation (m)	Baseline pressure (m)	Estimated N_1	Leakage share
DMA 1 (low)	2,300	4	66	1.6	high
DMA 2 (mid)	1,900	7	52	1.3	moderate
DMA 3 (high)	1,500	9	41	1.0	low

3.3. Predicted leakage reduction

Combining the zone-specific N_1 values with the FAVAD ratio (2) yields the leakage reduction achievable by pressure management. Figure 7 presents the reduction as a continuous surface over the two governing variables-the fractional pressure reduction and the exponent N_1-computed from equation (2). The surface is monotonic in both directions: leakage reduction grows with pressure reduction, and, for a fixed pressure reduction, it grows with N_1. For the case network, where realistic pressure reductions of 15-25 % are attainable and N_1 lies between 1.0 and 1.6, the predicted real-loss reduction is of the order of 20-30 %. Because DMA 1 combines the highest baseline pressure with the highest N_1, it dominates the aggregate saving, confirming that targeting the low-lying, high-pressure zone first is the most cost-effective sequence[18].

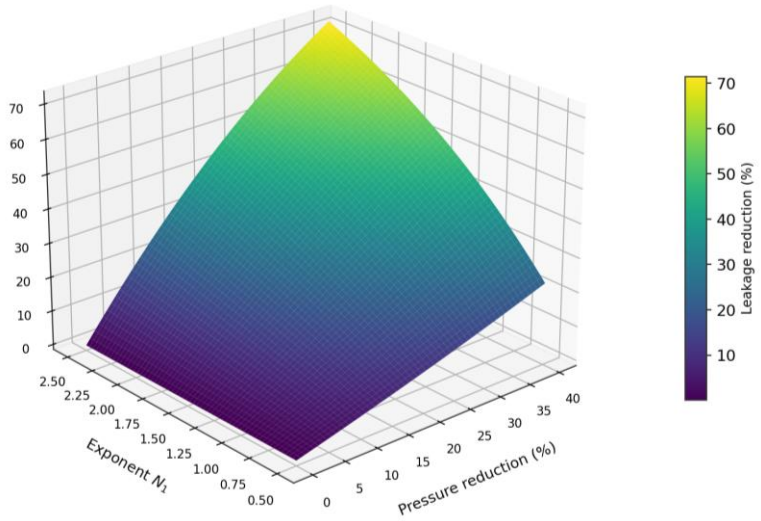


Figure 7. Predicted leakage reduction as a function of pressure reduction and the exponent N_1, from the FAVAD ratio. For the case-study range (N_1 = 1.0-1.6, pressure reduction 15-25 %) the achievable real-loss reduction is of the order of 20-30 %.

4. Discussion

The results reinforce three points of practical importance. First, in an aged, over-pressurized network the real-loss component of NRW is large and pressure-driven, so pressure management is the highest-leverage intervention available. The night-flow analysis showed leakage making up about two-thirds of the minimum night inflow, and the FAVAD relationship translates even modest pressure reductions into comparable leakage reductions. Pressure control is also comparatively inexpensive and rapid to deploy relative to wholesale pipe replacement, which makes it the logical first step in a staged NRW-reduction programme.

Second, the effectiveness of the approach hinges on obtaining a realistic, zone-specific N_1. Adopting a single textbook exponent for the whole network can substantially mis-estimate the achievable savings, because N_1 varies with material and leak morphology and, as Table 2 shows, spans a wide range. The MNF step-test procedure is the recommended means of anchoring N_1 to field evidence; it requires only inlet metering and controlled valve throttling, both of which are feasible for a regional utility once DMAs are in place[19].

Third, elevation-driven zoning is essential in cities with relief. Because pressure follows topography, a single system-wide pressure target would either starve high ground or leave low ground over-pressurized. Partitioning the network so that each zone occupies a narrow elevation band allows the pressure in each to be brought close to the service minimum independently, which is exactly where the FAVAD relationship delivers the greatest leakage benefit. This is why the low-lying DMA 1, with the highest pressure and highest N_1, is both the largest contributor to losses and the priority for intervention.

Several limitations apply. The N_1 values and leakage shares used here are representative and should be replaced by field measurements during implementation; the specific percentages are therefore indicative. The analysis addresses real losses and does not quantify apparent losses, which require separate commercial measures. Finally, pressure reduction must always respect the minimum service head and firefighting requirements, and the feasibility check in the delineation procedure (Figure 4) is included precisely to enforce this constraint. Within these bounds, the workflow provides a defensible, data-modest route to quantifying and reducing NRW[20].

5. Conclusions

This paper set out an integrated, transparent framework for reducing the real-loss component of non-revenue water in aging water distribution networks through pressure-dependent leakage

modelling and district-metered-area zoning. Locating real losses within the IWA water balance clarifies why pressure management is the appropriate lever; the FAVAD/N_1 relationship quantifies how strongly leakage responds to pressure; minimum-night-flow analysis supplies a field-based estimate of N_1 and the leakage baseline; and elevation-driven DMA delineation organizes the network so that pressure can be brought close to the service minimum zone by zone. Applied to a representative model of the Karshi network, the method identified three elevation-driven zones, showed leakage to be about two-thirds of the minimum night inflow, and-with N_1 in the range 1.0-1.6-predicted real-loss reductions of the order of 20-30 % for realistic pressure reductions, with the low-lying, high-pressure zone contributing most. The workflow is deliberately data-modest and is directly transferable to other arid-region utilities operating aging networks under data and budget constraints. Future work will validate the estimated N_1 values against field step-tests and integrate the zoning with the joint water-energy optimization of pumping operation.

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