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Storage Sizing and Demand Prioritization for Rooftop Rainwater Harvesting

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Abstract:
Rainwater harvesting performance depends on the timing of rainfall, available storage, and the demand served, making annual rainfall totals insufficient for design. This paper develops a reproducible daily water balance for a hypothetical 200-square-metre roof supplying nonpotable demand. A constructed 365-day rainfall sequence totals 840 millimetres, and a stated runoff and event-loss model yields 128.64 cubic metres of collectible inflow. Storage capacities from one to twenty cubic metres are compared with a constant daily demand of 0.30 cubic metres. Five cubic metres of storage supplies 79.44 cubic metres annually, corresponding to 72.55 percent volumetric reliability. Doubling capacity to ten cubic metres raises reliability only to 77.11 percent. Redistributing the same monthly rainfall into consecutive wet days reduces five-cubic-metre reliability to 51.14 percent. A reserve rule improves reliability for a designated priority demand while slightly reducing total water supplied. These are deterministic scenario results, not measurements from a building or forecasts for a city. The contribution is a transparent framework that distinguishes total yield, service reliability, overflow, and demand priorities and identifies the observations needed for site specific design.

Keywords: Rainwater harvesting; daily water balance; storage sizing; nonpotable demand; supply reliability; demand prioritization.

1 Introduction

Rooftop rainwater harvesting can provide water for uses that do not require potable supply, while changing the amount and timing of roof runoff reaching drainage systems. The roof collects rainfall, a conveyance system directs it toward storage, and a controlled outlet supplies the chosen demand. Although the physical arrangement appears straightforward, performance depends on a sequence of intermittent inflows and withdrawals. A tank can overflow during a wet period and later be empty during a dry period even when annual collectible rainfall exceeds annual demand.

Research on urban rainwater harvesting addresses technical performance, implementation, and the wider institutional context [1]. This literature makes clear that a storage tank cannot be sized responsibly from a single annual average alone. Two sites with the same annual rainfall can have different wet-season concentration, dry spells, roof areas, and daily uses. Similarly, a large tank may have little additional value if the roof cannot collect enough water, while a small tank may lose substantial rainfall through overflow before the next period of demand.

Demand definition matters as well. A building may have a relatively stable priority use and a more flexible use that can be reduced when storage is low. Supplying both uses proportionally maximizes neither service continuity nor necessarily the value of the available water. A reserve rule can protect the priority demand but leave more water in storage before a storm, potentially increasing overflow. Storage sizing and operating policy should therefore be assessed together using metrics that reveal these competing objectives.

This paper presents a daily analytical model with fully specified synthetic rainfall and demand. It asks how tank capacity, within-month rainfall timing, and a simple priority reserve alter annual yield and reliability. The aim is to demonstrate design logic and provide reproducible calculations rather than to recommend a tank for a particular

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location. No local rainfall record, building survey, water quality test, or cost quotation is claimed. All uses in the scenario are nonpotable, and the model does not determine treatment requirements or the safety of harvested water.

2 Detailed Literature Review

Fewkes and Butler examine the use of behavioral models to simulate rainwater collection and reuse [2]. Mitchell investigates how computational choices influence the accuracy of rainwater tank modeling [3]. These contributions establish that the order of inflow, overflow, and withdrawal, together with the simulation time step, can affect predicted yield. Consequently, a model should state its actual update equations rather than rely on an algorithm name that may be interpreted differently across implementations.

Basinger, Montalto, and Lall develop a reliability model using a nonparametric stochastic rainfall generator [4]. Hanson and Vogel examine generalized relationships among storage, reliability, and yield [5]. These approaches address variability beyond a single annual rainfall total. The current paper uses a deterministic constructed sequence so that all calculations can be reproduced exactly, but their work motivates subsequent evaluation with multiple years or generated sequences that preserve relevant rainfall characteristics. One synthetic year cannot establish a climatic reliability level.

Liaw and Tsai investigate optimum rooftop storage volume for domestic use [6]. Imteaz and colleagues apply daily water balance modeling to rainwater tanks in Melbourne [7], and a related comparison examines differences between parts of the city [8]. These studies support considering roof contribution, storage, and demand jointly. Their location specific outcomes are not transferred to the present scenario. Instead, the daily accounting structure is used to investigate how performance responds to explicitly stated hypothetical inputs.

Palla, Gnecco, and Lanza examine nondimensional design parameters [9], while Palla and colleagues compare domestic systems across European climate zones [10]. Such work helps relate storage and demand to rainfall characteristics rather than treating tank volume as an isolated variable. Villarreal and Dixon analyze a domestic collection system in Sweden [11]. Together, these studies demonstrate that meaningful design comparisons require attention to the intended use, the local rainfall regime, and the balance between collected volume and consumption.

Monitoring provides a different form of evidence from design simulation. Ward, Memon, and Butler assess the performance of a large building system [12]. Ghisi and Ferreira investigate potential potable water savings from rainwater and greywater use in a multistorey residential building [13]. These studies connect modeled opportunities with building demand and operation. The present paper does not combine rainwater and greywater; citing that work highlights the need to define system boundaries and avoid attributing all building water savings to one collection mechanism.

Supply and drainage objectives can interact. Sample and Liu optimize systems for both water supply and runoff capture [14], while Sample, Liu, and Wang evaluate dual benefits through reliability analysis [15]. A tank maintained full for supply has less empty capacity available for the next storm. Conversely, releasing water in anticipation of rain can improve detention while reducing stored supply if the forecast is wrong. The simple reserve rule studied here addresses demand priority, not forecast-based storm control, and its overflow consequence is reported explicitly.

Environmental and financial evaluation extends beyond water volume. Ward and colleagues examine energy consumption and carbon emissions associated with harvesting systems [16]. Ghimire and colleagues compare the life-cycle impacts of a commercial harvesting system with municipal supply [17]. Amos, Rahman, and Gathenya review economic feasibility [18]. These works caution against interpreting a larger annual yield as automatically lower environmental impact or better financial performance. Pump energy, tank materials, service life, maintenance, and local avoided water costs all affect the broader assessment.

Ward and colleagues also examine the sociotechnical setting of rainwater harvesting in the United Kingdom [19]. Campisano and Modica investigate the time resolution needed to evaluate water saving and retention potential [20]. These perspectives identify two limits of a compact numerical model: implementation depends on responsible operation, and daily averages may conceal short-duration behavior. The present focused narrative review therefore supports a transparent model as one part of design assessment, with local observations and finer time resolution added when required by the decision.

3 Detailed Methodology & Framework

3.1 Rainfall, roof, and demand inputs

The hypothetical building has a contributing roof area of 200 square metres. Monthly rainfall totals from January through December are 20, 20, 30, 40, 60, 120, 180, 160, 100, 60, 30, and 20 millimetres. These values sum to 840 millimetres. A non-leap calendar is used, giving 365 days. In the baseline sequence, each month's rain is divided equally among days five, fifteen, and twenty-five. Every other day is dry. This is a deliberately simplified seasonal pattern and is not presented as a measured or forecast Indian rainfall record.

Each wet day is treated as a separate collection event. An effective one-millimetre event loss is subtracted before a runoff coefficient of 0.80 is applied. The coefficient represents additional collection inefficiency and is not interpreted as an independently measured roof property. Since one millimetre over one square metre equals one litre, collectible inflow equals 0.16 times the event rainfall remaining after the loss, expressed in cubic metres. All 36 baseline events exceed one millimetre, so annual inflow is 128.64 cubic metres.

Total daily demand is fixed at 0.30 cubic metres, yielding 109.50 cubic metres annually. It consists of a designated priority use of 0.20 cubic metres and a flexible use of 0.10 cubic metres. These categories describe nonpotable operational priorities rather than drinking-water needs. Tank capacities of one, two, five, ten, and twenty cubic metres are evaluated. Every simulation begins with an empty tank, uses the same rainfall and demand, and reports final storage separately to preserve the annual water balance.

3.2 Daily balance and operating sequence

At the beginning of each daily calculation, inflow is added to the previous day's remaining storage. Any volume above tank capacity is counted as overflow. Demand is then withdrawn from the retained volume, up to the available amount. The remainder becomes end-of-day storage. Equation 1 states this sequence explicitly. It allows the same day's retained inflow to supply demand and places overflow before demand withdrawal. This ordering is a modeling assumption, not an assertion that rainfall and use occur in that exact order within every real day.

$$I_t = 0.16\, max(R_t - 1, 0)$$
$$O_t = max(0, S_{t-1} + I_t - K)$$
$$Y_t = min(D_t, min(K, S_{t-1} + I_t))$$
$$S_t = min(K, S_{t-1} + I_t) - Y_t$$

Equation 1. Daily inflow I, overflow O, supply Y and remaining storage S in m³; rainfall R is in mm, capacity is K and demand is D. Initial storage is zero.

In the baseline policy, any partial supply is divided proportionally between the priority and flexible uses. The reserve policy instead supplies the priority demand first and permits flexible withdrawal only from water remaining above a two-cubic-metre reserve. If less than the priority demand is available, all available water is assigned to that use. Flexible demand is forgone when necessary; it is not postponed and added to a later day's withdrawal. Figure 1 illustrates this branching operating logic and the separate recording of overflow, supply, and residual storage.

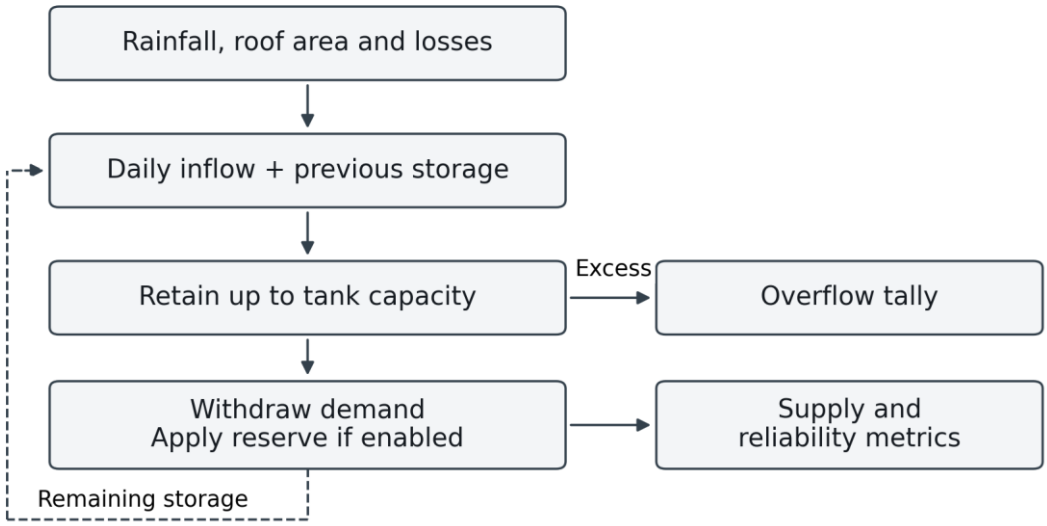


Figure 1. Daily water balance framework. Overflow is removed before demand withdrawal; remaining storage feeds the next day.

3.3 Metrics, sensitivity, and validation

Annual yield is the sum of daily supply. Volumetric reliability is that yield divided by total annual demand. Fully supplied days count days on which the entire 0.30-cubic-metre demand is met. Priority reliability uses only the priority supply and its annual demand of 73 cubic metres. Overflow is tracked separately from collection losses, and final storage is not treated as water already used. These distinctions prevent annual collection potential from being mistaken for delivered service.

The temporal sensitivity retains each monthly rainfall total but places its three events on consecutive days one, two, and three. This tests storage exposure to longer dry intervals without changing annual rainfall or event count. A second sensitivity reduces every rainfall event by 20 percent while retaining the fixed one-millimetre event loss. The reserve rule is evaluated at five cubic metres of capacity so that policy effects can be separated from capacity changes. All calculations use the same daily sequence of operations.

The implementation checks that initial storage plus inflow equals supplied water plus overflow plus final storage, within numerical rounding. No random rainfall generator or statistical estimation is involved. The script exports daily records for the five-cubic-metre baseline, allowing individual inflows, supplies, spills, and storage values to be traced. A real design study would require observed rainfall and demand, sensitivity to the initial storage condition, and simulations over an appropriate range of historical or projected weather sequences.

4 Detailed Results and Analysis

4.1 Capacity comparison

Table 1 shows that a one-cubic-metre tank supplies only 35.16 cubic metres annually, although 128.64 cubic metres are available as modeled inflow. Its overflow is 93.48 cubic metres and volumetric reliability is 32.11 percent. Increasing capacity to two cubic metres raises yield to 58.72 cubic metres and reliability to 53.63 percent. This large initial gain occurs because additional storage retains more of each event for use during the following dry days.

Table 1. Calculated storage performance for the constructed 365-day rainfall series.

Capacity (m^3)	Yield (m^3/year)	Volumetric reliability (%)	Fully supplied days	Overflow (m^3/year)	Final storage (m^3)
1	35.16	32.11	108	93.48	0.00

Capacity (m^3)	Yield (m^3/year)	Volumetric reliability (%)	Fully supplied days	Overflow (m^3/year)	Final storage (m^3)
2	58.72	53.63	177	69.92	0.00
5	79.44	72.55	259	49.20	0.00
10	84.44	77.11	276	44.20	0.00
20	87.80	80.18	288	34.20	6.64

Annual demand is 109.50 m^3 and annual inflow is 128.64 m^3. Every run begins with an empty tank.

At five cubic metres, yield reaches 79.44 cubic metres, with 72.55 percent volumetric reliability and 259 fully supplied days. Doubling capacity to ten cubic metres increases yield by only five cubic metres and reliability by 4.57 percentage points. Increasing capacity again to twenty cubic metres adds approximately 3.36 cubic metres of annual delivered supply. The progressively smaller gains show that storage cannot eliminate the mismatch between seasonal inflow and demand under this finite evaluation period.

The twenty-cubic-metre simulation ends with 6.64 cubic metres still stored. Its annual inflow is partitioned into 87.80 cubic metres supplied, 34.20 cubic metres overflow, and the residual storage. Counting residual water as annual supply would overstate service actually delivered. It may be useful in the following year, so a longer simulation could change the comparison. This result also shows why the empty initial condition and the choice of evaluation horizon should be disclosed rather than hidden within a reported reliability percentage.

4.2 Timing and priority effects

Clustering the same monthly rainfall into three consecutive days reduces five-cubic-metre yield from 79.44 to 56.00 cubic metres. Volumetric reliability falls from 72.55 to 51.14 percent, while overflow increases from 49.20 to 72.64 cubic metres. The result demonstrates that equal annual rainfall and equal roof area do not imply equal usable supply. The tank fills quickly during clustered rainfall and then experiences longer periods without replenishment. Within-month timing is therefore a material design input even in a simple daily model.

The reserve policy increases priority supply from 52.96 to 60.84 cubic metres and priority volumetric reliability from 72.55 to 83.34 percent. Days with full priority service rise from 259 to 296. However, total supply falls from 79.44 to 77.90 cubic metres, and fully supplied days for both uses fall from 259 to 169. The improvement is achieved by reducing flexible use and retaining water for priority demand, not by creating additional water. Table 2 makes this trade-off visible.

Table 2. Demand priority comparison for a 5 m^3 tank.

Operating rule	Total yield (m^3/year)	Essential yield (m^3/year)	Essential reliability (%)	Fully supplied essential days
Proportional baseline	79.44	52.96	72.55	259
Priority + 2 m^3 reserve	77.90	60.84	83.34	296

Annual essential demand is 73.00 m^3. Priority metrics concern the essential demand category, not the full daily demand.

The 20 percent rainfall reduction produces only 101.76 cubic metres of collectible inflow because the fixed event loss becomes a larger share of rainfall. Five-cubic-metre yield falls to 70.60 cubic metres and volumetric reliability to

64.47 percent. This is not a proportional scaling of the original inflow: event losses, overflow, and demand constraints introduce nonlinearities. A sensitivity analysis that simply multiplies baseline yield by 0.80 would therefore miss part of the system behavior.

4.3 Design interpretation and limitations

The five-cubic-metre option captures much of the yield available from the smaller capacity range, but the analysis does not establish it as an economic optimum. Tank costs, available space, pumping energy, maintenance, and the value of protected service are absent. The priority rule may be appropriate when flexible use can genuinely be forgone, yet unsuitable when that use has unmodeled consequences. These judgments require site information rather than a larger number of decimal places in the water balance.

The rainfall sequence also contains only three wet days per month and no variation in daily demand. Real rainfall can include multiple events within a day, and real buildings have weekday, seasonal, and occupancy patterns. The fixed event loss does not represent a verified first-flush device, and the model excludes treatment, water quality, leakage, and evaporation. These limitations define the scope of the conclusions: the calculations demonstrate relationships among timing, capacity, and priorities, while a site specific design requires a richer and locally validated representation.

5 Future Enhancement

Future work should replace the constructed rainfall with quality controlled local records and measure the intended demand at a resolution appropriate to the operating decision. Simulations should examine several initial storage conditions and multiple years, including dry periods that cross calendar boundaries. Hourly modeling would help test whether daily aggregation overstates supply or misrepresents overflow when storms and demand occur at different times within the day.

A broader design assessment should incorporate capital cost, pumping energy, maintenance, and the service value of priority demand. Alternative reserve levels can then be compared rather than assuming that two cubic metres is universally suitable. Forecast-based releases could be evaluated for stormwater objectives, with forecast errors included. Water quality assessment and appropriate treatment design must remain separate technical tasks. Monitoring an implemented system would finally allow predicted inflow, storage, supply, and overflow to be compared against observations and the model revised accordingly.

6 Conclusion

Daily storage accounting reveals performance differences that annual rainfall totals conceal. In the constructed scenario, increasing storage improves yield with diminishing returns, while redistributing the same rainfall into consecutive wet days substantially reduces usable supply. A priority reserve improves continuity for a designated nonpotable use but reduces flexible service and slightly increases overflow. Reporting total yield alone would miss that operating trade-off.

The model is transparent and reproducible, with a checked mass balance and explicit inputs. Its values are not a local design recommendation or evidence of observed building performance. The appropriate use of the results is to guide site specific data collection and compare clearly defined objectives. Rainfall timing, demand patterns, initial storage, and operating priorities should all be represented before choosing a tank or claiming a particular level of water supply reliability.

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