Scheme Assessment Model: Probabilistic Stress-Testing of Approved Housing Scheme Infrastructure in Lahore

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Lahore's private housing schemes are approved when their service designs conform to standards, but conformity does not show how their infrastructure will perform as they fill. The Scheme Assessment Model (SAM) developed here reconstructs an approval package as drawn and evaluates traffic, sewerage, drainage and electricity at ten occupation states. Traffic in all four schemes, and the sewerage and electricity run for the smallest scheme, used Monte Carlo simulation (3,000 scenarios per state); the other sewerage and electricity runs used fixed design inputs, and drainage a deterministic rainfall sweep. A Wilson-interval rule returns the highest supported occupation and its limiting asset. Applied to four approved schemes of 235 to G,580 dwellings, SAM assessed twelve of sixteen scheme–subsystem pairs; six supported full occupation and six did not. Electricity was limited to 40% occupation in both schemes with transformer data, in the largest despite 131,950 kVA installed against 25,870 kW of demand. Sewerage in the largest scheme was limited to 50% by a storm allowance set at 100% of sewage flow, and both drainage networks failed at full occupation far below the 2-year storm, at 17.1 and 1.8 mm/h. In three networks, 82–9G% of pipes ran below self-cleansing velocity at full occupation. Reconstructions reproduced the designers' flows and loads within 2% where checked, and limiting assets coincided with points the designers' own figures place beyond their limits; no boundary has been tested in operation. Three changes are proposed: rainfall-based storm design, per-transformer loading schedules with headroom, and self-cleansing checks at the flow rates the sewers carry.

Keywords: Housing Scheme Approval; Monte Carlo Simulation; Supported Occupation; Urban Infrastructure Capacity; Lahore

Introduction:

Lahore has grown largely through private housing schemes, and its built-up area continues to expand into the agricultural land around the city [1]Each scheme is approved under the Lahore Development Authority Private Housing Schemes Rules 2014, as amended to March 202G [2]. The Rules fix planning standards such as minimum road rights-of-way, require the water supply, sewerage, drainage and road designs to be prepared by registered engineers and approved by the responsible agencies, require the electrification design to be approved by the distribution licensee, and provide for inspection of the works during development.

The approval therefore establishes that a scheme conforms to prescribed requirements. It does not establish how the scheme's networks will perform as dwellings are occupied and loads accumulate. The difference matters in a city whose shared networks are already under stress: on 1 August 2024 up to 3G5 mm of rain fell on Lahore in about three hours and 410 electricity feeders tripped [3], and a drainage study of a Lahore residential area found that a network designed for the 2-year storm floods about G0% of its area in that storm [4]. Compliance and performance are related but distinct questions.

A minimum road width is a physical requirement; it does not determine how much traffic each link will carry or whether a narrow connector will be overloaded under a plausible combination of demand and route choice. Approval of a sewerage or electrical design confirms conformity with the approving agency's criteria; it is not the same as operating the proposed network under varying loads and observing whether its capacity limits are exceeded. The literature on performance-based planning draws the same distinction between conformance with prescribed requirements and the outcomes that a plan achieves [5]

Assessing performance before approval requires two things a conformity check does not provide. The first is uncertainty: demand, route choice, roughness, sediment and rainfall all vary, and a design adequate at the average condition may fail under less common but plausible combinations of them, which Monte Carlo simulation can represent [6]The second is integration: a scheme is adequate only if several networks are adequate together, and work on infrastructure decision support [7], interdependency[8][9][10] digital twins [11] and exploratory modeling [12] shows the value of a common framework.

Recent studies have extended each of these strands. Stochastic stress-testing now links the resource, network and demand models of urban water systems and attaches confidence bands to their resilience [13]. Monte Carlo assessment of distribution networks treats the hosting capacity of a feeder as a probability rather than a single value [14] calibrated models of operating sewer networks report how far real pipes fall short of self-cleansing criteria [15]and reviews of infrastructure resilience emphasize multiplex representations of networks that share failure pathways [16].

On the approval side, the digitization of building permits has begun to automate rule-based compliance checks, but these test documents against codes rather than predicting network performance [17] In Lahore, analysis of housing societies shows both how many schemes are approved and how slowly they fill: the LDA had registered 372 societies and identified 109 illegal ones, and about half of the plots in the schemes examined lay vacant, rising to 73% in schemes colonized after 2010 [18]. Occupation is therefore the quantity that changes most over a scheme's life, yet approval examines the design only as a whole.

This body of work addresses asset management, single networks, national systems, resilience and long-term investment, not the moment at which a private housing scheme is approved, when the question is whether the network drawn in the package will carry the loads the scheme will generate as it fills. The research gap is therefore one of application and evidence rather than method. The techniques used here are established; what has not been examined is whether they can stress-test real approval packages asset by asset, using only the

information the packages contain, and how far such results can be validated when, as is usual for new schemes, no record of operation exists [19][20].

Objectives:

The study has four objectives. (O1) To develop a reproducible framework that converts the design package of a proposed housing scheme into an occupation-staged, asset-level assessment of traffic, sewerage, drainage and electricity distribution under uncertainty. (O2) To apply the framework to four approved schemes in Lahore and identify the supported occupation of each subsystem, the asset that limits it and the mechanism responsible. (O3) To evaluate the credibility of the results against the designers' own figures, internal consistency and sensitivity tests and available evidence on the performance of comparable infrastructure, and to state what can and cannot be concluded from them. (O4) To derive design practices and amendments to the approval rules that are supported by the recurring findings.

Novelty Statement:

Table 1 compares SAM with the approaches reviewed above. Approval review and automated compliance checking test a design against prescribed requirements without simulating its operation[2][17]. Single-system probabilistic models simulate operation under uncertainty, but for one network at a time and usually for an existing system [4][13][14][21]. Interdependency, system-of-systems and digital-twin models integrate several networks, but at city or national scale and for resilience or long-term investment rather than for the approval of a single scheme [9][10][11][16].

As far as could be established, no study has combined the four networks of a proposed housing scheme in one occupation-staged probabilistic assessment built only from its approval package, and none has done so in Pakistan. The contribution is threefold: performance is stated as a supported occupation with a named limiting asset rather than a pass or fail verdict; every result is traceable to the scheme's own drawings, with each missing input declared within a stated scope or reported as unresolved; and each recurring finding is tied to a specific clause of the LDA Rules and to the evidence an approval submission would need to contain.

Table 1. Comparison of SAM with recent assessment approaches.

Approach	Examples	Networks covered	Treatment of uncertainty	Staging	Form of result	Input basis
Conformity review at approval	LDA Rules [2]	Each network separately	None	Full development only	Pass or fail against standards	Approval package
Automated permit compliance checking	[17]	Buildings	None	None	Compliance report	Digital submission
Single-system probabilistic and stress-test models	[4][13][14] [21]	One network	Monte Carlo or stochastic scenarios	Scenario or time horizon	Risk or resilience measure	Utility model, often with monitoring data
Interdependency, system-of-systems and digital-twin models	[9][10][11] [16]	Several networks	Scenarios or hazard events	Long-term scenarios	Resilience or Investment indicators	City or national datasets
SAM (this study)	Four Lahore schemes	Traffic, sewerage, drainage and electricity of one scheme	Monte Carlo with a Wilson- interval decision rule; rainfall sweep	Ten Occupation states	Supported occupation and limiting asset	Approval package as drawn

Table 2. Case-study schemes and the representation of each network.

Scheme	Location	Residential scale; area	Road network	Sewer network	Drainage system	Electrical inventory
Lake City Bella Verde	Mouza Maraka, Raiwind Road, Lahore	G,580 houses; G,74G kanal (341 ha)	2,290 nodes; 5,22G directional links; 79.7 km; 3 gates	3,328 manholes; 3,327 pipes; 59.G km; disposal station (2G cusecs)	Combined; storm load carried as an allowance in the sewerage run	318 transformers; transformer-capacity model
Al-Kabir OrchardPhase-II	Mouza Chak 45, Ferozewala, Sheikhupura	1,334 plots; 927 kanal (47 ha)	231 nodes; 542 directional links; 12.1 km; 1 gate	78 points; 77 reaches; 12.7 km; pumping station (5 cusecs)	Combined; drainage network data unavailable	No transformer schedule or distribution drawings

Lake City Meadows Phase-I Extension	Mouzas Kamahan, Jathol and Gurumanget Nau Abad, Lahore	2,315 dwellings; 1,991.85 kanal (101 ha)	1,7G1 nodes; 3,520 directional assets; 30.1 km; 2 gates	1,759 nodes; 1,758 conduits; 30.1 km; existing trunk sewer	Separate; 32 catchments; 4 recharge-well outlets	No transformer schedule or distribution drawings
Ali Housing Scheme	Mouza Mohlanwal, Multan Road, Lahore	235 plots; 98 kanal (5 ha)	33 nodes; 78 directional links; 1.7 km; 2 gates	28 manholes; 27 reaches; 1.G km; single outfall	Combined; 27 reach catchments; 1 outfall	7 transformers on an 11 kV ring operated radially; radial voltage model

Materials and Methods:

Study Area and Schemes:

SAM was applied retrospectively to the approval packages of four schemes in and around Lahore (Figure 1); none was prepared with the model's assumptions in mind. The schemes were selected purposively rather than at random, to span the conditions under which schemes are approved: 235 to G,580 dwellings, combined and separate drainage, networks supplied as full hydraulic tables or only as drawings, and packages with and without electrical designs. Selection was limited to packages whose drawings and design reports were available in full, because the documents of most approved schemes are not public. Table 2 summarizes the schemes.

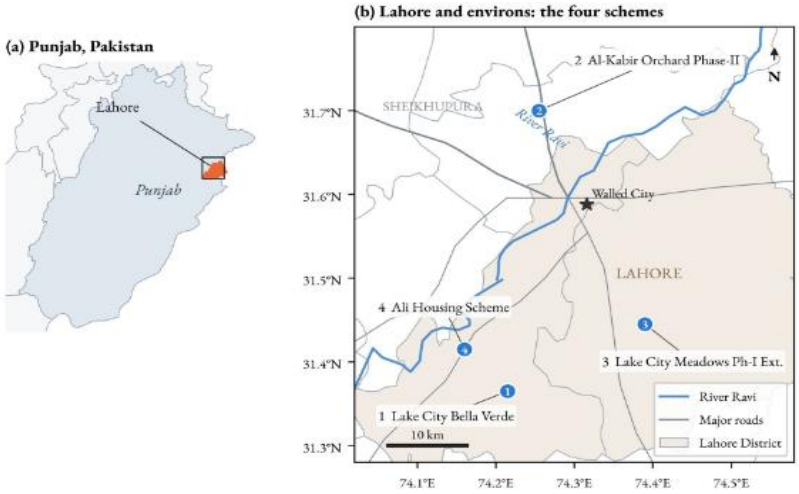

Figure 1. Location of the four case-study schemes: (a) Lahore District within Punjab; (b) approximate scheme locations at mouse level, with the River Ravi and major roads. Boundaries from geoBoundaries and Natural Earth.

Assessment Framework:

Figure 2 sets out the workflow. Each package was reconstructed as drawn from its layout plans, hydraulic statements, loading sheets and design reports, with every asset traceable to its source and the stated design basis (per-capita flow, peak factor, infiltration, storm allowance, roughness, plot loads, loading limits) adopted unchanged. Each missing input was either entered as a declared assumption within a stated scope or reported as unresolved. The declared assumptions are the pipe sizes, slopes and recharge acceptance of the Meadows storm network, the Meadows Road topology and gate positions, and the gullies, conductor properties and supply capacity at Ali Housing.

Where an input could not be supplied on a defensible basis, the dependent mechanism was reported as not assessable: the Meadows documents give every manhole the same placeholder ground level, so surcharge to the surface could not be assessed there, and neither Meadows nor Ali Housing states the capacity of its receiving sewer or drain. A subsystem lacking essential inputs was reported as not assessed rather than as a pass, and one whose load is carried within another model without an independent network, such as drainage at Bella Verde, was reported as integrated. The four subsystems are integrated in three ways. They share one occupation input, so that every subsystem sees the same dwellings occupied in the same order, one asset inventory and one decision rule.

They interact physically where networks are shared: in the combined systems the sewerage and drainage models run on the same pipes, with the storm allowance carried in the sewerage run and the sanitary flow of each state carried in the drainage sweep. And their results are combined at scheme level by Equation (2).

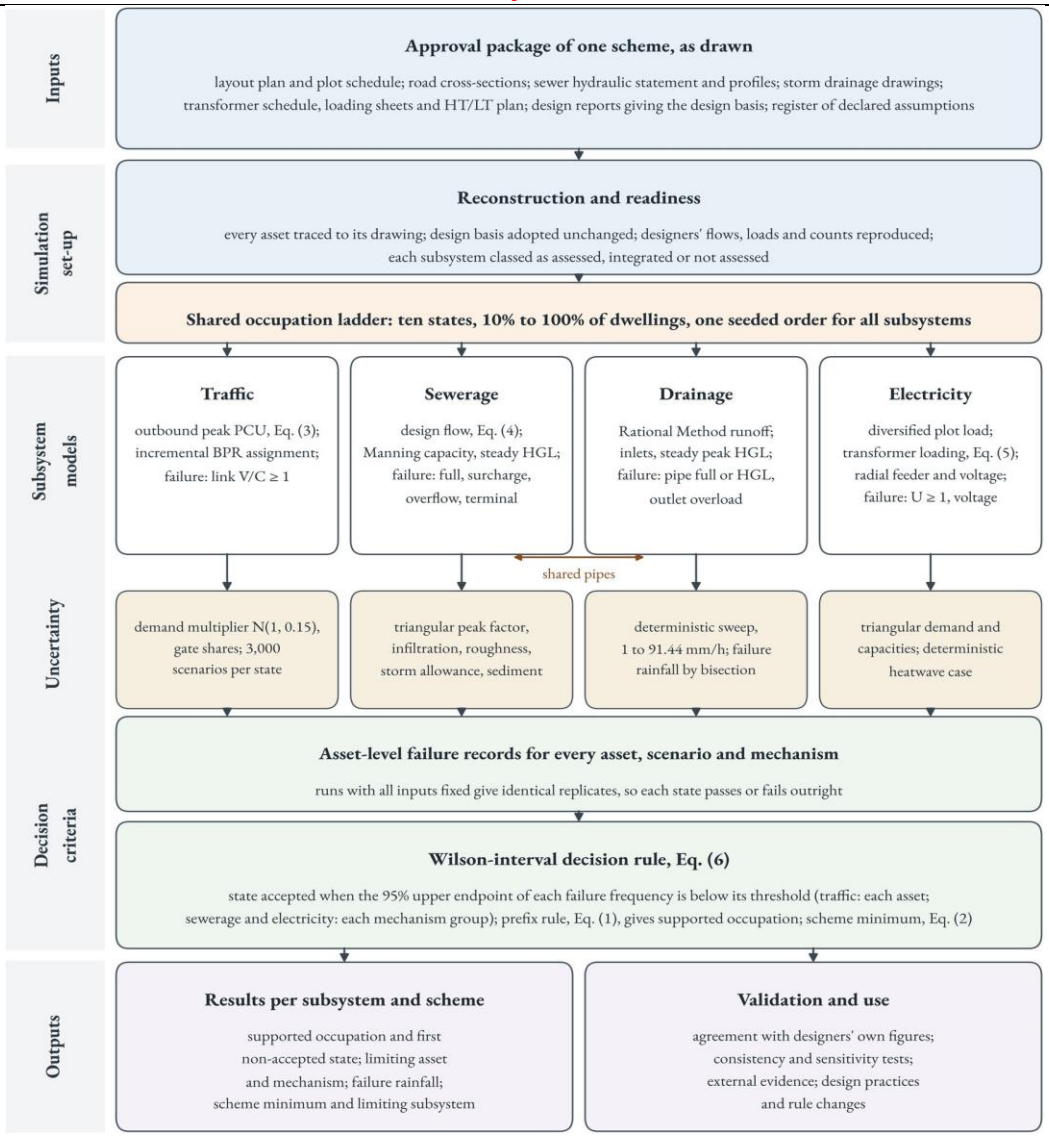

Figure 2. Methodology flow diagram of the Scheme Assessment Model: inputs from the approval package, reconstruction and readiness checks, the occupation ladder shared by the four subsystem models (sewerage and drainage share their pipes in combined systems), sampled uncertainty and the rainfall sweep, asset-level failure records, the Wilson-interval decision rule, and the outputs and their validation.

Each subsystem was evaluated at ten occupation states, 10% to 100% of the planned dwellings, filled in a seeded random order; unoccupied dwellings generate no demand and retain the runoff of undeveloped land. A state is accepted when every decision criterion of the subsystem is met, and the supported occupation Φ_s of subsystem s, evaluated at states $\phi_1 \in \ldots \in \phi_K$, is the highest state for which that state and all lower states are accepted:

$$\Phi_s = max\,\{\phi_k : \phi_1, \ldots, \phi_k \text{ all accepted for } s\} \quad (1)$$

Where every required subsystem in the set R has a valid result, the scheme value and its limiting subsystem follow from

$$\Phi_{\text{scheme}} = \min_{s \in R} \Phi_s \quad (2)$$

Φ_s is a lower bound, reported with the first state that is not accepted. For drainage it is evaluated at each rainfall level. Equations (1) and (2) rest on three assumptions. Occupation

grows monotonically, each state adding dwellings to the previous one in the same order, because no package contains a phasing plan. The prefix rule is conservative: a state accepted above a failing state does not count, because a scheme must pass through the failing state to reach it. And Equation (2) treats the scheme as a series system in which every required subsystem must be adequate; it does not combine subsystem probabilities, because the subsystems were run separately. Because occupation is evaluated only at discrete states, the true transition lies between Φ_s and the first non-accepted state. The 10% spacing brackets each transition within ten percentage points; the gain from finer spacing is quantified under Results.

Subsystem Models:

Table 3 summarizes the four engineering models and Table 4 the basis of their principal assumptions. Traffic is the residential outbound morning peak. Dwellings of up to 5 marla, 5 to 15 marla and 15 marla or more are assigned 0.8, 1.4 and 2.2 cars and 1.3, 0.9 and 0.5 motorcycles, and the peak-hour demand of dwelling i in scenario r, in passenger-car units per hour, is

$$q_{i,r} = m_r \left(0.25\, C_i + 0.15 \times 0.3\, M_i\right) \tag{3}$$

where C_i and M_i are its cars and motorcycles, $\overline{0.25}$ and 0.15 are the fractions of cars and motorcycles leaving in the peak hour, 0.3 is the passenger-car equivalent of a motorcycle, and m_r is the sampled demand multiplier. No package contains traffic counts or trip-generation data, so these values are declared stress values rather than calibrated rates (Table 4). Demand is split among the gates by a scheme-level preference vector and loaded in four increments (40%, 30%, 20%, 10%) with link times from the Bureau of Public Roads function [22][23]. Capacity is 1,000 PCU/h per standard lane per direction and G00 PCU/h for narrow two-way local roads; excess demand is retained so that the size of an overload remains visible.The sewerage model accumulates the average sanitary flow Q_p upstream of each pipe p, applies the design-basis peak factor once to it, and adds infiltration and any storm allowance:

$$Q_{\text{design},p} = \mathrm{PF}_p \overline{Q_p} + Q_{\text{inf},p} + f_s \left(\mathrm{PF}_p \overline{Q_p} + Q_{\text{inf},p}\right) + Q_{\text{other},p} \tag{4}$$

where PF_p is the peak factor, $Q_{\text{inf},p}$ the infiltration, $Q_{\text{other},p}$ non-residential flow where the package locates it, and f_s the storm-allowance fraction, all flows in m³/s. Equation (4) reproduces the design basis of the packages, which express the storm allowance as a fraction of peak sanitary flow plus infiltration; with $f_s = 1$ it doubles the design flow of every pipe whatever its catchment, imperviousness or rainfall. Because this allowance carries no information about rainfall, the Ali Housing combined system was also run with the storm component replaced by Rational Method runoff from the 2-year storm, and the Bella Verde network with the allowance removed. Capacity follows Manning's equation [24]; where invert levels and a terminal boundary exist, a steady hydraulic grade line is propagated upstream to identify surcharge, surface overflow and terminal overload as separate mechanisms. Velocity is evaluated at the partial depth of the flow each pipe carries in the state, in these runs its design flow, and low velocity is a serviceability condition that does not limit supported occupation.

The drainage model generates peak runoff by the Rational Method, $Q = 0.00278\, C\, I\, A$ [25], where Q is the peak runoff in m³/s, C the dimensionless runoff coefficient, I the rainfall intensity in mm/h for a duration equal to the time of concentration, and A the catchment area in hectares. Each plot's runoff coefficient changes from that of bare land to the area-weighted value of its roof, paved and garden surfaces when occupied. Captured flow is accumulated as a steady peak without attenuation, which is conservative for conveyance, and a steady peak hydraulic grade line is computed from the outfall.

The steady approach matches the peak-flow basis on which the designs were made and

locates the rainfall at which each network first fails [26]; it does not represent storage, so the Meadows recharge wells are represented by an acceptance rate rather than by the filling of their tanks. Because the Rational Method gives one peak per intensity, each state was evaluated deterministically at nine uniform intensities: 1, 2, 5, 10, 20, 30 and 50 mm/h and the 15-minute intensities of the Lahore 2-year and 5-year storms, G8.58 and 91.44 mm/h [27]. The failure rainfall of each state was located by bisection to 0.01 mm/h. In the pipe-full definition a link reaching full-flow capacity fails; in the hydraulic-grade definition it fails only if it causes surcharge, flooding, inlet ponding or outlet overload.

The electricity model aggregates diversified plot demand, from the designer's loading sheet or the NEPRA housing-society schedule with a development factor of 0.85 and a diversity divisor of 1.25 [28], through the transformer that serves each plot. For transformer j in operating case c,

$$U_{j,c} = \frac{S_{j,c}}{S_{\text{rated},j} L_{\text{limit}} k_c} \tag{5}$$

where $S_{j,c}$ is the apparent load in kVA, $S_{\text{rated},j}$ the nameplate rating, L_{limit}=0.8 the designers' loading limit and k_c the capacity multiplier of the case; failure occurs at $U_{j,c} \geq 1$. Where conductor and source data exist, feeder current and node voltage are computed along the radial path [29]. A deterministic heatwave case (demand ×1.15; transformer, feeder and source capacity ×0.90, ×0.92 and ×0.95) represents a hot-season peak. The loading limit is the designers' own and equals the permissible normal loading of transformers in Pakistan's transmission planning criteria [30]The transformer multiplier of 0.90 corresponds, under the ambient correction of the IEEE loading guide for self-cooled transformers, to a 24-hour mean ambient temperature of about 37 °C[31], some 3 °C above Lahore's June normal [32]; the other multipliers are declared stress values (Table 4).

Table 3. Engineering models, sampled uncertainty and decision thresholds. Triangular distributions are given as (minimum, mode, maximum).

Subsyste m	Demand or forcing	Engineering model	Physical failure in a scenario	Sampled uncertainty	Persistence threshold
Traffic	Peak-hour outboundPCU, Equation (3)	Incremental BPR assignment on the directed	Directional volume/capacit	Demand multiplier N(1, 0.15) clipped to [0.G, 1.4]; gate shares uniform, none above 0.85	0.35 road links; 0.15 gate approaches
Sewerage	Design flow, Equation (4)	Manning capacity; steady hydraulic grade line	Pipe full; surcharge; surface overflow; terminal overload	Peak factor (0.90, 1.00, 1.15); infiltration (0.80, 1.00, 1.30); roughness (0.95, 1.00, 1.10); storm allowance (0.90, 1.00, 1.20); sediment depth (0, 0.005, 0.02) m	0.05 capacity and surcharge; 0.01 surface overflow; 0.25 velocity (serviceability)
Drainage	Rational Method runoff	Inlet capture, surface bypass, steady peak hydraulic grade line	Pipe full or hydraulic-grade failure; outlet overload	None; deterministic sweep of nine intensities	Failure rainfall at each state
Electricity	Diversified plot demand per transformer	Transformer loading, Equation (5); radial feeder and voltage	Transformer, feeder or source utilization ≥ 1; voltage outside limits	Demand (0.85, 1.00, 1.20); transformer (0.92, 1.00, 1.03); feeder (0.90, 1.00, 1.05); source (0.95, 1.00, 1.05)	0.10 thermal; 0.05 voltage and supply

Table 4. Basis of the principal assumptions and how their effect was tested or bounded.

Assumption	Value used	Basis	How its effect was tested or bounded
Occupation states	Ten states, 10% to 100% of planned dwellings	Brackets each transition within ten percentage points at one scenario set per state	Transition located between states from the saved outputs, under Results
Order of occupation	One seeded random order per scheme, shared by all subsystems	No package contains a phasing plan; a random order favors no part of a scheme	Not varied in these runs; its likely effect on the Ali Housing electricity boundary is assessed under Results, and multiple orders are proposed as future work
Vehicles per dwelling	0.8, 1.4 and 2.2 cars;	Declared stress values graded by plot size, well above city-wide ownership (19.5% of Lahore households with a car and 44.8%	Demand multiplier N(1, 0.15) in every scenario; margins reported under Results

	1.3, 0.9 and 0.5 motorcycles, by plot size	with a motorcycle in 2010), because car ownership rises with income [33]	
Peak-hour departures	0.25 of cars and 0.15 of motorcycles	Declared; no package contains traffic counts or trip-generation data	Demand multiplier; recommended peak-hour counts
Motorcycle equivalence	0.3 PCU	Equivalence factors are region-specific and vary widely between studies [34]	At 0.5, peak demand per dwelling rises by 3% to 15%, within the sampled demand variation
Storm allowance	As stated in each design report, a fraction of peak flow plus infiltration	Reproduces the design basis	Allowance removed at Bella Verde; replaced by Rational Method runoff at Ali Housing
Rational Method inputs	C from surface areas; I from the Lahore profile at its 15-minute floor; A by catchment	Design reports and [27]	Rainfall sweep from 1 to 91.44 mm/h; vacant-plot runoff test
Steady peak hydraulics	No attenuation or storage	Same peak-flow basis as the designs; locates the onset of failure [26]	Two failure definitions; storage discussed under Limitations
Transformer loading limit	0.8 of nameplate	The designers' own limit and the permissible loading of transformers under normal operation in Pakistan's transmission planning criteria [30]; the same fraction defines heavy overload in large-scale monitoring of distribution transformers [35]; loading guides allow short periods above nameplate at the cost of accelerated aging [36]	NEPRA plot loads; gradient of failure probability with design loading
Heatwave case	Demand ×1.15; transformer, feeder and source capacity	Hot-season evening peak. The transformer multiplier follows the IEEE ambient correction for self-cooled transformers, a reduction of about 1.5% of rated load for each °C by which the 24-hour mean ambient exceeds 30 °C [31] at a mean of	Case removed

	×0.90, ×0.92 and ×0.95	about 37 °C; Lahore's June normal mean is 33.G °C, and in June 2024 the monthly mean was 34.9 °C with a highest maximum of 44.5 °C [32]. The feeder, source and demand multipliers are declared, the last reflecting the cooling load that drives Pakistan's summer peaks[37][38]	
Decision thresholds	Table 3	Policy parameters set by severity and recoverability: 0.01 for surface overflow, which puts sewage on streets; 0.05 for capacity and surcharge, which precede it; 0.05 for voltage, as supply-quality standards are framed as weekly exceedance limits [39]; 0.10 for transformer heating, which is tolerated briefly[36]; 0.35 for road links, whose congestion is recoverable, and 0.15 for gate approaches, through which all of a gate's traffic must pass	Halving and doubling every threshold, under Results

Statistical Decision Rule:

For each asset a and mechanism, the failure frequency over N valid scenarios is

$$\hat{p}_a = \frac{1}{N}\sum_r I_{a,r},$$

where $I_{a,r}=1$ if the asset fails in scenario r. The decision is taken on the upper endpoint of the two-sided 95% Wilson score interval [40][41]:

$$U_a = \frac{\hat{p}_a + \frac{z^2}{2N} + z\sqrt{\frac{\hat{p}_a(1-\hat{p}_a)}{N} + \frac{z^2}{4N^2}}}{1+\frac{z^2}{N}}, z=1.96 \qquad (6)$$

The quantity to which Equation (G) is applied differs between subsystems. For traffic, each road link and gate approach is judged on its own failure frequency, and a state is accepted when the upper endpoint of every asset lies below its persistence threshold (Table 3). For sewerage and electricity, $\hat{p}$ is the frequency with which any asset of a mechanism group, such as physical capacity or surface overflow, fails in a scenario, and a state is accepted when the upper endpoint of every group lies below the group's threshold; per-asset intervals, Bonferroni-adjusted across asset–mechanism pairs, identify the assets responsible but do not decide acceptance. The thresholds govern how often a physical failure may recur across scenarios; the physical limit remains a ratio of1. They are policy parameters, not standards, set according to the severity and recoverability of each mechanism (Table 4), and their effect is reported under Results. A subsystem is strained when any asset reaches 80% of capacity in any valid scenario, and a scenario with unresolved routing or unreconciled demand is invalid rather than successful.

The number of scenarios limits what the rule can resolve (Table 5). With no observed failure, Equation (G) reduces to $z^2/(N+z^2)$, so a threshold T can be met only if $N > z^2(1-T)/T$: 8 scenarios for 0.35, 35 for 0.10, 73 for 0.05 and 381 for 0.01. Above zero, the interval narrows with $\sqrt{N}$; at 3,000 scenarios its half-width is about 0.008 at a frequency of 0.05 and 0.017 at 0.35. Runs with every input fixed produce identical replicate, so their results depend neither on N nor on the thresholds: each state passes or fails outright.

Table 5. Resolution of the decision rule by number of scenarios per state.

Scenarios per state	Upper endpoint with no failure	Thresholds that can be met with no failure	95% interval at a frequency of 0.05	95% interval at a frequency of 0.35	Runs in this study
1	0.794	None of those used	—	—	Meadows's sewerage, inputs fixed and decided deterministically
100	0.037	0.05 and above	0.022–0.112	0.2G4–0.448	Meadows's sewerage risk run
500	0.007G	0.01 and above	0.034–0.073	0.310–0.393	Al-Kabir sewerage, inputs fixed
3,000	0.0013	All thresholds used	0.043–0.058	0.333–0.3G7	All traffic; Ali Housing sewerage and electricity, sampled; Bella Verde electricity, inputs fixed

Run Configuration:

Traffic used 3,000 scenarios per state in all four schemes; at Bella Verde the 90% and 100% states were run in isolation after the ladder stopped, without a boundary decision. The Ali Housing sewerage and electricity runs sampled their inputs over 3,000 replicates per state; the Al-Kabir sewerage run used 500 replicates with inputs fixed; the Bella Verde sewerage run checked pipe capacity at the design basis and its electricity run held all inputs fixed, so that each state passed or failed outright; and the Meadows sewerage result used one replicate per state with a 100-replicate risk run. Ali Housing sewerage was run with the design allowance and with the 2-year storm applied by the Rational Method at G0- and 15-minute durations. The Ali Housing electricity run applied a transformer threshold of 0.05, whose effect is reported with the result. Authorization labels are reported as recorded: Al-Kabir traffic is final; the other traffic, sewerage and electricity runs are exploratory, except the Meadows sewerage run, which carries no label; and the drainage sweeps carry no authorization flag.

Results:

The results address the second and third objectives: the supported occupation, limiting asset and mechanism of each scheme–subsystem pair (O2; Table G and Figures 3 to G), and the reconstruction checks, decision basis and sensitivity of each result (O3; Table G and the sensitivity analyses at the end of this section).

Reconstruction Checks:

The reconstructions reproduced the designs closely wherever a direct comparison existed. At Al-Kabir, reconstructed sewer flows differed from the designer's hydraulic statement by +0.9% and−1.5%, and 75 of 77 reaches reproduced the stated number of contributing plots exactly. At Ali Housing, the transformer loads matched the consultant's loading sheet to within 0.5 kVA for each of the seven transformers (9G4.89 kVA including losses against 954 kVA of load in the report), and a recomputed full-bore pipe capacity differed from the hydraulic statement by 0.9% (1.110 against 1.100 cusecs). At Meadows, the corrected plot mix reproduced the design population of 15,0G9 persons exactly, and reconstructed road lengths agreed with the consultant's tabulated values to within 0.3%. Bella Verde has no equivalent single numerical check; its sewers and transformers were traced individually to the drawings.

Supported Occupation Across the Portfolio:

Table G lists the outcome of every scheme–subsystem pair, with the basis on which each decision was made and its evidential standing, and Figure 3 shows the state reached at every occupation level. Twelve of the sixteen pairs were assessed. Six support full occupation: traffic and sewerage at Al-Kabir, Meadows and Ali Housing. Six stop below it: traffic, sewerage and electricity at Bella Verde, drainage at Meadows and Ali Housing, and electricity at Ali Housing. Each boundary is attributed to a named asset or asset group, and in none of them is any state above the first non-accepted state accepted, so the prefix rule of Equation (1) does not alter any boundary.

The remaining four pairs carry no result because the evidence required was absent: drainage and electricity at Al-Kabir and electricity at Meadows were not assessed, and drainage at Bella Verde is integrated in the sewerage run.Every result in Table G is a model prediction for the design as drawn; none has been compared with observed operation. Of the six boundaries below full occupation, two rest on sampled uncertainty (Bella Verde traffic and Ali Housing electricity) and four on fixed inputs or a deterministic sweep. Four results are, in addition, linked to a weakness that can be seen in the designers' own figures without the model, and these are distinguished in the last column of Table G and in Figure 3.

Table 6. Supported occupation of every scheme–subsystem pair, with the basis of each decision and its evidential standing. Drainage is reported under the 2-year design storm (G8.58 mm/h); its dependence on rainfall is reported under Drainage. The governing value is the upper endpoint of the 95% Wilson interval for sampled runs and the utilization of the governing asset (1.0 at its limit) for fixed-input and deterministic runs, with the threshold in brackets. P denotes a model prediction for the design as drawn; P+D a prediction linked to a weakness, in the governing asset or in the input that decides the result, that is visible in the designers' own figures without the model. At Ali Housing the report's own Rational Method inputs give a 2-year runoff 32 to 55 times its storm allowance, an inconsistency within the package; at Bella Verde the allowance is applied consistently with the stated design basis, and only the model shows its effect on the pipes.

Scheme	Subsystem	Supported occupation (first not accepted)	Mechanism and limiting or most-loaded asset	Decision basis	Governing value, last accepted → first not accepted	Evidence
Lake City Bella Verde	Traffic	G0% (70%)	Persistent link overload; RD02G0, segments S01–S05 (30 ft)	Monte Carlo, 3,000 scenarios	0.298 → 0.3G4 (0.35)	P
	Sewerage	50% (G0%)	Pipe full-flow capacity; SP-01030 (9 in.)	Design basis, inputs fixed	Below 1.0 → 1.10	P; cause in the stated storm allowance
	Drainage	—	Storm load carried in the sewerage run	—	—	Integrated
	Electricity	40% (50%)	Transformer capacity; LC-TR-0009 (200 kVA)	3,000 replicates, inputs fixed	0.8–1.0 (strained) → 1.13	P
Al-Kabir Orchard Phase-II	Traffic	100% (none)	None reached; R075a-BA (40 ft)	Monte Carlo, 3,000 scenarios	0.0013 at every state (0.35)	P
	Sewerage	100% (none)	None reached, strained by low velocity; outfall pipe AC–DIS (18 in.)	500 replicates, inputs fixed	0.007G at every state (0.01)	P+D; AC–DIS beyond its stated capacity with non-residential load
	Drainage	—	—	—	—	Not assessed
	Electricity	—	—	—	—	Not assessed

Lake City Meadows Phase-I Extension	Traffic	100% (none)	None reached; ROAD-CO-270-R, western gate route	Monte Carlo, 3,000 scenarios	0.114 at 100% (0.35)	P; declared topology
	Sewerage	100%, domestic load (none)	None reached, strained by low velocity; SEWER-CO-413	One replicate per state, inputs fixed	0.75 at 100%	P; domestic load only
	Drainage	20% (30%)	Outlet overload; four recharge-well outlets	Deterministic sweep	0.8G → 1.35	P; declared recharge rate
	Electricity	—	—	—	—	Not assessed
Ali Housing Scheme	Traffic	100% (none)	None reached; GATE-SOUTH-OUT	Monte Carlo, 3,000 scenarios	0.0013 at every state (0.15)	P
	Sewerage	100% (none)	None reached, strained by low velocity; outfall reach SEWER-CO- 27	Monte Carlo, 3,000 replicates	0.019G at 100% (0.05)	P+D; allowance 32 to 55 times below 2-year runoff
	Drainage	No state (10%)	Link full-flow capacity, pipe-full definition; SEWER-CO-27	Deterministic sweep	1G.G at 10%	P+D; same allowance
	Electricity	40% (50%)	Transformer capacity; T-3	Monte Carlo, 3,000 replicates	0.0013 → 0.0G5 (0.05)	P+D; T-1 beyond the 80% limit on the consultant's sheet

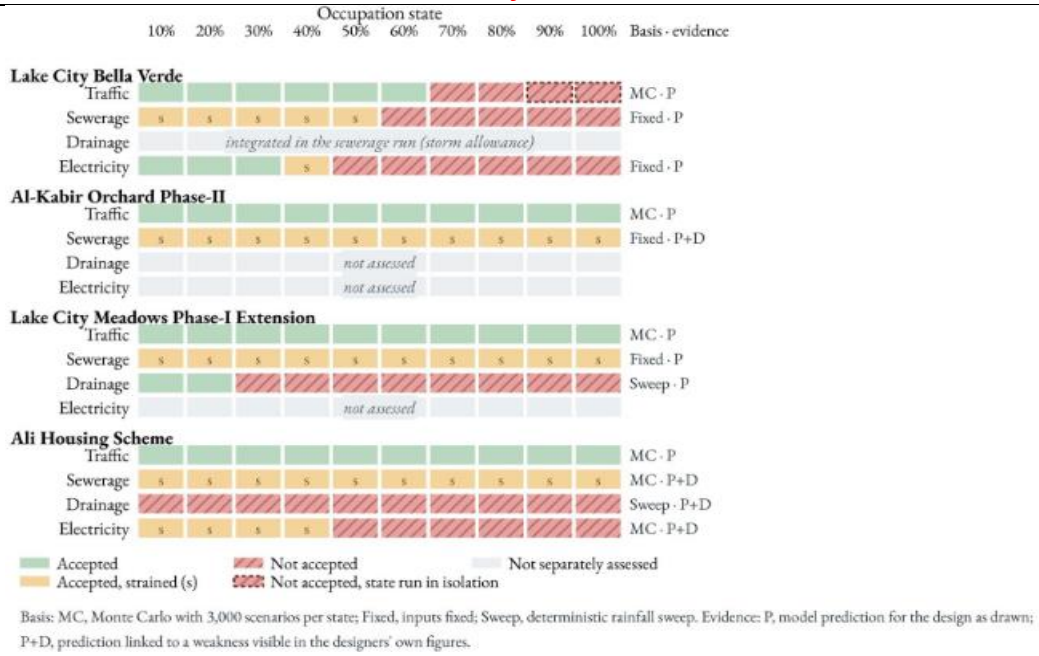

Figure 3. Engineering state of each subsystem at each occupation state. Drainage rows show the 2-year design storm (G8.58 mm/h). The labels at the right give the decision basis (MC, Monte Carlo with 3,000 scenarios per state; Fixed, inputs fixed; Sweep, deterministic rainfall sweep) and the evidential standing (P, model prediction for the design as drawn; P+D, prediction linked to a weakness visible in the designers' own figures). The Bella Verde traffic states at 90% and 100% were run after the ladder had stopped and carry no boundary decision.

Two features of Figure 3 recur throughout. No sewer network reaches an accepted state that is free of strain. The four boundaries outside drainage lie between 40% and G0% occupation, whereas the drainage boundaries depend on rainfall and, under the 2-year storm, fall to 20% at Meadows and below the lowest evaluated state at Ali Housing.

Traffic:

Traffic supports full occupation in three schemes, two of them by a wide margin (Figure 4). At Al-Kabir no link fails in any scenario at any state, so every asset sits at the zero-failure floor of 0.00128. In a 10-scenario sample at full occupation, with demand multipliers of 0.G0 to 1.03, the most heavily used link, R075a-BA (40 ft), peaks at a volume–capacity ratio of 0.220 and the single gate approach at 0.202, and at the demand ceiling of 1.4 the worst link would reach about 0.30. Because all 394 PCU/h of outbound demand passes one gate, the one constraint this result cannot exclude is the junction with Chak 44 Road beyond it. Ali Housing records no failure in 30,000 scenarios; in one sampled assignment at full occupation, with 7G.9 PCU/h of outbound demand, its most heavily used asset, GATE-SOUTH-OUT, reaches a utilization of 0.078.

At Meadows no asset fails in any scenario up to G0%. Above that, failures appear without persisting: the fraction of scenarios with any failure is 0.0007, 0.014, 0.081 and 0.201 at 70%, 80%, 90% and 100%, and the number of assets failing in at least one scenario rises from 9 to 50, 105 and 11G. The most persistent asset, ROAD-CO-270-R on the route into the western gate, fails in 309 of 3,000 scenarios at full occupation, an upper endpoint of 0.114 against the threshold of 0.35. Because the Meadows topology follows the sewer layout and its gates were declared from external road labels, the location of this concentration follows from the declared gate positions, and a network without alternative routes makes its magnitude conservative.

Bella Verde is the only scheme with a traffic boundary. Traffic is accepted up to G0% and first fails at 70%, where five directional segments of one 30 ft road, RD02G0 (S01 to S05), exceed

the threshold together. The boundary is narrow: the upper endpoint rises from 0.298 at G0% to 0.3G4 at 70%, 1.4 percentage points above the threshold. At 80% the 45 ft approach to the north-west gate roundabout joins them with an upper endpoint of 0.1GG against 0.15, and in the isolated 90% and 100% runs the number of failing assets rises to 12 and 17, the worst being RD0224-S02-F at 0.711. Every failing asset other than the gate approach is a 30 ft road that no house fronts and that carries traffic from other parts of the scheme to a gate, while no 100 ft or 150 ft road fails at any state. The boundary therefore arises from the routing of outbound traffic over a few narrow connectors, not from a shortfall in the arterial roads.

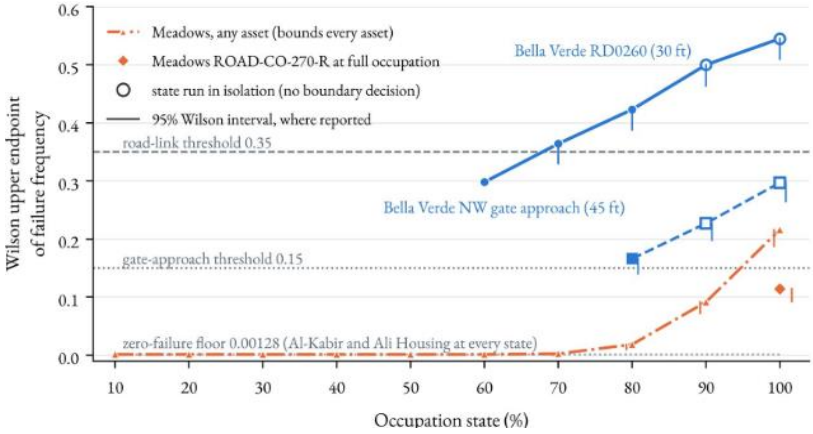

Figure 4. Upper endpoint of the 95% Wilson interval of the failure frequency for the traffic assets that govern or most nearly govern each result, against the persistence thresholds; vertical bars show the full interval where the output reports it. For Meadows the any-asset frequency is shown, which bounds the frequency of every individual asset, with the most persistent asset at full occupation marked separately. Open markers are states run in isolation. All values are model predictions over 3,000 scenarios per state.

Sewerage:

Table 7. Sewer networks at full occupation.

Scheme	Pipes over full-flow capacity	Most-loaded pipe; utilization	Terminal; utilization	Pipes below self-cleansing velocity	Engineering state
Lake City Bella Verde	9G of 3,327	SP-01030; 1.83	Disposal station; 0.809	Not counted (laterals at every accepted state)	Failing
Al-Kabir Orchard Phase-II	0 of 77	AC–DIS; 0.94	Pumping station; 0.813	G3 of 77	Strained
Lake City Meadows Phase-I Extension	0 of 1,758	SEWER-CO-413; 0.75	Existing trunk sewer; not assessable	1,GG1 of 1,758	Strained
Ali Housing Scheme	0 of 27	SEWER-CO-27; 0.81	Receiving drain; not assessable	2G of 27	Strained

Table 7 compares the four networks at full occupation. Bella Verde is the only network with a capacity boundary. One pipe exceeds its full-flow capacity at G0%, and 8, 34, 83 and 9G at the successive states, while the worst utilization rises from 1.10 to 1.83. The first and worst failing pipe is SP-01030, a 9 in. pipe that carries the sewage of 554 houses. The failures of

G0% and 70% are all in 9 in. pipes; at full occupation they are concentrated in the sub-mains, affecting G of 7 pipes of 24 in., 29 of 74 of 21 in. and 21 of G4 of 18 in., together with 15 pipes of 12 in. and 3 of 15 in., against 22 of the 2,721 pipes of 9 in. and none of the 284 pipes of 27 in. and above. The disposal station never overloads, reaching 0.809 of its 2G cusecs. The storm allowance alone causes these failures: with it removed, no pipe exceeds capacity at any state, the worst reaching 0.92 and the disposal station 0.404 at full occupation.

The other three networks carry full occupation without a capacity failure. At Al-Kabir the outfall pipe AC–DIS (18 in.) reaches 0.94 of capacity and the pumping station 0.813 of its duty (4.07 of 5 cusecs); the surface-overflow acceptance rests on zero failures in 500 replicates, an upper endpoint of 0.007G against 0.01. This result is for residential load, and the designer's own hydraulic statement loads the same pipe at 4.514 cusecs against a stated capacity of 4.41 cusecs once commercial plots and public buildings are included. At Meadows the maximum flow-to-capacity ratio under domestic load rises from 0.083 at 10% to 0.753 at full occupation in SEWER-CO-413.

The documents do not state which manholes serve the shops, mosque and school, so the non-residential flow, 38% of the design flow, could not be placed; scaling the governing conduit for it gives 0.753/0.G2 = 1.21 at full occupation and a capacity limit near 82% occupation, on the assumption that the missing flow reaches the conduit in proportion to the domestic flow. At Ali Housing the design-allowance case supports full occupation, with 44 capacity failures in 3,000 replicates at full occupation, a probability of 0.0147 (Wilson interval 0.0109–0.019G) against
0.05. Applying the 2-year storm by the Rational Method changes the result entirely: at both durations the first state, 10% (24 of 235 plots), already fails with a probability of 1.0 for both capacity and surface overflow, the governing asset is SEWER-CO-9 by surcharge at almost every state, and at full occupation 27 of the 28 manholes overflow. The design allowance is 0.449G cusecs, whereas the Rational Method runoff over the 12.25-acre catchment is 14.24 cusecs at G0 minutes and 24.81 cusecs at 15 minutes, 32 to 55 times the allowance, against a full-bore pipe capacity of
1.100 cusecs.

Every accepted sewerage state is strained, because low velocity is present at every accepted state of every network. At Al-Kabir G9 of 77 pipes are below self-cleansing velocity at 10% and G3 at full occupation. At Meadows the count rises from 90G at 10%, as more pipes begin to carry flow, to 1,G78 at 80%, and is 1,GG1 of 1,758 (94.5%) at full occupation. At Ali Housing 2G of 27 reaches are below 0.7G2 m/s at both 10% and full occupation, with mean velocities of 0.30G and 0.512 m/s, and only the outfall reach reaches 0.845 m/s, at full occupation, where it is also at 81.0% of capacity. The Ali Housing report tabulates 0.7G2 m/s for every reach, which is the velocity of a 9 in. pipe at 0.45% slope running full, whereas at full occupation the sewage in the 2G slower reaches flows at 8% to 48% of the pipe depth. The same contrast holds at Meadows, where, with the report's own roughness values of 0.010 for uPVC and 0.013 for concrete pipes, only G1 of the 1,758 conduits (3.5%) fall below 0.7G2 m/s running full, all of them 15 in. or larger.

Drainage:

Both occupation–rainfall grids are monotone: no failure clears as rainfall or occupation increases (Figure 5). At Meadows every state is supported up to 10 mm/h. Supported occupation then falls to 80% at 20 mm/h, 50% at 30 mm/h, 30% at 50 mm/h, 20% under the 2-year storm and 10% under the 5-year storm. The failure rainfall falls from 80.10 mm/h at 20% to 17.11 mm/h at full occupation, and the 10% state does not fail within the sweep.

The mechanism is always outlet overload at the recharge wells. Under the 2-year storm at full occupation the sweep generates 4.21 m^3/s of runoff, of which 4.00 m^3/s is connected to the network and delivered to four outlets that together accept 1.01 m^3/s, so that 2.99 m^3/s

(75% of the connected flow) leaves as surface overflow, all 44 links are surcharged, 40 of 48 nodes flood and the governing outlet carries 4.0 times its capacity. In every cell the most heavily loaded link carries at most 0.72 of the utilization of the governing outlet, so the outlets overload before any link fills and the boundary is the same under either failure definition. The outlet acceptance of 0.2525 m³/s each corresponds to filling the designed 909 m³ harvesting volume in one hour; no percolation test, soil report or groundwater level exists in the documents.

At Ali Housing the network fails in light rain. Under the pipe-full definition, which is also the design report's basis, supported occupation is 100% at 1 mm/h and 80% at 2 mm/h, and no state is supported from 5 mm/h upward. The failure rainfall falls from 3.89 mm/h at 10% to 1.82 mm/h at full occupation, governed in every failing cell by the outfall reach SEWER-CO-27, whose utilization at full occupation rises from 0.73 at 1 mm/h to 30.5 under the 5-year storm. Under the 2-year storm at full occupation 23 of 27 links exceed capacity, all 27 are surcharged and 27 of 28 manholes flood, while inlets never limit (highest gully utilization 0.24).

The consultant's storm allowance is equivalent to 1.23 mm/h over the fully built scheme, below the failure rainfall of every state, which is why the design-allowance sewerage case passes. Under the hydraulic-grade definition the failure rainfall lies between 8.0G mm/h at 10% and 4.51 mm/h at full occupation; the later response arises because the steady solution raises the head above the crown only when friction alone lifts it there, at about twice the full-bore capacity. Under either definition no state is supported at 10 mm/h or more.

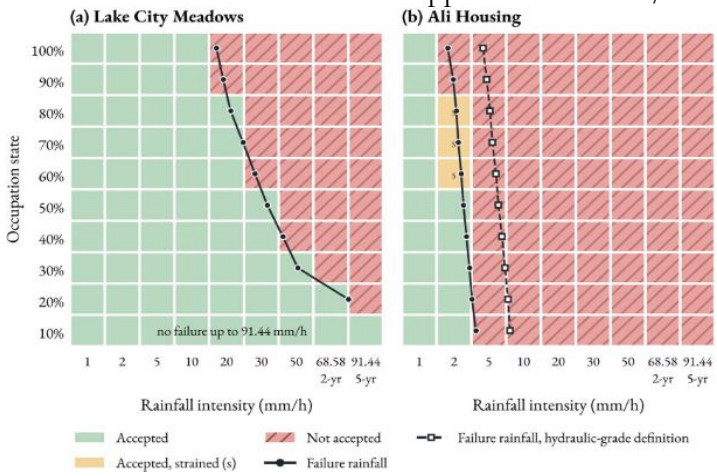

Figure 5. Occupation–rainfall grids of the drainage sweeps: (a) the separate storm network of Lake City Meadows; (b) the combined network of Ali Housing under the pipe-full definition, with the failure rainfall of the hydraulic-grade definition overlaid. The failure-rainfall line is placed between level columns by linear interpolation of intensity. The sweeps are deterministic and carry no sampling uncertainty; their dependence on declared inputs is shown by the two failure definitions in (b) and discussed for the Meadows recharge rate under Discussion. All cells are model predictions for the designs as drawn.

Electricity:

The two electricity results reach the same supported occupation, 40%, by different routes (Figure G). At Bella Verde, states up to 30% are acceptable and 40% is strained. From 50% onward 3, 10, 23, 35, 45 and 57 transformers exceed their safe limit at the successive states, and the worst utilization rises from 1.13 to 2.5G. The first to fail are LC-TR-0009, LC-TR-01G9 and LC-TR-015G, 200 kVA units serving G4 to 87 houses, and 400 kVA units join the failing set from 70%. The scheme is not short of capacity in aggregate, with 131,950 kVA installed against 25,870 kW of residential load at full occupation; the failures arise from the distribution of load among transformers. An independent assignment rule, which links each house to the

nearest low-tension distribution box along the drawn cable and moves 28.4% of houses to a different transformer, returns the same boundary, first non-accepted state and driving asset.

At Ali Housing the transformer failure probability is zero up to 40%, where the states are strained, and then rises to 0.05G at 50%, 0.129 at G0% and 70%, 0.329 at 80%, 0.4G0 at 90% and 0.G82 at full occupation. The supported occupation of 40% corresponds to 94 plots and 452 persons. Transformers enter the failure set as their plots are occupied: T-3 alone at 50% (1G8 of 3,000 replicates), joined by T-G at G0%, T-4 at 80%, T-7 at 90%, and T-1 and T-2 at full occupation, where T-1 is the most likely to fail. In the deterministic design case at full occupation, the consultant's own loads place T-1 at 1G0.72 kVA against the 1G0.00 kVA allowed by the 80% limit, or 100.4% of safe capacity, and the other transformers at 75.5% (T-5, which serves only the tubewell, park and street lighting) to 98.5% (T-2).

Under the heatwave case six of the seven exceed their safe capacity, at 103.7% to 128.4%. Removing the heatwave case leaves the boundary and the failure probability at every state unchanged, so the boundary comes from the consultant's own design condition under the sampled uncertainty. Replacing the consultant's plot loads with the NEPRA schedule raises the connected load by 2.G% and the failure probability of T-1 at full occupation from 0.G82 to 0.88G, but leaves the boundary at 40%; opening the RMU-1 to T-1 leg of the ring also leaves it at 40%, with feeders loaded to at most 18.5% of their rating as designed and 2G.4% with the leg open, and lowest node voltages of 0.9993 and 0.9985 pu respectively.

These feeder and voltage results assume a source with 2,000 kVA available and no external load, set to be non-binding because the package does not state what the 11 kV feeder can spare, and standard aluminum XLPE conductor values, because the package gives no table of conductor resistance, reactance or ampacity. The run applied a threshold of 0.05 rather than 0.10; the boundary as designed does not depend on that choice because the mandatory heatwave case fails at 50%, but for the normal case alone the 50% state would pass at 0.10, with an upper endpoint of 0.0G5.

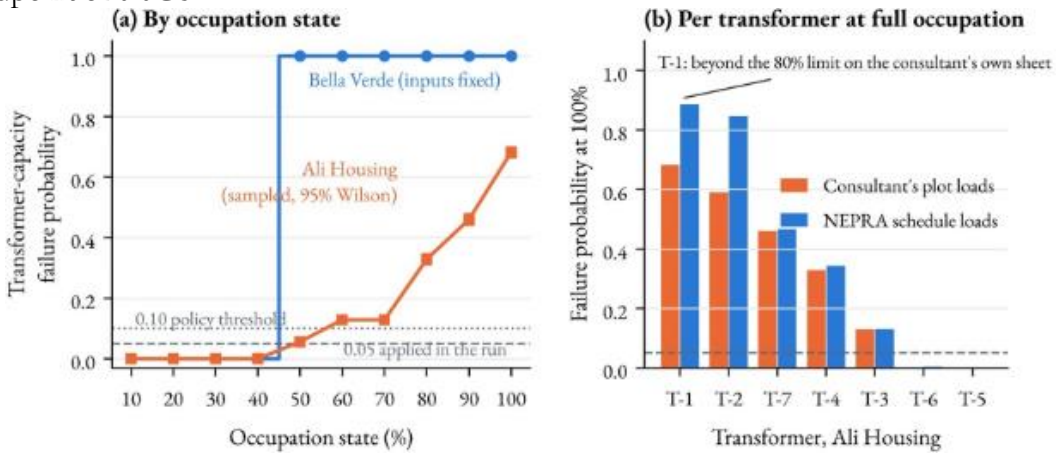

Figure 6. Transformer-capacity results: (a) failure probability by occupation state at Bella Verde, where every input is fixed so that each state passes or fails outright, and at Ali Housing, with 95% Wilson intervals over 3,000 sampled replicates; (b) failure probability of each Ali Housing transformer at full occupation under the consultant's plot loads and under the NEPRA schedule, with T-1, which the consultant's own loading sheet places beyond the 80% limit, marked. All values are model predictions for the designs as drawn.

Scheme-Level Outcome and Recurring Patterns:

Only Ali Housing has a result for every subsystem, so Equation (2) can be applied only there, and only as a conditional comparison of the assessed boundaries: the capacities of its receiving drain and of its 11 kV supply are unverified, and the subsystems were run separately rather than on one jointly sampled occupation. On that basis the minimum depends on rainfall:

40% at 1 and 2 mm/h, limited by electricity, and no supported state from 5 mm/h upward, including both design storms, limited by drainage. At Bella Verde the most restrictive assessed subsystem is electricity at 40%, ahead of sewerage at 50% and traffic at G0%. At Meadows it is drainage, whose supported occupation falls from 100% at 10 mm/h to 20% under the 2-year storm. At Al-Kabir both assessed subsystems support full occupation for residential load.

Four patterns recur. First, boundaries are set by individual assets rather than aggregate capacity: at Bella Verde the installed transformer capacity and the disposal station are adequate at full occupation while individual transformers fail from 50% and individual pipes from G0%. Second, in all three combined systems the storm allowance is a multiple of sewage flow rather than a quantity calculated from rainfall, and its size largely decides the sewerage result.

Third, serviceability is lost before capacity: no sewer network has an accepted state free of low-velocity strain. Fourth, two packages contain components beyond their own stated limits in the designers' own figures, T-1 at Ali Housing and the Al-Kabir outfall pipe once non-residential load is included. No design modification was verified: the candidates submitted for Ali Housing sewerage were declined because storm separation requires a drainage re-evaluation, infiltration reduction requires rehabilitation evidence, and no modification can be verified while the network fails its self-cleansing criterion. The boundaries reported are therefore those of the designs as drawn.

Sensitivity to Decision Thresholds and Occupation Step:

Only results decided by sampled frequencies can depend on the thresholds. The fixed-input runs and the drainage sweeps return frequencies of 0 or 1, so their boundaries are the same for any threshold between the zero-failure floor and 1. Table 8 gives, for the sampled results, the range of

thresholds within which each boundary holds and the boundary if every threshold were halved or doubled. Of the six boundaries below full occupation, four do not depend on the thresholds. The Ali Housing electricity boundary is held at 40% by the deterministic heatwave case; for the normal case alone, it holds for thermal thresholds up to 0.0G5 and would rise to 50% at the specified 0.10 and to 70% at 0.20. Only the Bella Verde traffic boundary moves: it holds for road-link thresholds between 0.298 and 0.3G4, and would fall to 50% or below if the thresholds were halved and rise to 90% if they were doubled. The full-occupation results are unchanged by halving or doubling, with one exception that concerns sample size rather than physics: with 500 replicates the Al-Kabir sewerage run cannot resolve a halved surface-overflow threshold of 0.005, which needs at least 7G5 scenarios, so no state could be accepted although no failure occurred.

The saved outputs also show how much a finer occupation step would change. Interpolating the governing quantity linearly between the last accepted and the first non-accepted state locates each transition approximately. For Bella Verde traffic the upper endpoint would cross 0.35 near G8% occupation, so a G5% state would probably be accepted and the boundary would rise from G0% to G5%. For Bella Verde electricity, LC-TR-0009 reaches 1.13 of its safe limits at 50% and would be near 1.02 at 45%, so the boundary would stay at 40%; for Bella Verde sewerage, SP-01030 would sit at about 1.01 of capacity at 55%, too close to call.

Under the 2-year storm the Meadows outlets would exceed their acceptance near 23%, so a 25% state would fail and the boundary would stay at 20%, and Ali Housing drainage fails at the lowest state at every rainfall above 2 mm/h. At Ali Housing electricity the outcome at 45% depends on whether the first of the plots newly served by T-3 are occupied before that state: in the heatwave case T-3 is at 9G.9% of its safe limit at 40% and 109.7% at 50%. A 5% step would therefore have raised one, or at most two, of the six boundaries by five percentage points, lowered none and changed none of the limiting assets or mechanisms.

Table 8. Sensitivity of the boundaries to the decision thresholds, from the saved outputs. Halving and doubling apply to every threshold of the subsystem as applied in the run; for Ali Housing electricity the applied thermal threshold of 0.05 becomes 0.025 and 0.10.

Result	Decision basis	Threshold applied	Governing upper endpoint	Boundary holds for	All thresholds halved	All thresholds doubled
Bella Verde traffic	3,000 scenarios	0.35 road links; 0.15 gate approaches	0.298 at G0% → 0.3G4 at 70%	Road-link thresholds 0.298–0.3G4	50% or lower	90%, using the states run in isolation
Meadows' s traffic	3,000 scenarios	0.35; 0.15	No failing state; worst asset 0.114 at 100%	Thresholds above 0.114	80% to 100%; gate approaches at 90% and 100% not resolved in the outputs	100%
Al-Kabir and Ali Housing traffic	3,000 scenarios	0.35; 0.15	0.0013 at every state	Thresholds above 0.0013	100%	100%
Ali Housing sewerage, design allowance	3,000 replicates	0.05 capacity; 0.01 overflow	Capacity 0.019G at 100%	Capacity thresholds above 0.019G	100%	100%
Ali Housing sewerage, 2-year storm	3,000 replicates	0.05; 0.01	1.0 at every state	Any threshold below 1	No state	No state
Al-Kabir sewerage	500 replicates, inputs fixed	0.05; 0.01	0.007G at every state	Overflow thresholds above 0.007G	No state: 500 replicates cannot resolve 0.005	100%
Ali Housing electricity	3,000 replicates and heatwave case	0.05 thermal (0.10 specified)	0.0013 at 40% → 0.0G5 at 50%; heatwave case fails at 50%	Any threshold; normal case alone up to 0.0G5	40%	40%; normal case alone 50%

Bella Verde sewerage and electricity, Meadows sewerage, both drainage sweeps	Inputs fixed or rainfall sweep	-	0 or 1	Any threshold between 0.0013 and 1	Unchanged	Unchanged

Discussion:

The results should not be read as a verdict on the four schemes. Each design was prepared by qualified consultants to pass the approvals that the LDA Rules require, and for most of its length each network does what its design report says. What the results show is where conformity and performance part company. In every scheme the boundary falls at a specific asset governed by a design convention, such as a storm allowance written as a percentage of sewage flow, a velocity checked with the pipe running full, or a transformer schedule judged by its total capacity, and these conventions are shared across the profession rather than peculiar to one designer. This is the central finding of the study: the weaknesses are systematic, and systematic weaknesses can be corrected systematically, at the approval stage, where correction is cheapest.

Model Validation:

Validation is the most demanding question this study has to answer, and the claims made here are limited to what the evidence supports. A model of an open system, whose inputs and boundary conditions are never fully known, cannot be proved true; it can only be shown to agree with the evidence available [19][20]. Model validation separates the conceptual validity of a model, the verification of its implementation, the validity of its data, and its operational validity. The first rests here on established engineering methods. The second rests on tracing the implementation to the model specification, on automated tests, and on the agreement of the rainfall sweep with the model's standard design-storm workflow. The third rests on the reconstruction checks. The fourth, agreement with observed behavior, is the one a regulator would most want and the one that cannot yet be claimed. The headings below set out what the available evidence does and does not support.

Comparison with Actual Scheme Performance:

There is no operating record for any of the four schemes: no flow or level measurements, flooding reports, traffic counts or transformer logs, and a search of news and regulatory sources found no incident attributable to any of them. The absence of reports is not evidence of adequate performance. The schemes are at early stages of occupation, below the levels at which most of the predicted boundaries lie, and problems inside private schemes are seldom reported publicly. Every boundary in this paper therefore remains a prediction for the design as drawn, and the networks actually built may differ from the drawings.

What can be tested is whether the failure modes SAM predicts are those that Lahore's infrastructure actually suffers, and the available evidence indicates that they are. A SWMM study of a Lahore residential area drained to a 2-year standard found much of it flooding in that storm [4] The storm of 1 August 2024 delivered, over about three hours, an average intensity above the 5-year 15-minute intensity used in the sweep [3]and in the 202G monsoon drains around Ferozewala, where Al-Kabir lies, overflowed under flows beyond their design capacity [42]On the electrical side, overloading is widespread at transmission level [43]LESCO's interruption record is poor [44], storms trip hundreds of feeders [3], and transformer burn-outs rise in the summer peak [45]. None of this test the particular numbers, but it indicates that SAM identifies the mechanisms through which such networks fail. A model that found comfortable

margins in every subsystem of every scheme would be harder to reconcile with this record.

One external figure bear directly on an input and points in the unfavorable direction. The Meadows recharge outlets were credited with accepting water at the rate at which their storage tanks would fill in an hour, about thirty times the capacity estimated for the pilot recharge wells at Gaddafi Stadium[46]. The pilot does not establish what the Meadows wells can accept, but if anything like it applies, a rough screening of the sweep suggests that Meadows would flood in light rain rather than in heavy rain. The Meadows drainage result is therefore the optimistic end of the plausible range, and a percolation test at those wells is the single most valuable measurement that could be made for that scheme.

Identification of Known Infrastructure Behavior and Problems:

SAM behaves as engineering theory predicts. Drainage fails at lower rainfall as plots are built over; outlet-controlled and pipe-controlled networks fail in different ways; traffic failures gather where streams from several parts of a scheme converge on a narrow link to a gate; and electrical failures follow the occupation of each transformer's plots rather than the scheme's total demand. This is necessary, but it is what any competent model should do. Stronger evidence is that SAM located, without being directed, weaknesses that are visible in the packages themselves once they are looked for. The transformer most likely to fail at Ali Housing is loaded beyond the consultant's own limit on the consultant's own sheet. The pipe most heavily loaded at Al-Kabir is over its stated capacity in the designer's own statement once non-residential load is added. The Meadows report declares a separate sewer system while carrying a storm allowance, and its topographic survey annex, which Rule 11(b) requires, is empty.

The Ali Housing report declares the Rational Method but sizes its storm load as a percentage of sewage flow. In each case the model's localization pointed to the asset or input that an experienced reviewer would flag after a careful reading. This is the strongest validation the study can offer, because it is agreement with calculations the designers made independently, not with the model's own assumptions. It also indicates a role for SAM before it is validated against operation: directing a reviewer's limited time to the few places in a large package where it matters.

Consistency Across Schemes:

The results are internally consistent. Every assessed subsystem fails, where it fails, in a single transition along the occupation ladder, both drainage grids are monotone, and the tests in Table 9 either left the boundaries where they were or moved them in the direction the physics predicts. The storm-allowance test is the most informative: removing the allowance removes the Bella Verde sewerage boundary altogether, which identifies its cause.

The more important consistency is across schemes. Four designs, prepared by different consultants for different developers at very different scales, share the same weaknesses: a storm allowance unrelated to rainfall in every combined system, low velocity in every sewer network, and transformers judged in aggregate or loaded to the limit in both electrical designs. Independent errors would be expected to differ from scheme to scheme. That they do not indicates that they arise from common design conventions, which is the level at which a rule can act.

Table 9. Consistency tests.

Test	Scheme and subsystem	What was varied	Effect on the boundary
Alternative house-to-transformer assignment	Bella Verde, electricity	Houses linked to the nearest LT box along the drawn cable; 28.4% reassigned	None: 40%, same first failing state and driving asset

NEPRA plot loads	Ali Housing, electricity	Connected load +2.G%	None: 40%; T-1 failure probability 0.G82 to 0.88G
Ring leg out of service (N-1)	Ali Housing, electricity	RMU-1 to T-1 leg opened	None: 40%; feeders at most 2G.4% of rating
Heatwave case removed	Ali Housing, electricity	Mandatory deterministic case dropped	None: identical failure probability at every state
Runoff from vacant plots	Ali Housing, drainage	Vacant plots shed no runoff	Failure rainfall at 10% from 3.89 to 4.58 mm/h; no state supported at 5 mm/h
Failure definition	Lake City Meadows, drainage	Pipe-full against hydraulic-grade	None: outlets overload first in every cell
Failure definition	Ali Housing, drainage	Pipe-full against hydraulic-grade	Failure rainfall 1.82–3.89 to 4.51–8.0G mm/h; no state supported at 10 mm/h
Storm allowance removed	Bella Verde, sewerage	Allowance set to zero	Boundary from 50% to 100%; worst pipe 1.83 to 0.92

Effect of Differences Between the Schemes:

The schemes differ in size, design type and available data, and these differences shape what the results can show. Scale changes how a boundary arises: at Bella Verde the limiting assets are a few among thousands, so boundaries arise from the distribution of load among assets, whereas at Ali Housing a single transformer or outfall reach governs a whole subsystem, and its result is correspondingly sensitive to the plots that asset serves.

Design type changes which mechanisms can be tested: drainage could be assessed directly only where a storm network or a combined network with catchments was drawn, and the separate Meadows network fails at its outlets while the combined Ali Housing network fails in its pipes. Data availability decides what can be assessed at all: four of the sixteen pairs carry no result, and the Meadows results rest on a declared topology, pipe sizes and recharge rate. The recurring findings are those that survive these differences, which strengthens them; but four purposively chosen schemes show where and how such schemes fail, not how often.

Resolution of the Boundaries:

A boundary reported at 10% spacing locates a transition within ten percentage points, and a 5% ladder would halve that bracket. The saved outputs indicate what this gain would amount to: one, or at most two, of the six boundaries would rise by five points, none would fall, and no limiting asset or mechanism would change. Against this, a 5% ladder doubles the computation of every stochastic subsystem, from 30,000 to G0,000 scenarios per run. For the portfolio assessed here it would raise the traffic runs from 120,000 to 240,000 network assignments and each Ali Housing sewerage and electricity case from 30,000 to G0,000 hydraulic or load-flow solutions, and it would double the asset-level output that must be checked.

The finer resolution would also be partly illusory, because a boundary already moves

by comparable amounts with the order in which plots are occupied and with the choice of thresholds (Table 8). Ten percent is therefore the appropriate standard spacing. Where a decision depends on the exact figure, as a staged approval condition would, a single additional state between the last accepted and the first non-accepted state provides the refinement for 3,000 scenarios rather than 30,000.

What Can and Cannot Be Concluded:

Table 10 summarizes where each kind of result stands. Four conclusions are secure. Where a numerical check was possible, SAM represents the design as its designer described it. The limiting assets it identifies are genuine weak points of the documented designs. The recurring design-basis findings are properties of the packages rather than artifacts of the model, because they can be seen in the packages' own numbers. And the order in which assets fail within a scheme is stable under the alternatives tested.

Table 10. Evidential standing of the results.

Category	What it establishes	Results in this category	What would test it further
Reconstruction agreement	That SAM represents each design as described	Flows, plot counts, transformer loads, pipe capacity, population and road lengths reproduced	An equivalent numerical check at Bella Verde
Agreement with the designers' own figures	That SAM's limiting assets coincide with points the package shows to be marginal	T-1 beyond the 80% limit; Al-Kabir outfall beyond stated capacity; Ali Housing storm allowance not from the declared method	Review of the same assets by the approving agencies
Prediction for the design as drawn	Supported occupation, first non-accepted state and failure rainfall	Every boundary in Table G	Observed performance of the built networks at the occupation reached

Four things cannot be concluded. The supported occupations are not yet forecasts of when the built schemes will experience distress: operational validity is untested, the built networks may differ from the drawings, and the probability thresholds are policy choices that can move a sampled boundary (Table 8). Four purposively chosen schemes cannot show how common these problems are across Lahore. Results that rest on declared assumptions, above all the Meadows drainage result, hold only within the domain those assumptions define [47]. And because the subsystems were run separately, nothing here supports a statement about several systems failing together.

The predictions are, however, inexpensive to test, and testing them is the most important next step. One wet season at Ali Housing would show whether its combined sewers surcharge in light rain as predicted. Loading records for the Bella Verde transformers predicted to fail first, read together with the occupation of the plots they serve, would test the electrical mechanism, recognizing that a different order of occupation could change which transformer fails first. A percolation test would settle the Meadows input. Multi-site comparisons of predicted and observed surcharge of the kind now used to build trust in urban drainage models [21][48], and the structured verification and validation applied to simulation models in other regulated settings [49]show how such evidence can be accumulated over time.

Comparison with Recent Studies:

The two most notable quantitative findings have counterparts in recent work. The share of sewer pipes below self-cleansing velocity, 82% to 9G% at full occupation, is larger than, but consistent with, what calibrated models of operating networks report: in a 2G.9 km branch of a city sewer network modeled in SWMM and checked against flow monitoring, only 30.84% of pipe sections met the self-cleansing criterion in operation [15]

The difference is in the expected direction, because the schemes assessed here are residential networks dominated by small, lightly loaded laterals, and because SAM evaluates velocity at the depth of the flow each pipe carries rather than at full bore. The consequence of low velocity is also documented: a review of Swedish sewer performance reports earlier evidence that G8% of blockages occurred in sewers running below self-cleansing velocity [50]. The literature on partial-flow design reaches the same conclusion from the other direction, that full-bore checks overstate self-cleansing in lightly loaded pipes [51][52][53].

For electricity, no occupation-staged study of housing schemes was found, but three strands of evidence bear on the 40% limit. The mechanism, individual transformers overloaded while aggregate capacity is ample, is the one that probabilistic hosting-capacity studies describe at feeder level, where local voltage and loading constraints rather than total capacity set the limit [14]. The 80% loading criterion is the permissible normal loading in Pakistan's transmission planning [30], and 48.8% of the 500/220 kV transformers were reported above it in 2020 [54]; the same fraction is used in large-scale monitoring of distribution transformers, where heavy overload is defined at 80% of capacity and predicted, among other factors, from temperature-driven cooling and heating demand [35]And transformer burn-outs in Lahore concentrate in the summer peak [45] None of these tests the 40% figure itself, but together they indicate that a design without margin at the level of the individual transformer is the normal route to failure in this setting rather than an artifact of the model.

Compliance and Performance:

All four designs were prepared to pass the approvals the LDA Rules require, yet every scheme has either a boundary below full occupation or, at Al-Kabir, a figure in the designer's own statement beyond its stated limit. This does not mean that the approvals were improperly given. It means that each failure arises from a quantity that a conformity check does not examine. A transformer schedules whose total capacity comfortably exceeds the scheme's demand passes an aggregate check, while individual transformers are overloaded from half occupation. A road hierarchy that meets the minimum widths passes a dimensional check, while the routing of outbound traffic places a gate's demand on a narrow connector. A sewer that self-cleans when running full passes, a full-bore check, while the flows it actually carries never reach that velocity. A storm allowance expressed as a percentage passes a check that an allowance has been made, while saying nothing about the rainfall it can carry.

This is the strongest argument for adding performance assessment to approval. A conformity check confirms that the prescribed inputs have been used; it cannot show whether those inputs produce the required outcome. Both kinds of check are legitimate, and SAM is not a substitute for engineering review, but the risk lies in the gap between them, and under the present Rules no agency is responsible for examining it. The integration of subsystems mattered in practice as well as in principle. In the three combined systems the sewerage and drainage networks are physically the same pipes, so the sewerage result depends on how storm water is represented, and the drainage result carries the sanitary flow. A storm-separation proposal could not be accepted as a sewerage improvement without re-evaluating drainage, a dependency that separate approvals by separate agencies would miss.

Implications for Scheme Design and the LDA Rules:

Three of the recurring findings pass three tests: they appear in more than one scheme, they are visible in the designers' own numbers, and they point to a specific clause of the Rules.

Each is developed below as a design practice paired with a change to the approval submission that would enforce it. Figure 7 shows the evidence, Table 11 summarizes the proposals and Table 12 ranks them.

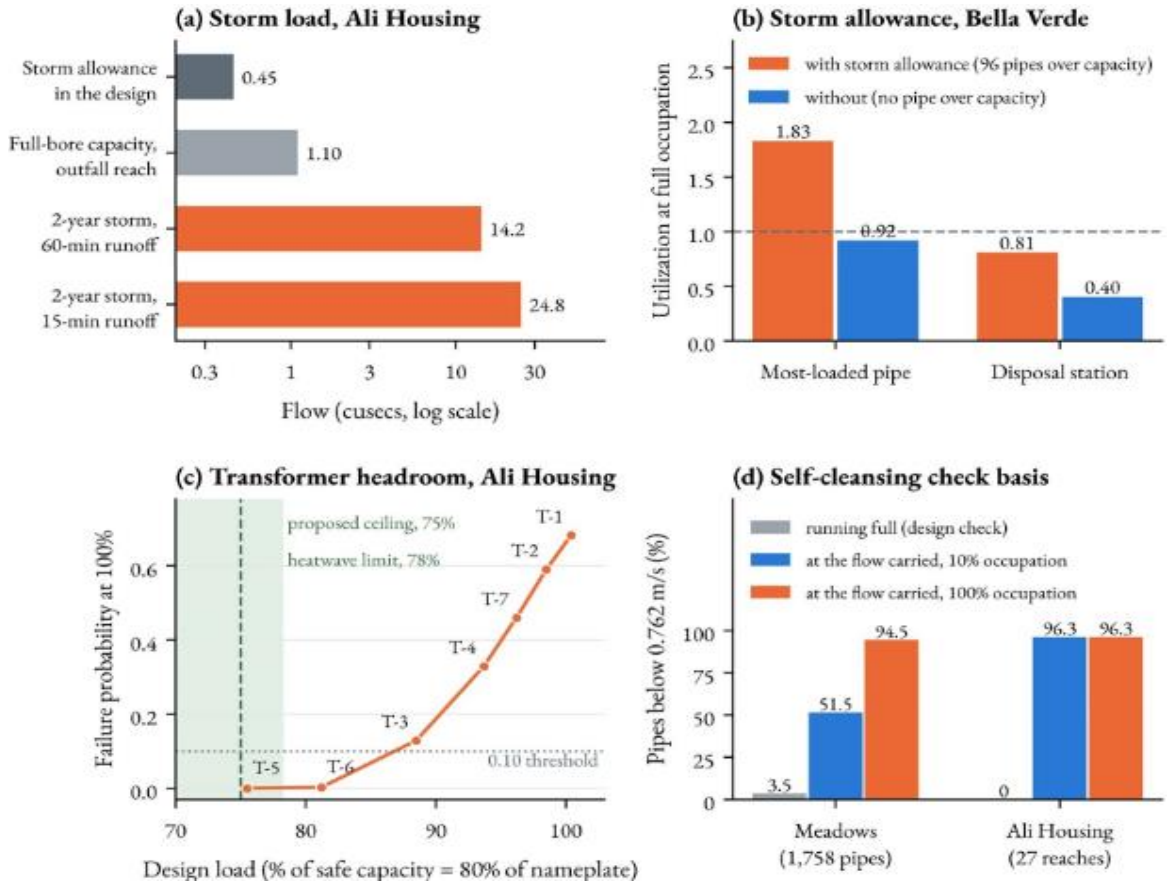

Figure 7. Evidence for the three changes: (a) storm load at Ali Housing, comparing the design allowance with the 2-year storm runoff and the outfall capacity; (b) Bella Verde sewers at full occupation with and without the storm allowance; (c) failure probability of each Ali Housing transformer at full occupation against its design load, with the proposed 75% starting ceiling (dashed) and the range of design loads that remain within safe capacity in the heatwave case (shaded); T-5 serves fixed non-residential loads; (d) share of pipes below 0.7G2 m/s when checked running full, from the designers' own diameters, slopes and roughness values, and at the flows carried.

Keep Storm water out of Sewers and Size Storm Flow from Rainfall:

The storm allowance decides more of the sewerage results than any other input. Where it is set equal to the peak sewage flow, it doubles the design flow of every pipe; at Bella Verde that alone takes almost a hundred pipes beyond capacity, and without it the network carries full occupation. At Ali Housing the opposite happens: the allowance is a small fraction of what a 2-year storm would actually deliver to its combined sewers, by a factor of more than thirty, and the network fails in light rain. At Meadows an allowance was carried in a network the same report declares to be separate. A percentage of sewage flow therefore either fills sanitary pipes with water that should not be in them or understates the storm load of a genuinely combined system by more than an order of magnitude. It cannot do both jobs, because it does not change with catchment area, imperviousness or rainfall.

The allowance persists because it is simple to state and simple to check, not because it describes a storm. The remedy is therefore to make the rainfall calculation equally simple to check. In design terms, sanitary sewers should be sized for sewage and infiltration only, roof

and yard drainage should go to a separate storm network sized by the Rational Method for each catchment and discharging to a positive outfall, and the rainwater harvesting and recharge now required by Rule 12(1)(d) should be treated as additional to that outfall rather than as a substitute for it. Inflow to separate sewers is a well-recognized problem in its own right, and methods now exist to detect it from flow records even where data are scarce [55][56], so separation should also be inspected under the existing provisions for testing works. Where a combined system is unavoidable, the storm component of every pipe and of the downstream station should be computed from rainfall over its contributing catchment.

The corresponding rule change concerns Rules 12(1)(b) and 12(5)(a) [2]The submission should state, for every sewer designed to receive stormwater, its contributing catchment, runoff coefficient, time of concentration, design intensity and the storm flow derived from them, and an allowance expressed only as a percentage of sewage flow should not be accepted as the storm design flow.

Size Each Transformer for Its Own Load, with Headroom:

Both electrical designs reach their boundary at 40% occupation, and in neither is the scheme short of capacity overall. At Bella Verde the installed capacity is several times the residential demand, yet individual transformers carrying the largest loads relative to their rating fail from half occupation. At Ali Housing the consultant's own sheet leaves almost no headroom, and Figure 7c shows how quickly the risk rises as design loading approaches the limit. A loading limit is a planning margin, not a buffer against the variation in demand and capacity that real networks experience; a transformer designed to sit at its limit on an average peak will exceed it on a hot one. Two of the four packages contain no electrical design at all, which, in a city where distribution assets are already stretched [37][43][44], is the most consequential gap in the record.

The proposed design practice is to allocate plots to transformers so that each transformer's diversified load at full occupation, calculated from the NEPRA housing-society schedule, is no more than about 75% of its safe capacity, or about G0% of nameplate at the 80% loading limit. This is a conditional starting point rather than a proven safe limit. It follows from the uncertainty bounds used here: below roughly this loading a transformer cannot exceed its safe limit under the sampled variation in demand and capacity, and remains within it in the heatwave case. The Ali Housing transformers are consistent with this gradient, although the one below the ceiling serves fixed non-residential loads and is not a matched residential case. Where the target cannot be met with standard ratings, more and smaller transformers placed at load centers, with plinths reserved for later units, are preferable to fewer units loaded to the limit, and they also slow the loss of transformer life that sustained loading at high ambient temperature causes [36]

The corresponding rule change concerns Rule 14, which requires the electrification design to be approved by the distribution licensee, and Rule 11, which lists the documents submitted with the service designs [2]The submission should include a loading schedule for each transformer listing the plots it serves, their diversified load at full occupation and the resulting loading against rating, within a stated margin below the licensee's limit; a total of installed capacity should not be accepted on its own, and the approved electrification design should appear in the Rule 11 list.

Design Sewers to Self-Clean at the Flows They Actually Carry:

Low velocity is the only condition found in every sewer network, and it is found almost everywhere in them. The designs nevertheless pass, or almost pass, their own velocity checks, because those checks are made with the pipe running full, a condition the small laterals of a residential scheme almost never reach. At the depths at which sewage actually flows, most pipes in every network that could be counted fall below the velocity their own design reports require, and SAM's counts if anything understate the problem, because they are taken at design flow,

which includes the peak factor and the storm allowance.

This is a maintenance liability that is invisible at approval and passes from the developer to the residents and the utility that inherit the network. It is also worst early in a scheme's life, when laterals carry the least flow and a maintenance regime is least likely to be in place. Research has long held that self-cleansing should be judged at the flows and depths a sewer actually carries rather than at full bore[51][52][53], and manuals of practice relate the criterion to design flow [57]

The design practice is to check velocity, or boundary shear stress, at the depth of the peak dry-weather flow at full occupation and at the first stage of occupation, and where a reach cannot meet the criterion, to steepen the head of the run, use the smallest practical diameter there, provide flushing at dead ends and declare a jetting schedule. Steeper slopes deepen the downstream network, so the check is most useful before the profile is fixed.The corresponding rule change concerns Rules 12(1)(b) and 12(5)(a) [2]: the hydraulic statement should report partial-depth velocities for each reach and the maintenance provisions for those below the criterion, and a full-bore velocity alone should not be accepted.

Table 11. Recommended design practices and rule changes.

Change	Rule clause	Proposed submission requirement	Evidence from this study	Chec at approval
Keep stormwater out of sewers; size storm flow from rainfall	12(1)(b); 12(5)(a)	Catchment area, runoff coefficient, time of concentration, design intensity and storm flow for every sewer receiving storm water; percentage allowance not accepted	Bella Verde: allowance alone fails 9G pipes; Ali Housing: allowance 1/32 to 1/55 of 2-year runoff; Meadows: allowance in a declared separate system	Storm flow recomputed from rainfall for each pipe and terminal
Size each transformer for its own load with headroom	14; 11	Per-transformer schedule of plots served, diversified load under the NEPRA schedule, and loading against rating within a stated margin; electrical design in the Rule11 list	Bella Verde: 57 overloaded despite 131,950 kVA installed; Ali Housing: 75.5% to 100.4% of safe capacity, T-1 beyond its limit; two packages without electrical design	Each transformer's load checked against rating and margin
Self-cleansing at the flows carried	12(1)(b);12(5)(a)	Velocity at peak dry-weather depth at full and first-stage occupation; reaches below criterion with flushing and maintenance provisions	82% to 9G% of pipes below criterion at full occupation in three networks; at full bore every Ali Housing reach and 9G.5% of Meadows conduits meet it	Partial-depth velocity recomputed for each reach

Table 12. Prioritization of the recommended changes by effectiveness, cost, feasibility and implementation route.

Priority	Change	Cost to the developer	Expected effectiveness	Feasibility at approval	Implementation route
1	Storm flow from rainfall; stormwater kept out of sanitary	Calculation negligible; separate storm drains are the largest capital item, least costly when built with the roads	Highest: causes the Bella Verde sewerage boundary and the Ali Housing failures in light rain	High for the calculation; requires an outfall of stated capacity	Agency condition under Rule 12(1)(b) at once; storm schedule added to Rule 12(5)(a) by notification

	sewers				
2	Per-transformer loading schedule with headroom	Low: more or smaller transformers and reserved plinths	High: sets the 40% limit in both schemes with transformer data	High: the licensee already approves the design	Licensee condition under Rules 14(b) and 25 at once; schedule and approved design added to the Rule 11 list
3	Self-cleansing check at the flows carried	Low: steeper heads of runs and flushing points; some deeper excavation	Moderate: serviceability and long-term capacity in every network	High: the designer already computes the flows	Agency condition under Rule 12(1)(b); partial-depth velocities in the Rule 12(5)(a) statement
4	Stated receiving capacities and percolation tests	Low: a statement from the receiving agency and one test per recharge site	Enabling: completes results that are now not assessable	High	Percolation tests in the Rule 11(d) soil test report; outfall and feeder capacity in the Rule 25 referral
5	Network schedules in machine-readable form	Very low: the tables already exist in design software	Enabling: allows the checks above to be automated	High	Format specified for the soft copies already required by Rule 25(e)

Priority and Implementation:

Table 12 ranks the three changes, together with two supporting measures, by their expected effectiveness, cost to the developer and feasibility at approval. Rainfall-based storm design ranks first because it addresses the most serious consequence, sewage and stormwater on streets in light rain, and caused the only sewerage boundary found; its calculation costs almost nothing, although the separate storm drains it may require are the largest capital item and are cheapest when built with the roads.

Per-transformer schedules rank second: they address the lowest boundary outside drainage at little cost, through an approval the licensee already gives. Partial-depth velocity checks rank third, because they protect serviceability and long-term capacity rather than preventing an immediate failure. The supporting measures, stated receiving capacities with percolation tests and machine-readable schedules, cost least and make the other checks possible. The amendments can be applied by two routes. In the short term no amendment is needed: Rule 12(1)(b) already requires designs to follow the guidelines of the approving agency, Rule 14(b) requires the licensee's approval of the electrification design, and Rule 25 gives each agency twenty days to raise objections to a submitted design [2]

The agencies can therefore require the storm schedule, the transformer schedule and the partial-depth velocities as conditions of their own approval at once. In the longer term the requirements should be written into Rules 11 and 12(5) by notification of the Housing, Urban Development and Public Health Engineering Department, the route by which the Rules were amended in 2024 and 202G [2]so that they apply uniformly to every scheme and agency. The soft copies of approved designs that Rule 25(e) already requires provide the vehicle for machine-readable schedules, and the soil test report required by Rule 11(d) the vehicle for percolation tests at recharge sites.

None of these changes requires an approving agency to adopt SAM; any competent hydraulic or load-flow check would apply them, and each asks only for information the designer must calculate anyway. What SAM adds is the ability to show, before approval, where a design that satisfies the present requirements will fail as the scheme fills. The occupation-dependent form of the results also suggests a use that a pass or fail cannot support: a supported occupation of 40% does not mean a scheme should be refused, but that capacity serving the first plots occupied would need augmenting before occupation passes that point. Attaching such a condition to an approval is a proposed application that would need further validation, including of how sensitive each boundary is to the order of occupation.

Real-World Implications:

For the people who buy plots, the boundaries in this paper describe when service begins to degrade. Residents who move in early experience the scheme as adequate; the failures arrive as it fills, as summer outages when transformers overload, as blockages in slow-running sewers, and as standing water in streets after ordinary rain. They fall on households that had no way of knowing the scheme's limits when they bought. There is a case for disclosing a scheme's supported occupation to buyers, in the same way that buildings in many countries carry an energy rating, so that the limits are known before the money is spent rather than discovered afterwards.

For developers, the economics favor acting at design. Reserving space for an extra transformer, upsizing a sub-main or steepening the head of a lateral costs little when the roads are unbuilt; the same changes after occupation mean excavation, outages and disruption to residents. For the utilities the stakes are longer-lived. Rule 12(4) allows the sewerage network to be taken over by the operating agency once it is connected to a public trunk sewer [2]and the electrical network is ordinarily operated by the distribution company once it is energized, so design weaknesses become public liabilities that outlast the developer's involvement. With distribution companies already financially stretched, and part of their revenue at risk as consumers export rooftop solar [58]the money available to remedy inherited weaknesses is unlikely to grow.

For the regulator, the practical constraint is review capacity. A large scheme's package runs to thousands of assets, delivered mostly as drawings and tables in PDF form, and no reviewer can check every pipe and transformer by hand. Two modest steps would help whether or not SAM itself is adopted: requiring network schedules in machine-readable form, so that the checks proposed above can be automated, and using a model to direct reviewers to the small number of assets that govern each result.

Validity Today and in the Future:

SAM's results are valid for present designs because the model represents the conventions those designs use: pipe networks sized for a peak flow, transformers loaded at an evening peak, and morning traffic carried by cars and motorcycles. The results are also conditional on present rainfall statistics, patterns of demand and technology. Each of these is changing, and it is therefore necessary to ask which conclusions will survive the change.

Rainfall is the clearest case. Heavy precipitation has become more frequent and more intense over most land regions and is projected to intensify further with warming [59]Climate change probably intensified the extreme monsoon rainfall behind Pakistan's 2022 floods, even if its share could not be quantified precisely [60]and downscaled projections for five Punjab cities, Lahore among them, suggest that 100-year rainfall intensities could rise by roughly 30–55% over this century under high emissions [61]The intensity–duration–frequency profile used here dates from 2010 and assumes that past rainfall statistics describe the future, an assumption the literature on updating such curves increasingly rejects [62]

The drainage boundaries are therefore more likely to be optimistic than pessimistic over the networks' design lives. One feature of the method mitigates this. Because SAM reports supported occupation as a function of rainfall intensity rather than against a single design storm, a revised design intensity can be read directly from the existing grids: when the design storm changes, the results do not expire; only the line marking the design storm moves. This is the strongest argument for the rainfall-sweep format.

A second change is the move toward storing and reusing storm water rather than conveying it away as fast as possible. The sponge-city approach, developed most extensively in China, adds green infrastructure that absorbs, stores, cleans and reuses rainwater to conventional pipe drainage, so that a city holds rain where it falls [63][64]Lahore has moved in this direction: the city now has a network of underground storm water tanks at its worst waterlogging points [65]the first of which stores rainwater for park irrigation and groundwater recharge and pumps its overflow to a drain once full [66]and Rules 12(1)(d) and 12(1)(e) now require new schemes to provide rainwater harvesting and groundwater recharge and to use recycled or rain water for irrigating their parks [2]It has been suggested that such storage could make drainage problems disappear altogether.

The evidence does not support that expectation. Sponge measures perform well for frequent storms and in reducing annual runoff, but their benefit falls away for short, intense storms beyond the most frequent events [67]Storage helps most when it is empty, and a monsoon brings storms on successive days when there is little demand for irrigation, so a tank filled by one storm may still be full when the next arrives; permeable surfaces also clog unless they are maintained. Meadows is itself a small example. Its storm network is a sponge design, delivering runoff to harvesting tanks and recharge wells rather than to a drain, and SAM finds those outlets to be the first point of failure in every cell of the sweep.

Even the acceptance rate credited to them would fill the designed harvesting volume within an hour, after which the scheme depends entirely on how fast the wells drain into the ground, a rate no document measures. Storage and reuse therefore change the drainage problem rather than remove it, and they make the questions SAM asks more important, not less: how much is stored, how fast it empties and what happens when it is exceeded. They also make the model's present method less adequate. A steady peak calculation ignores storage, so for a scheme with extensive

storage it would overstate the peak in a moderate storm while saying nothing about a sequence of storms. Representing such schemes properly would need a storage model level with measured infiltration and emptying rates, run continuously through storm sequences rather than at a single peak. The modular structure of SAM allows this to be added without changing the rest of the framework.

The electricity results face a different kind of change. Pakistan has installed distributed solar on a scale few expected, with an estimated 38 GW in place by mid-2025 and solar on almost one household in five, and this has shifted the national peak into the evening, when solar cannot supply it, while residential grid demand has continued to rise [68].

This has two consequences for the findings. Because the transformer checks in this study are made at the evening peak, rooftop solar does not relieve them, and the boundaries remain as relevant as before. But solar introduces a mechanism the current runs do not represent: export at midday, which can push power backwards through a transformer and raise local voltage, and which recent regulations now limit through a transformer hosting threshold [58]SAM's radial voltage level could evaluate this if solar injections were added as inputs. Household batteries, which the move from net metering to net billing may encourage [68]could in time flatten the evening peak and relieve the boundaries reported here. The electricity results are therefore the most likely to change with technology, in either direction, and they should be re-run as the pattern of household demand settles.

Two slower changes affect every subsystem. Demand per household is rising, most visibly for cooling [37]which the heatwave case only partly anticipates. And plots are increasingly subdivided or built with additional floors, so a dwelling may house more people, more vehicles and more connected load than the design assumed. SAM measures occupation in dwellings, with population, vehicle ownership and demand per dwelling as inputs; if those inputs rise, the same occupation fraction carries more load, and every boundary in this paper would move downward. The same is true of traffic, where car ownership and travel habits are the inputs most likely to drift. The remedy is not a different model but current inputs, and the growing availability of smart-meter and sensor data offers a way to replace assumed loads with observed ones.

The particular numbers in this paper will therefore age, but the method that produced them need not. The conclusions most robust to the future are those about design conventions: a storm allowance that ignores rainfall becomes more inadequate as rainfall intensifies; a transformer loaded to its limit has even less room as demand grows; and a sewer that self-cleans only when running full stays slow however the city changes around it.

Limitations:

The model-specific limitations are as follows. First, no result has been compared with observed operation. Second, every run except Al-Kabir traffic is labeled exploratory or carries no authorization label, and several results rest on declared assumptions: the recharge rate and pipe dimensions of the Meadows storm network, its traffic topology and gate positions, the gullies, conductor properties and supply capacity at Ali Housing, and the placement of non-residential load where it is excluded.

Third, the hydraulic models are steady-state: the drainage sweep applies uniform intensities and accumulates peaks without attenuation or storage, and the steady grade-line solution under-represents backwater in sewers loaded beyond their open-channel maximum, so the model identifies the onset of failure rather than flood depth or duration. Fourth, the depth of the probabilistic analysis varies between runs, from 3,000 sampled replicates per state to design-basis evaluations without sampled uncertainty, and the Meadows sewerage result rests on one replicate per state.

Fifth, each scheme was evaluated under one seeded occupation order, and a boundary can depend on when the plots served by one asset are occupied. Sixth, traffic is limited to the residential outbound morning peak without the junctions beyond the gates, its demand rates are declared rather than calibrated, water supply is not modeled, the subsystems were run separately so that no joint failure probability is reported, and four schemes in one city indicate where to look rather than how common a problem is. Seventh, in the sewerage output, failures at manholes are listed a second time among the link records, which inflates the number of comparisons in the Bonferroni adjustment of per-asset intervals; subsystem decisions use the unadjusted mechanism-group interval and are unaffected, no per-asset sewerage interval is relied on here, and the velocity counts are taken from the link hydraulic results.

Finally, every input describes present conditions, a stationary rainfall record, present demand and present technology, whose likely evolution is discussed above. Other limitations come from the world the model describes rather than from the model itself. SAM assesses a scheme as approved, but schemes are built, maintained and used in ways the drawings do not record. Networks are altered during construction, sewers silt up and drains are blocked by solid waste, households connect roof drains to sewers and add load that no schedule anticipated, and a distribution company facing an overloaded transformer may shed load rather than let it fail, so that the failure appears as outages rather than as damage. Most of these would move a boundary downward.

Nor does the model see the institutions around a scheme: whether the operating agency takes over the networks, whether their maintenance is funded, and whether the trunk sewer, drain or grid feeder to which the scheme connects has capacity to spare. Better modeling cannot remove these limitations. They are the reason a supported occupation should be read as the performance of the design as approved, which the scheme as built and operated may not reach, and the reason approval-stage assessment needs to be followed by inspection of what was actually built.

Recommendations and Future Work:

The approving agencies should adopt the changes of Tables 11 and 12 in order of priority: storm flow derived from rainfall for every sewer receiving stormwater, a loading schedule with headroom for every transformer, and self-cleansing checks at the flows sewers carry, supported by stated receiving capacities, percolation tests at recharge sites and network schedules in machine-readable form. These can be required at once as conditions of agency approval and later written into Rules 11 and 12(5). Once validated against observed operation, supported occupation could also be tested as a staged approval condition, with augmentation verified before the next stage is released.

Future work should close the validation gap identified above: loading records for the named Bella Verde transformers, peak-hour counts on its narrow connectors, rainfall and surcharge observations at Ali Housing, and percolation tests at the Meadows wells. The model should be extended to joint scenarios drawn coherently across subsystems, to multiple occupation orders, to dynamic hydraulic routing where flood depth matters, and to water supply, and it should be applied to a larger and randomly drawn sample of schemes so that the prevalence of the problems found here can be estimated.

Because the inputs most likely to change lie outside the schemes, they should be kept current rather than fixed at approval. The intensity–duration–frequency profile should be replaced with climate-adjusted intensities as projections for Lahore mature, and the design-storm line on the existing drainage grids re-read accordingly. Rainwater harvesting, recharge and other storage should be represented by a storage level with measured infiltration and emptying rates, run continuously through monsoon storm sequences. The electricity model should take rooftop solar injections, household batteries and time-of-day loads as inputs, so that midday reverse flow and voltage rise are assessed alongside the evening peak. Persons, vehicles

and connected load per dwelling should be updated as plots are subdivided and built higher, and smart-meter and sensor records offer the most direct way to replace assumed inputs with observed ones.

Conclusion:

SAM converts an approval package into an occupation-staged, asset-level assessment of traffic, sewerage, drainage and electricity under uncertainty (O1), and it does so from the package's own evidence, with every missing input declared or reported as unresolved. Applied to four approved schemes in Lahore, it assessed twelve of sixteen scheme–subsystem pairs and found six boundaries below full occupation, each attributed to a named asset (O2): electricity at 40% in both schemes with transformer data, sewerage at 50% and traffic at G0% at the largest scheme, and drainage networks that support at most 20% occupation under the 2-year storm at Meadows and fail in less than 4 mm/h of rain at Ali Housing.

The findings differ in their standing (O3). Verified against the packages themselves are the reconstructions, which reproduced the designers' flows and loads to within 2% where a numerical check was possible, and weaknesses visible in the designers' own figures: a transformer at 100.4% of its safe capacity, an outfall pipe beyond its stated capacity once non-residential load is included, a storm allowance 32 to 55 times below the runoff of the declared design storm, and velocities checked only at full bore. The supported occupations and failure rainfalls remain model predictions for the designs as drawn until they are compared with observed operation; they are robust to the alternatives tested, except that the Bella Verde traffic boundary depends on the threshold chosen, and a finer occupation step would refine at most one or two of them by five percentage points.

The method applies to any scheme whose package contains its network schedules, and its recurring findings, storm allowances unrelated to rainfall, transformers judged in aggregate or loaded to the limit, and sewers that self-clean only when running full, arise from conventions common to the profession, so they are likely to recur in other schemes approved on the same basis. Field validation at the named assets is the necessary next step. The design-basis findings nonetheless support three changes to approval submissions now (O4): rainfall-based storm design, per-transformer loading schedules with headroom, and self-cleansing checks at the flows sewers actually carry. Because the results are reported against occupation and rainfall intensity rather than a single design storm, they can be re-read as standards change; the particular boundaries will move as rainfall intensifies, rooftop solar spreads and dwellings house more people, but the design conventions they expose will matter more, not less.

Publication and Submission Declaration:

The authors declare that this manuscript has not been published previously and is not under consideration for publication elsewhere, and that all authors have approved its submission.

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Data Availability:

The run reports and the derived data underlying the figures and tables are available from the

corresponding author on reasonable request. The scheme design packages are the property of their sponsors and consultants and can be shared only with their permission.

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