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Rainwater Harvesting Potential of Residential Roofs in Selected Tropical Cities: A Secondary Data Assessment

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Abstract

Residential rooftop rainwater harvesting is frequently assessed from annual rainfall, although water arrives unevenly and must meet a defined demand. This study compares Singapore, Mumbai, and Chennai using published 1981-2010 monthly rainfall normals and literature released before 1 May 2023. Original calculations distinguish effective roof inflow, a monthly pooling benchmark without intermonth carryover, and an idealized seasonal carryover requirement. A standardized 100-square-metre connected roof, collection fraction of 0.80, four occupants, and illustrative target of 50 litres per person per day produce annual inflows of 173.27, 189.86, and 110.63 cubic metres, respectively, against annual demand of 73 cubic metres. All three are annually adequate, but monthly pooling matches 100.0 percent of demand in Singapore, 44.5 percent in Mumbai, and 65.4 percent in Chennai. Ideal seasonal carryover quantities are zero, 40.51, and 25.22 cubic metres; these are mean-month diagnostics, not recommended tank capacities. Rescaling each rainfall profile to 2,000 mm annually preserves the contrast, demonstrating the importance of seasonal distribution independently of annual amount. Sensitivity analysis across 81 roof, efficiency, and demand combinations shows that additional catchment has limited effect on dry-season matching where rainfall is nearly absent. At the higher demand scenario, Chennai becomes annually insufficient, which storage alone cannot remedy. The findings support differentiated service objectives and evaluation of roof area per resident. Daily rainfall sequences, building inventories, usable-water quality, local costs, and operating responsibilities remain necessary before claiming dependable household supply or citywide benefit. The assessment provides a reproducible screening basis while defining the limits of inference from monthly secondary data.

Keywords: rooftop rainwater harvesting; tropical cities; secondary data; rainfall seasonality; residential water demand; seasonal storage; water security

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1 Introduction

Residential roofs offer a measurable surface on which rainfall can be intercepted before it enters urban drainage systems. Their attraction is straightforward: a building already occupies the land, its roof concentrates runoff, and some household activities can use water of a quality different from that required for drinking. Yet a roof that receives substantial annual rainfall does not necessarily provide water when residents need it. Losses occur during collection, tanks overflow, dry periods exhaust storage, and maintenance affects both quantity and quality. A useful assessment must therefore connect rainfall to a defined service rather than equate precipitation with water security. This article treats rooftop harvesting as a potentially valuable supplementary supply whose contribution depends on the interaction of climate, roof access, demand, storage, and operation.

The international literature establishes a substantial basis for investigating this contribution. Campisano et al. (2017) reviewed the technical, practical, and social dimensions of urban rainwater harvesting and identified considerable variation in implementation. Such breadth supports examining harvesting as part of urban water management, but it also makes universal claims about performance difficult to defend. Systems described under the same name can differ in catchment size, intended use, storage capacity, treatment, and responsibility for upkeep. Their reported benefits consequently cannot be transferred by copying a percentage from one city to another. Comparative research becomes more informative when it standardizes the physical questions being asked and then makes the remaining contextual differences explicit.

Tropical cities provide a particularly useful setting for this comparison because substantial rainfall and persistent water-service needs can coexist. Nevertheless, the category “tropical” does not identify a single rainfall regime. A relatively even distribution across the year differs operationally from a short monsoon season followed by months with little rain, even when the annual totals are similar. Moreover, rainfall measured at a meteorological station is not identical to runoff collected from every residential roof. The analytical opportunity is therefore to compare published historical reference climates under common assumptions, while resisting the temptation to describe those assumptions as representative households or the stations as complete municipal rainfall inventories.

Singapore, Chennai, and Mumbai are selected to examine this distinction. The comparison uses published 1981-2010 monthly rainfall normals, allowing the reference period to be held constant while contrasting different seasonal distributions. This choice strengthens climatic comparability, although it does not make the three cities equivalent in housing, water tariffs, institutional capacity, or household behavior. Two Indian cities are included because their contrasting rainfall timing contributes more to the research question than an arbitrary requirement to maximize the number of countries. The resulting study is a purposive comparison of climatic opportunity and seasonal constraints, not a statistically representative sample of all tropical urban settlements.

The central problem is the ambiguous meaning of “potential.” An annual roof-volume calculation can describe water that might enter a collection system, whereas a household may be interested in the proportion of toilet demand supplied, the number of days without shortages, or the ability to continue receiving water during a service interruption. These are different outcomes. Hanson and Vogel (2014), for example, investigated explicit storage-reliability-yield relationships using daily data rather than identifying reliability from annual rainfall alone. The present assessment accordingly separates annual input, a monthly pooling benchmark, and an idealized seasonal carryover requirement. None is presented as a measured daily service reliability.

The research asks three connected questions. First, how much effective rooftop inflow is implied by the selected rainfall normals under a transparent range of roof areas and collection efficiencies? Second, how does the distribution of that rainfall change the relation between annual adequacy and month-by-month demand? Third, what implications follow for residential design and urban policy once water quality, building density, and implementation constraints are considered? Secondary data can answer the first question and illuminate the second, but cannot

independently establish local affordability or actual adoption. The third question is therefore addressed through bounded interpretation of the calculations and verified literature, rather than through invented household observations or unsupported economic estimates.

The contribution lies in making these distinctions operational and reproducible. The study applies the same equations and scenario grid to all three reference climates, publishes the monthly inputs, and identifies cases in which storage cannot overcome an annual water deficit. This is an original comparison, although the underlying rainfall records and the principles of reservoir accounting are established knowledge. It is not claimed to be the first investigation of rainwater harvesting in the cities, nor does it substitute for a site design. Its value is a defensible screening framework that shows which claims follow from accessible secondary data and which require additional evidence.

2 Conceptual and empirical foundations

2.1 From roof rainfall to usable supply

The first stage of assessment is a physical accounting problem: rainfall depth multiplied by connected roof area gives a gross volume, which must then be reduced by collection losses. This relationship is simple enough to audit and useful for comparing differently sized buildings. Its apparent simplicity can nevertheless hide errors in the definition of area. Sloping roof surface area, total building floor area, and the horizontal roof projection are not interchangeable. Ndiritu et al. (2017) explicitly used roof projection in their harvesting analysis. The appropriate quantity here is the horizontal area that actually drains to the proposed system; other surfaces cannot be credited merely because they are part of the property.

Collection efficiency also requires a precise interpretation. Runoff depends on material, roughness, slope, wetting, conveyance, and deliberate diversion, so a single coefficient can provide a convenient screening assumption. Measurements by Farreny et al. (2011) demonstrate why roof characteristics matter for both runoff quantity and quality. Those measurements were made in a Mediterranean setting and do not calibrate the roofs of the present cities. Accordingly, this article uses an explicit range of effective collection fractions rather than assigning a supposedly universal coefficient to every residential roof. The coefficient combines losses before useful storage and must not be treated as independent of another unreported first-flush deduction.

Residential demand provides the other half of the accounting problem. A roof may supply a large share of one end use and a small share of total household consumption, even with identical rainfall and storage. Using a standard demand scenario permits comparison, but calling that scenario a measured household average would create false empirical authority. Takagi et al. (2018) showed that household characteristics can materially alter estimates of rainwater availability relative to an average-household approach. The present scenarios are therefore defined by specified occupant numbers and target volumes. Their results indicate how performance changes with demand, while leaving actual local consumption to future measurement.

2.2 The temporal limits of rainfall totals

Storage transfers water across time, making rainfall sequence as important as annual volume when demand continues through dry weather. A tank can be empty during a shortage and full during the next storm; neither state is visible in the annual total. Fewkes and Butler (2000) demonstrated that behavioral-model performance depends on temporal resolution and the relationship between storage and catchment input. Their guidance should not be converted into a universal sizing rule, but it establishes that monthly data are not automatically adequate for small tanks. This study therefore uses mean months to identify seasonal mismatch and deliberately stops short of estimating dependable supply from a specified household tank.

Long-term monthly normals involve a second loss of information because they average across years as well as within months. A mean wet month may combine years of moderate rainfall with years dominated by a few extreme events, while a mean dry month cannot identify the duration of a particular drought. Applying a nonlinear storage calculation to these averaged inputs is not

equivalent to averaging results from observed daily sequences. Zhang et al. (2020) examined the influence of rainfall-series length, temporal scale, and operating algorithm on system assessment. The implication is to regard a climatological calculation as a diagnostic of structure, then use daily observations and an explicit operating rule for design verification.

Evidence from tropical settings reinforces the relevance of this distinction without removing the need for local data. Lo and Koralegedara (2015) examined rainwater harvesting in Colombo under historical and projected climate conditions, illustrating the importance of connecting rainfall change to household supply. Their study concerns a different city and a different modeling purpose, so its outputs cannot be inserted as observations for Singapore, Chennai, or Mumbai. It nevertheless supports treating climate assumptions as part of the model rather than as an invisible background. Historical normals can establish a baseline for comparison, but cannot certify future resilience or eliminate the need to examine dry years.

2.3 Multiple objectives and incompatible denominators

Water-supply savings and stormwater control can arise from the same installation, but their objectives are not identical. Supply benefits depend on water retained and subsequently used, whereas stormwater benefits depend partly on available capacity when a storm arrives. Quinn et al. (2021) developed performance measures for dual-use systems that recognize this event-sensitive behavior. A tank kept full for security may offer little immediate space for runoff, while deliberate drawdown can sacrifice a reserve. The present analysis consequently evaluates neither flood-peak reduction nor emergency reserve reliability. It identifies potential water inputs and seasonal demands that a later, explicitly multipurpose design would need to reconcile.

Harvesting also has distinct meanings across urban water strategies. Direct storage for household use is different from routing roof runoff into a recharge structure, even though both may be described as rainwater harvesting. In Chennai, Srinivasan et al. (2010) assessed urban water-supply options within a broader system that included rainwater harvesting and groundwater processes. That evidence is relevant to integrated planning but does not justify counting every cubic metre directed toward recharge as immediately available household tank water. The present system boundary follows water from a connected residential roof toward direct use. Recharge may complement that system, but requires a separate assessment of infiltration, groundwater behavior, water quality, and recoverability.

3 Materials and methods

3.1 Study design and source eligibility

This research is a comparative secondary-data assessment with deterministic scenario analysis and a focused critical review. Eligible literature and source publications were released before 1 May 2023; subsequent website access was used to retrieve those works, not to incorporate later findings. Official meteorological publications were preferred for rainfall, while scholarly sources were checked against publisher records, institutional repositories, or indexed primary abstracts. This procedure supports traceability, but does not constitute a systematic review with an exhaustive database search or registered screening protocol. The review supplies the concepts necessary to interpret the calculations, rather than a claim to have captured every relevant publication.

Three selection criteria guided the city comparison: location within the geographical tropics, availability of a clearly identified historical monthly rainfall reference, and a seasonal pattern informative for residential collection. A common 1981-2010 normal period was favored over a wider international spread with mismatched baseline periods. These criteria yield Singapore, Chennai, and Mumbai, but they do not control for urban form or institutional setting. City names in the numerical results therefore denote the selected published station reference series. They should not be read as spatial averages over complete metropolitan boundaries or as estimates of the proportion of residents who can install a working system.

Singapore rainfall was transcribed from the 1981-2010 reference row in the Changi climate

table of Meteorological Service Singapore's (2015) annual report. The report also documents changes in the location of the national climate station, so this assessment does not independently certify the homogeneity of the entire reference record. Chennai and Mumbai rainfall was taken from the India Meteorological Department's (2015) climatological normals, with the selected station identities retained. Official station tables provided accessible checks of the monthly values. The comparison uses the published reference series as issued; it does not splice later normals, substitute individual wet years, or infer missing months from neighboring stations.

Table 1. Published monthly rainfall normals for the 1981-2010 reference period (mm)

Month	Singapore	Mumbai Santacruz	Chennai Nungambakkam
Jan	234.6	0.3	25.9
Feb	112.8	0.4	3.4
Mar	170.3	0.0	3.5
Apr	154.8	0.1	14.4
May	171.2	11.3	34.2
Jun	130.7	493.1	55.8
Jul	154.4	840.7	103.8
Aug	148.9	585.2	126.8
Sep	156.5	341.4	147.7
Oct	154.6	89.3	315.6
Nov	258.5	9.9	374.4
Dec	318.6	1.6	177.4
Monthly sum	2,165.9	2,373.3	1,382.9

Sources: Meteorological Service Singapore (2015, p. 9); India Meteorological Department (2015, pp. 185, 511). Chennai rainfall uses 29 contributing years. Mumbai monthly entries sum to 2,373.3 mm; the source prints 2,373.4 mm annually. Calculations use the monthly sum. Singapore is the published Changi reference row.

The monthly values in Table 1 were transcribed without interpolation and summed independently. Chennai is the Nungambakkam station and Mumbai is Santacruz; the sourcebook reports 29 rainfall years for Chennai within the nominal 1981-2010 period. Mumbai's rounded monthly entries sum to 2,373.3 mm, whereas its printed annual normal is 2,373.4 mm. The calculations consistently use the monthly sum, avoiding a small internal discrepancy. These checks establish traceable inputs but do not independently verify instrument performance or record homogenization. No new rainfall observations, household survey, or roof inventory was undertaken, so the resulting household equivalents remain scenarios rather than measured citywide resources.

3.2 Standardized residential scenarios

The principal scenario specifies 100 square metres of connected horizontal roof area, four occupants, an effective collection fraction of 0.80, and a target demand of 50 litres per person per day. Annual target demand is consequently 73 cubic metres in a non-leap year. These values describe an analytical household equivalent rather than the average dwelling in any selected city. In particular, the 50-litre target is neither an official non-potable-use standard nor a claim about observed consumption. It is a transparent

workload against which the climate series can be compared, and the sensitivity analysis shows how conclusions change when that workload changes.

The scenario grid combines roof areas of 50, 100, and 150 square metres, collection fractions of 0.70, 0.80, and 0.90, and target demands of 20, 50, and 100 litres per person per day, holding occupancy at four. This produces 27 combinations per city and 81 in total. The grid explores plausible analytical variation, but its bounds are not statistical confidence intervals and its combinations are not sampled households. No probability is assigned to any scenario. The purpose is to distinguish conclusions that remain stable across specified assumptions from conclusions that depend on a favorable roof-to-demand relationship.

The effective collection fraction is applied once to rainfall multiplied by roof area. It represents water reaching useful storage after aggregate pre-storage losses; it does not separately model each rainfall event, roof wetting, gutter overflow, or first-flush operation. Treating these losses in one fraction simplifies a secondary-data comparison, although actual loss fractions can vary with season and storm size. A future engineering model should replace the aggregate parameter with locally appropriate components where data permit. In the current assessment, subtracting an additional undocumented diversion would double-count losses and create an untraceable difference between cities.

3.3 Quantities and equations

For month m, effective inflow is I_m = C A P_m / 1000, where I_m is in cubic metres, C is the effective collection fraction, A is connected horizontal roof area in square metres, and P_m is rainfall in millimetres. Demand is D_m = n d h_m / 1000, where n is occupancy, d is the target in litres per person per day, and h_m is the number of days in that month. The conversion follows from one millimetre over one square metre equaling one litre. These equations provide a transparent volume balance, but inflow is not identical to delivered water because storage, treatment, and operation remain unresolved.

Annual effective inflow is V = sum(I_m), and annual target demand is D = sum(D_m). The annual supply-to-demand ratio is R = V / D, while the ideal annual coverage ceiling is U = min(1, R). Keeping the two measures separate prevents a ratio above one from being misreported as more than 100 percent of demand supplied. This ceiling assumes that water can be reassigned perfectly across the year without additional losses. It is useful for identifying a necessary annual condition for complete supply, but it is not sufficient evidence that a practical tank can provide that supply.

To expose seasonal mismatch, the monthly pooling benchmark is M = sum[min(I_m, D_m)] / D. It credits each month with no more than that month’s demand, permits perfect pooling within the month, and carries no surplus into another month. This optimistic treatment of within-month timing means M is not a prediction for a small tank or a measurement of reliability. Equally, M is not an upper bound on every physically possible system, because actual intermonth storage can raise delivery above it. Its restricted interpretation is the share of demand matched by the mean-month volumes before seasonal carryover is allowed.

An idealized seasonal carryover requirement is calculated only when V is at least D. Define each monthly deficit as e_m = D_m - I_m. The carryover quantity B is the larger of zero and the maximum sum of e_m over every contiguous cyclic interval of one to twelve months, including intervals crossing December and January. Enumerating all starting months and interval lengths identifies the largest accumulated seasonal deficit. This calculation is exact for the stated mean-month abstraction with perfect internal pooling and no storage losses, but it does not identify a reliable installed tank capacity. A zero value means no monthly seasonal deficit, not that a real harvesting system needs no tank.

If annual inflow is less than annual demand, complete perpetual supply is reported as infeasible under the stated scenario, rather than assigning a very large tank. Storage can redistribute water that arrives; it cannot generate the missing annual volume. Where B is positive, its physical interpretation is the amount that would need to be transferred across the most demanding sequence of mean months after an appropriate wet-season replenishment. The analysis assumes a repeating reference climate and does not impose an arbitrary

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empty January start. Installation timing and initial filling are important operational questions, but including them here would confuse a seasonal requirement with a one-time commissioning deficit.

The annual roof area required per resident is calculated as a_required = 365 d / (C P_annual). This relation cancels the household occupant count and makes the constraint of shared roofs visible. It identifies the area necessary to supply the selected annual volume under ideal redistribution, but it leaves seasonal storage and quality constraints untouched. The analysis also reports the fraction of annual rainfall in the wettest consecutive three-month period, allowing the period to cross the year boundary. Together these indicators connect the geometry of access with rainfall concentration while avoiding an unsupported estimate of citywide residential demand coverage.

3.4 Verification and interpretation

The calculations use a non-leap calendar, retain unrounded values internally, and round reported volumes and percentages only for presentation. The seasonal-deficit calculation was checked against repeated monthly balances to confirm that the identified buffer supports the ideal mean-month target and that a slightly smaller buffer fails where a positive buffer is required. These checks validate the implementation of the chosen abstraction, not its adequacy for engineering design. No significance tests are applied to the twelve normals, because they are climatological summaries rather than independent household observations. Uncertainty is represented by explicit scenario variation and limitations, not by manufactured sampling precision.

An additional counterfactual assigns every city an annual rainfall total of 2,000 mm while preserving its observed-normal monthly proportions. Each monthly value is multiplied by 2,000 divided by that city's original annual sum, after which the same calculations are repeated. This transformation separates the effect of seasonal distribution from the effect of annual amount. It is neither an observed climate series nor a future rainfall projection, and it cannot reproduce changes in event intensity or dry-spell duration. Its limited purpose is a controlled arithmetic test: whether contrasting seasonal outcomes remain when the annual input volume is made identical.

4 Results

4.1 Annual abundance and seasonal concentration

The annual totals derived from the monthly inputs are 2,165.9 mm for Singapore, 2,373.3 mm for Mumbai, and 1,382.9 mm for Chennai. Under the principal 100-square-metre roof and 0.80 collection scenario, these correspond to effective annual inflows of 173.27, 189.86, and 110.63 cubic metres, respectively. All exceed the selected annual demand of 73 cubic metres. This result establishes annual resource adequacy under the scenario, but not continuous service or economic feasibility. Indeed, an assessment ending at this point would obscure the principal distinction revealed by the monthly balances: the city with the largest annual volume has the weakest no-carryover monthly match to the selected demand.

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Table 2. Baseline roof and demand assessment

Indicator	Singapore	Mumbai	Chennai
Effective annual inflow (m³)	173.27	189.86	110.63
Annual target demand (m³)	73.00	73.00	73.00
Annual inflow / demand	2.37	2.60	1.52
Monthly pooling volume (m³)	73.00	32.49	47.78
Monthly pooling fraction (%)	100.0	44.5	65.4
Mean months meeting target	12	5	6
Ideal seasonal carryover (m³)	0.00	40.51	25.22
Annual area threshold (m²/person)	10.53	9.61	16.50
Wettest three months (% of rain)	37.5	80.9	62.7

Original calculations from Table 1. Assumptions: 100 m² connected roof, effective collection fraction 0.80, four occupants, 50 L/person/day. Pooling assumes perfect within-month matching and no intermonth carryover. Seasonal quantities are not installed tank recommendations; zero does not imply no physical storage.

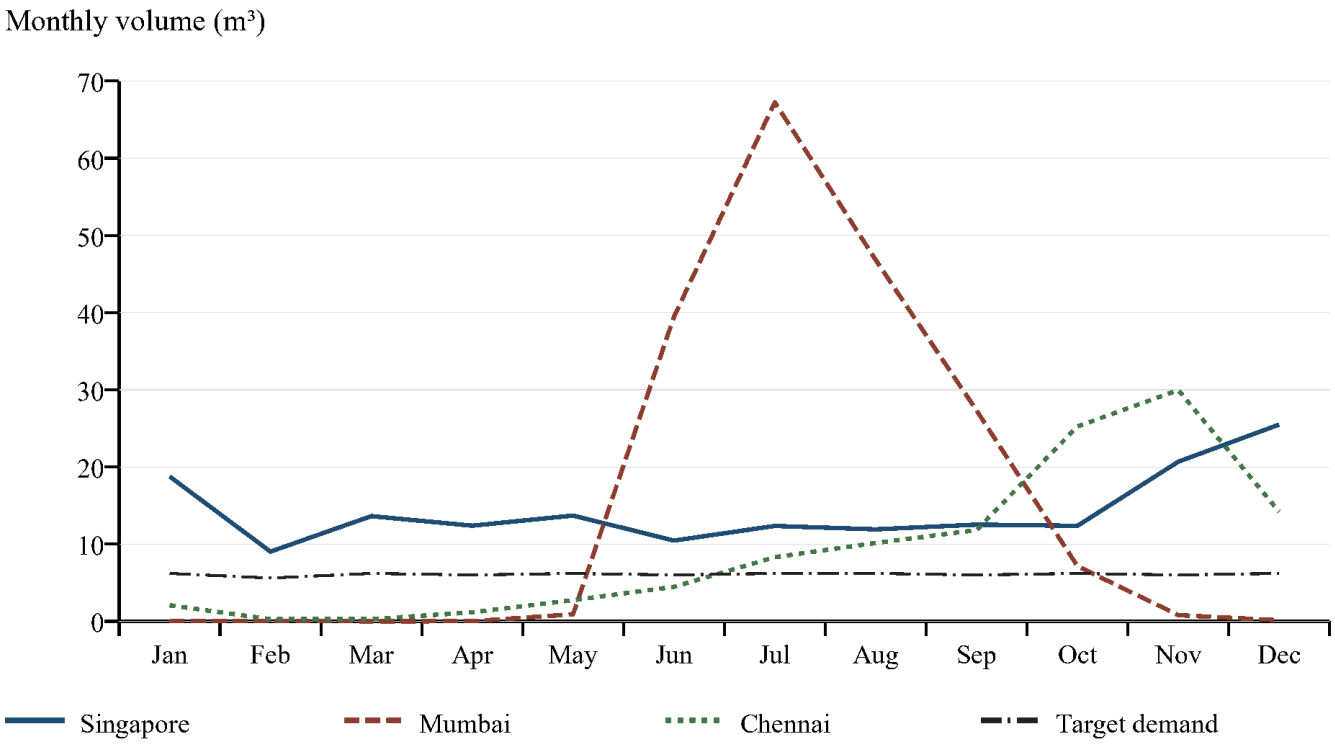


Figure 1. Monthly effective inflow and baseline target demand

Original calculations from Table 1 using the baseline assumptions. Lines connect mean-month values and do not represent daily rainfall sequences.

Rainfall concentration explains why the annual ranking is incomplete. The wettest consecutive three months account for 37.5 percent of Singapore's annual total, 80.9 percent of Mumbai's, and 62.7 percent of Chennai's. The relevant periods are November-January, June-August, and October-December, respectively. These percentages describe the selected normal profiles, not the distribution of every individual year. Nevertheless, they show

that equal annual roof areas confront different scheduling problems. Singapore’s relatively distributed input can repeatedly replenish storage, whereas Mumbai’s concentrated monsoon input creates a much larger requirement to retain water for later months if full-year service is the objective.

Mumbai’s annual effective inflow is approximately 9.6 percent greater than Singapore’s under identical roof and efficiency assumptions. Yet the monthly pooling benchmark is only 44.5 percent in Mumbai, compared with 100 percent in Singapore. Chennai, with substantially less annual rain than Mumbai, reaches 65.4 percent on this benchmark. These are not measured household supply fractions and should not be described as installed-system efficiencies. Their significance is comparative: prioritizing cities by annual rainfall alone can reverse the ordering suggested by a clearly specified seasonal-demand metric. A planning screen must therefore state which dimension of potential it ranks.

4.2 Monthly deficits and seasonal carryover

For Singapore, every mean month has sufficient effective inflow to match the baseline demand. The monthly pooling volume equals the annual target of 73 cubic metres, and the idealized seasonal carryover requirement is zero. Interpreting this as a zero-storage design would be a serious error because the calculation permits perfect matching within each month. Rain may arrive on only part of a month, and a roof cannot supply a fixture during rainless intervals without retained water or another source. The result identifies an absence of seasonal deficit in the mean-month balance; daily storage and backup requirements remain separate questions.

For Mumbai, adequate mean-month inflow occurs from June through October, while November through May form a continuous deficit season. Only 32.49 cubic metres of the 73-cubic-metre target are matched without intermonth carryover, leaving a seasonal mismatch of 40.51 cubic metres. The idealized buffer is also 40.51 cubic metres because the maximum cumulative deficit spans that uninterrupted dry-season block. This equality is specific to the input sequence and demand, rather than a universal identity between total monthly shortfall and storage. The result directs attention toward the long interval requiring transferred water, not simply toward the intensity of monsoon collection.

Chennai’s baseline deficit extends from January through June. The monthly pooling calculation matches 47.78 cubic metres, leaving 25.22 cubic metres to be transferred from wetter months if the entire mean-year target is to be met. Annual inflow remains sufficient, so this is a temporal constraint within the idealized balance rather than an annual resource shortage. Nevertheless, 25.22 cubic metres is a substantial carryover quantity for the specified household equivalent. The calculation does not establish that such storage is structurally, spatially, or financially feasible. It instead clarifies why a system intended mainly for wet-season substitution faces a different design problem from one intended to supply a constant demand throughout the year.

Expressed as days of baseline demand, the Mumbai and Chennai seasonal quantities equal approximately 203 and 126 days, respectively. This conversion helps communicate their scale, but it must not be mistaken for observed maximum dry spells or a guarantee of that many days of emergency autonomy. Actual seasonal inflows continue during some deficit months, and daily timing remains unresolved. The appropriate interpretation is a demand-equivalent volume that highlights the magnitude of seasonal transfer. A realistic design may choose a smaller tank and accept supplementary supply rather than attempt complete seasonal independence.

4.3 Demand and roof-area sensitivity

Reducing the target from 50 to 20 litres per person per day raises the monthly pooling benchmark to 100 percent in Singapore, 48.4 percent in Mumbai, and 80.1 percent in Chennai. Mumbai’s annual inflow then exceeds annual target demand by a factor of approximately 6.50, but its long dry season still leaves a large monthly mismatch. This illustrates a limit to demand reduction as a seasonal remedy: low demand cannot draw water from an almost rainless month without carryover. It can, however, reduce the volume that must be carried. Mumbai’s ideal

seasonal requirement falls to 15.07 cubic metres, while Chennai's falls to 5.82 cubic metres.

Table 3. Demand sensitivity at 100 m² roof area and 0.80 collection fraction

City	Target (L/person/day)	Annual coverage ceiling (%)	Monthly pooling (%)	Seasonal carryover (m³)
Singapore	20	100.0	100.0	0.00
Singapore	50	100.0	100.0	0.00
Singapore	100	100.0	97.1	2.18
Mumbai	20	100.0	48.4	15.07
Mumbai	50	100.0	44.5	40.51
Mumbai	100	100.0	39.6	88.17
Chennai	20	100.0	80.1	5.82
Chennai	50	100.0	65.4	25.22
Chennai	100	75.8	53.5	Annual deficit

Original calculations. Four occupants in every scenario. "Annual deficit" means full recurring demand cannot be met by this roof irrespective of storage size. The annual ceiling permits ideal redistribution; monthly pooling and seasonal carryover retain the definitions in Section 3.

Increasing the target to 100 litres per person per day produces a different constraint in Chennai. Its annual effective inflow of 110.63 cubic metres is below the 146-cubic-metre target, so no finite tank can provide complete recurring supply from this roof under the stated mean climate. Singapore and Mumbai retain annual adequacy at that demand, but their ideal seasonal requirements are 2.18 and 88.17 cubic metres. The contrast separates two problems that are often conflated: annual insufficiency requires more source water or less demand, while temporal insufficiency may be addressed by storage, operational changes, or supplementary supply. Tank enlargement alone is not a universal solution.

Increasing roof area from 100 to 150 square metres improves the baseline monthly pooling benchmark to 72.0 percent in Chennai, but only to 45.8 percent in Mumbai; Singapore remains at its ceiling. In Mumbai, additional roof area predominantly increases wet-season surplus because the driest months contain very little rainfall. This does not mean larger connected roofs lack value: they can support higher wet-season use or replenish shared storage more quickly. It means their marginal contribution depends on the service objective. Where year-round demand is fixed, additional catchment can have a much smaller effect on seasonal adequacy than an annual-volume calculation suggests.

Halving the roof to 50 square metres further exposes the interaction between area and demand. At the baseline per-person target, the monthly pooling fractions become 97.1 percent for Singapore, 39.6 percent for Mumbai, and 53.5 percent for Chennai. Chennai also becomes annually insufficient, because halving roof input is mathematically equivalent to doubling demand when evaluating the annual ratio. This equivalence is useful for comparing shared buildings without assuming that all residents have access to a detached roof. It supports reporting connected area per resident alongside total roof area, since a large building roof can still provide limited individual access when divided among many occupants.

4.4 Collection efficiency and annual area thresholds

Changing collection efficiency from 0.70 to 0.90 alters annual inflow proportionally, but its effect on monthly matching is nonlinear.

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Singapore’s baseline monthly pooling benchmark remains at 100 percent across the range. Mumbai changes only from 44.2 to 44.8 percent, while Chennai changes from 63.6 to 67.3 percent. Once wet-season inflow already exceeds demand, further collection in those months does not increase the no-carryover benchmark. The limited movement in Mumbai should therefore be interpreted as saturation of that particular metric, not as evidence that gutter condition or diversion losses are unimportant. Their effects may emerge through stored volume, wet-season uses, and actual event-scale performance.

At the 50-litre target and 0.80 collection fraction, the annual area requirement is 10.53 square metres per person in Singapore, 9.61 in Mumbai, and 16.50 in Chennai. These thresholds are necessary for complete annual-volume coverage under ideal redistribution; they are not sufficient conditions for reliable service. Mumbai’s low annual threshold coexists with its large seasonal carryover requirement, demonstrating why a single minimum-roof-area rule would be incomplete. A useful residential assessment pairs area per resident with an explicit storage and demand strategy. Where adequate area cannot be connected, the service target must be reduced or supported by another supply.

The implications for shared roofs can be shown without inventing a local housing inventory. If the same 100-square-metre roof serves twenty residents instead of four, the annual target at 50 litres per person per day becomes 365 cubic metres. Even with perfect redistribution, the annual coverage ceilings fall to 47.5 percent in Singapore, 52.0 percent in Mumbai, and 30.3 percent in Chennai. These are constructed allocation examples, not measured apartment-block outcomes. They show why residential density can dominate an apparently favorable rainfall resource and why citywide claims require occupancy and building-form data rather than multiplying a nominal household yield by population.

4.5 Equal-volume comparison and temporal non-identifiability

When all three rainfall profiles are rescaled to 2,000 mm annually, each baseline roof receives the same effective annual inflow of 160 cubic metres. Nonetheless, the monthly pooling fractions remain sharply different: 100 percent for Singapore, 43.9 percent for Mumbai, and 71.5 percent for Chennai. The corresponding ideal seasonal quantities are zero, 40.99, and 20.78 cubic metres. This controlled transformation demonstrates that the observed contrast is not merely a consequence of different annual rainfall amounts. It does not remove station uncertainty or describe a future climate, but it isolates the contribution of the monthly distribution within the chosen mathematical framework.

A constructed daily example shows why even these carefully defined monthly results cannot identify household delivery. Consider a 30-day month with 8 cubic metres of effective inflow, demand of 0.2 cubic metres per day, an initially empty 2-cubic-metre tank, and a rule that serves daily demand before spilling any remaining volume above capacity. Uniform daily inflow supplies all 6 cubic metres of demand. If all inflow arrives on day one, only 2.2 cubic metres are supplied; if it arrives on day thirty, only 0.2 cubic metres are supplied during that month. All three examples share the same monthly rainfall volume, roof, demand, and tank capacity. Their different outcomes establish that monthly totals alone cannot determine delivery.

The example also depends on declared boundary conditions: the three cases end with different tank contents, and another operating sequence could change the numerical outcome. It is therefore an explanatory counterexample rather than a model of any selected city. Mitchell (2007) examined the importance of computational choices in rainwater-tank modeling, supporting the need to report those choices explicitly. The broader inference is precise: a monthly seasonal benchmark can organize comparison, but a claim about daily reliability requires rainfall timing, initial storage, demand timing, and an operating algorithm. No calibration of annual roof yield can recover information that the monthly input does not contain.

5 Discussion

5.1 Water quality and the meaning of usable supply

A roof-based calculation establishes a physical opportunity, but the water delivered to a fixture also has to be suitable for that fixture's use. The distinction matters because roof deposits, animal contamination, storage conditions, and treatment operation lie outside the rainfall-area calculation. Hamilton et al. (2019) document the diversity of microbial hazards and exposure routes associated with harvested rainwater; their review does not establish contamination on the particular roofs represented here. Consequently, neither universal safety nor universal unsuitability can be inferred from the present secondary data. The practical implication is to treat estimated yield as water potentially available for a specified service, subject to a separate assessment of source condition, exposure, and controls. This makes the endpoint of evaluation a usable volume rather than a volume entering a tank.

An illustrative demand of 50 litres per person per day is useful for comparing roofs under a common service target, but it cannot define the treatment appropriate to that target. The same numerical demand could include toilet flushing, washing, or other activities with different exposure patterns. Treating these activities as interchangeable would conceal a major determinant of feasibility, particularly where a system supplies several fixtures. A subsequent building assessment should therefore disaggregate the target into actual uses before selecting treatment and distribution arrangements. Restricting the first screening calculation to a defined demand does not remove this requirement; it clarifies the question that remains. The relevant design comparison is how much suitably controlled rainwater can replace each intended use, with the associated treatment losses and costs recorded explicitly.

First-flush diversion and other pretreatment measures also create a connection between water quality and water quantity. Diverted water cannot simultaneously be counted as household supply, yet a generic reduction factor cannot reveal whether a particular diversion practice provides adequate contamination control. The timing of rainfall complicates the relationship: an equal annual rainfall total can occur through different numbers of events and intervening dry periods. For this reason, the collection-efficiency scenarios in this assessment are best understood as transparent arithmetic assumptions, not validated specifications for a first-flush device. Detailed design would replace the aggregated factor with an event-sensitive assessment where data permit. Such refinement can alter both usable yield and maintenance requirements, and should precede claims that a system achieves a particular quality at a particular annual supply volume.

Roof material is one reason that quality cannot be inferred from rainfall volume. Mendez et al. (2011) found meaningful differences among tested roofs and emphasized treatment requirements, but their experimental results do not establish contamination levels in these cities. Equally, selecting a material associated with better results elsewhere cannot certify a particular installation. The World Health Organization (2022) places rainwater within a preventive approach covering catchment condition, storage, treatment where appropriate, and handling. The appropriate synthesis is an end-use-specific control strategy backed by inspection and relevant testing, with treatment performance evaluated separately from the physical collection opportunity.

5.2 Financial and environmental feasibility

The economic value of harvested rainwater depends on the water actually used and the expenditures it replaces. Gross roof yield alone cannot be multiplied by a tariff to obtain a defensible saving, because some water may overflow, some may have no suitable demand, and some charges may remain payable regardless of consumption. Rahman et al. (2012) demonstrate this conditionality in Sydney, where their modelled household systems had benefit-cost ratios below one without rebates despite providing water savings. Their result is evidence that hydrological benefit and financial benefit are distinct, rather than evidence that systems in the present cities are uneconomic. Local evaluation should therefore apply marginal avoidable charges to delivered volumes and compare those benefits with the full incremental installation, operation, and replacement costs.

Existing infrastructure can materially alter that comparison, because a building that already has suitable storage and segregated plumbing faces a different investment decision from one requiring substantial reconstruction. Nevertheless, an existing tank is not automatically available for rainwater: its current service, usable capacity, plumbing configuration, and operating requirements can constrain conversion. The accounting boundary should identify which assets would be required even without harvesting and which additional expenses harvesting creates. This avoids charging the intervention for unrelated infrastructure while also avoiding the opposite error of assuming shared assets have unlimited free capacity. A building-specific cash-flow analysis can then compare feasible configurations. The present roof-normalized assessment identifies where that analysis is worth undertaking, but provides no basis for a uniform payback period across residential buildings or cities.

Rainwater collection can also affect energy use, although reduced reliance on municipal water does not by itself establish a net energy saving. Vieira et al. (2014) found substantial differences between theoretical and measured energy intensities in the literature, drawing attention to pump operation and system configuration. Those reported values should not be imported as fixed coefficients for Singapore, Chennai, or Mumbai. Instead, a defensible comparison would include the energy required to lift, treat, and distribute rainwater and the municipal supply energy actually avoided under the relevant operating conditions. Gravity-assisted configurations may change this balance, while storage location and pressure requirements can create different constraints. The bounded conclusion is that hydrological potential identifies a candidate resource; environmental preference requires additional evidence about the complete service arrangement.

Stormwater management introduces another possible benefit, but its evaluation needs a different performance measure from household water substitution. Sample and Liu (2014) model water supply and runoff capture as joint objectives, demonstrating the importance of considering both within an explicit design and economic framework. An annual roof yield, however, reveals neither the empty tank space before a particular storm nor the timing of overflow into a drainage system. A tank that contributes substantially to household supply may already be full when intense rainfall arrives. Accordingly, this assessment does not translate captured annual volume into an unsupported percentage reduction in flooding. Any credit for drainage performance should be established through event-scale or continuous simulation linked to relevant drainage conditions, with the consequences of reserving storage for stormwater management made explicit.

5.3 Housing form and the distribution of benefits

Normalizing yield per unit roof area makes the climatic comparison interpretable, but it leaves the distribution of roof access unresolved. A detached dwelling, a shared apartment block, and a subdivided property may have similar rainfall exposure while allocating very different catchment areas to each resident. Takagi et al. (2018) show why that distinction matters: their Hanoi modelling found that an average-household calculation could misrepresent the potential achieved across a heterogeneous population. This supports using the present scenarios as reference cases rather than claims about the typical household in each city. To estimate social coverage, further work would need distributions of connected roof area, occupancy, demand, and storage access. Reporting those distributions would help identify who benefits from a physically promising resource and who remains poorly served.

Shared collection may offer a way to use roof space collectively, although its hydrological advantages should be separated from its institutional requirements. Pooling a roof and storage system does not create additional rainfall, and a larger user group can increase demand faster than the available catchment. At the same time, shared installation may change the costs and responsibilities borne by individual households. A meaningful comparison should therefore retain roof area per resident and storage per unit demand while examining rules for access, payment, maintenance, and service allocation. Without those rules, nominal household participation does not establish reliable access to the harvested water.

The practical implication is to evaluate collective systems as specified arrangements with accountable operators, rather than infer their desirability from the size of the roof alone.

Equity also concerns how programmes select recipients and allocate obligations. A subsidy tied only to roof ownership could favor households with already favorable physical assets, while residents with less roof access or insecure tenure may receive little direct benefit. These are possible programme effects requiring local investigation, not observed distributions established by this study. Radonic and Zuniga-Teran (2023), in research on urban water interventions in Tucson, show why justice encompasses more than the aggregate distribution of infrastructure. A tropical-city programme should consequently examine participation, eligibility, maintenance burdens, and access to benefits alongside cubic metres captured, rather than assuming that an increase in total harvesting implies a fairer water service.

5.4 Governance and the wider urban water system

Public acceptance is another condition between potential collection and actual use. Takagi et al. (2019), studying Galle, found that acceptance differed across uses and could change with information about water quality, quantity, and cost. Their findings cannot establish resident preferences in the three selected cities, but they indicate why a uniform adoption assumption is weak. A programme designed around a technically feasible demand may encounter different preferences concerning fixtures, maintenance, or payment. Building-level consultation should therefore accompany engineering assessment, with information tailored to the proposed service and its responsibilities. This is particularly relevant when households share infrastructure, because agreement about the uses of collected water may be as consequential as agreement about financing. Adoption should be assessed through the functioning service that residents accept and sustain.

The wider planning question is how harvesting complements existing water-management measures. Srinivasan et al. (2010) evaluated Chennai policies across several criteria and found advantages in combining rainwater harvesting with efficiency improvement. Their harvesting intervention included aquifer recharge, so its estimated benefits cannot be assigned directly to rooftop cisterns in this assessment. The useful lesson concerns the evaluation boundary: direct reuse, managed recharge, leakage reduction, and demand management provide different services and may interact. A roofwater proposal should be compared with feasible alternatives using consistent costs, demands, and performance criteria. This prevents a favourable rooftop yield from becoming an unsupported claim that harvesting is the preferred citywide investment. The present calculations can inform that comparison while remaining explicit about the narrower resource they quantify.

The strongest policy implication of the screening assessment is therefore differentiated investigation. Roofs with favourable rainfall exposure, sufficient catchment per resident, and a clear nonpotable demand warrant detailed examination; these conditions do not establish a universal installation rule or a single optimum tank. Campisano et al. (2017) identify operational evidence, maintenance, and institutional support as continuing needs in urban harvesting research. Translating the present results into practice would require those same elements: data on actual buildings, a stated service objective, testing at an adequate time resolution, and responsibility for operation. Measured performance could then refine future screening assumptions. In this sequence, secondary-data assessment has a useful but bounded role: it organizes decisions about where and how to investigate residential rainwater harvesting without presenting preliminary arithmetic as an assurance of dependable supply.

6 Limitations and priorities for stronger evidence

6.1 What the secondary data establish

The use of a common nominal normal period improves comparability, but it does not make the records identical in completeness, spatial support, or observation history. Chennai’s 29 contributing rainfall years illustrate the distinction between a labeled reference period and a fully complete thirty-year series. Singapore’s published station history also warrants caution about assuming an

unchanged national reference location. These limitations do not invalidate transparent calculations from the issued tables, but they constrain how finely differences should be interpreted. The strongest findings concern large seasonal contrasts and conditional relationships; small intercity differences should not be attributed confidently to urban characteristics without a more detailed meteorological appraisal.

Spatial variation presents a separate limitation. A station reference can describe a local rainfall climate, while a metropolitan roof inventory may span coastal, inland, elevated, and heavily built environments. Applying one normal to every roof would ignore possible spatial differences in rainfall and exposure. The present study avoids that extrapolation, although its city labels still require careful interpretation. A municipal extension should combine multiple suitable rainfall records with mapped residential roof areas and inspect station representativeness before aggregation. Where data are sparse, results should be reported by explicit coverage zones or uncertainty ranges rather than as a falsely precise total for the entire urban population.

The analysis is also limited by the use of long-term means. Its equal-total transformation demonstrates a seasonal mechanism, but cannot establish the frequency of empty tanks, the consequences of consecutive dry years, or the reliability of emergency supply. A mean-month deficit may be absent even where damaging dry spells occur in particular years. Daily or finer historical rainfall records should therefore be used to estimate delivered-volume distributions, full-demand days, shortage duration, and overflow under stated capacities. Reporting several of these outcomes is preferable to attaching the single word “reliability” to an unspecified denominator that readers cannot reproduce.

6.2 From scenarios to representative residential evidence

A residential survey would strengthen the comparison by measuring connected roof area, occupancy, intended uses, existing storage, and the condition of gutters and distribution systems. Yet a convenience sample of accessible buildings would not automatically represent all residents, especially those in shared or informal accommodation. Sampling should therefore identify the housing forms relevant to the policy question and record how roof access is allocated. This would permit the standardized scenarios to be replaced by distributions of feasible household service. It would also allow the analyst to distinguish low potential caused by limited catchment from low performance caused by maintenance or an unsuitable demand connection.

Observed demand deserves the same attention as rainfall. The constant daily targets used here isolate climatic differences but omit seasonal behavior, occupancy changes, and the timing of individual uses. Some discretionary demands may rise during dry weather, while other demands could be shifted toward periods of surplus; neither pattern is estimated in this paper. A building study should measure or transparently model the relevant end uses and test whether demand management can improve matching. The appropriate objective may be a reliable small service, a larger seasonal service, or a reserve for particular interruptions, rather than complete substitution of an undifferentiated household water total.

Commissioning and post-installation monitoring would test whether modeled opportunity becomes delivered service. Ward et al. (2012) found that observed occupancy and system sizing mattered in a monitored office installation, a lesson that supports verification without transferring that building’s numerical performance to tropical residences. Useful measurements include tank levels, delivered rainwater, supplementary supply, pump operation, and periods of disconnection or failure. Such monitoring should distinguish wet-weather abundance from actual substitution at fixtures. A system may collect a large amount yet deliver little if its controls or demand connections are poorly configured, making operational evidence essential to interpreting a successful installation.

6.3 Economic and institutional uncertainty

The absence of comparable dated cost data prevents calculation of defensible intercity payback periods. This is a substantive analytical boundary because investment decisions depend on construction access, storage location, treatment, energy, replacement schedules, and the charges or

purchases actually avoided. Nevertheless, financial incompleteness does not render the hydrological screen useless. It identifies configurations that merit local quotations and detailed assessment, and it rules out the assumption that every collected cubic metre automatically earns the same return. Subsequent appraisal should report both household cash flows and any independently justified public benefits, taking care not to count the same avoided water or drainage benefit twice.

Institutional performance cannot be read from a rainfall table either. A programme may install equipment successfully while failing to maintain it, or may achieve modest uptake but durable service among participants. The present study has no empirical basis to rank the cities on these dimensions. Future evaluation should specify who owns the assets, who pays for repair, how quality concerns are addressed, and how shared users resolve access and cost disputes. Tracking operational persistence alongside installation counts would connect policy evaluation to the service actually delivered. This would support explanations of performance that distinguish physical constraints from shortcomings that better management could address.

6.4 Interpreting future climate and causal claims

Historical normals provide a baseline, not a forecast. More annual rainfall could raise potential roof inflow while leaving seasonal shortages unresolved or increasing overflow if the extra rainfall falls in already wet months. Conversely, a change in rainfall timing might improve or worsen matching without a large change in the annual total. These possibilities follow from the model structure but are not predictions for the selected cities. A future-climate extension would need appropriate scenarios, attention to rainfall sequencing, and sensitivity to how climate-model information is translated to building scale. Simply adding a percentage to annual rainfall would leave the most important temporal uncertainties unexamined.

Finally, the comparative results do not identify causal effects of adopting harvesting on municipal supply security. They calculate conditional physical opportunity using secondary climate data and standardized assumptions. Demonstrating a citywide causal benefit would require a credible counterfactual for water use, displacement of other supplies, operational persistence, and wider system interactions. This distinction protects the practical value of the study: the evidence supports targeted further investigation and transparent service design, while withholding stronger claims until the necessary observations exist. A limited but reproducible conclusion is more useful for decisions than a comprehensive-sounding estimate whose central inputs have not been measured.

7 Conclusion

Residential roofs in the selected tropical reference climates receive enough annual rainfall to support meaningful supplementary supply, but annual abundance alone is an inadequate indicator of year-round opportunity. Under the common baseline, Mumbai has the largest effective annual inflow and the smallest monthly pooling fraction, while Singapore has a lower annual inflow and complete matching at the mean-month scale. Chennai occupies an intermediate position in seasonal matching despite its smaller annual rainfall total. These results are conditional on specified roof area, demand, and collection efficiency; they establish a comparative seasonal mechanism rather than observed household performance.

The equal-annual-rainfall calculation strengthens that interpretation by preserving pronounced differences after all three profiles are assigned the same annual volume. Sensitivity analysis further distinguishes cases where collection area or demand controls annual adequacy from cases where long dry seasons dominate the transfer requirement. The seasonal quantities reported here are not engineering tank recommendations, and a zero seasonal deficit is not evidence that physical storage is unnecessary. Detailed design must recover the rainfall timing, operational rules, usable-water quality, and building constraints excluded by the monthly screen.

The resulting planning implication is to define the service before promoting the technology. Wet-season substitution, a dependable restricted end use, and full-year household supply impose different requirements on the same roof. Roof area per resident, the seasonal rainfall profile, and

explicit supplementary-supply arrangements should therefore guide the next stage of assessment. When paired with local quality, cost, and governance evidence, this framework can support more credible residential decisions; without those additions, it remains a transparent and useful estimate of physical opportunity rather than a promise of water independence.

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