Designing roof catchment water supply systems using water budgeting methods

B. H. Wall and R. L. McCown

This paper describes the use of a water balance model to simulate the performance of a roof-tank system over many years of historical rainfall data. Repeating this for a wide range of system specifications enables the construction of a set of design curves from which the most economic proportioning of roof and tank can be determined, for a nominated reliability of supply or a nominated cost. Two stations having identical mean annual rainfall but contrasting distributions are used as examples. Accuracy, problems of rainfall data availability, and practical aspects of computation are discussed.

Improvement in the supply and quality of domestic water is increasingly recognized as an important objective in rural development for its benefits to human health and welfare, as evidenced by the declaration by the United Nations of the period 1981–90 as the International Drinking Water Supply and Sanitation Decade (Bourne, 1981). An important benefit is improved farm productivity via an improved labour economy. Not only is labour released from water-carrying for more productive activities, but improved health results in higher quality of labour.

One potential source of water is rainwater collected from the roofs of domestic and farm buildings. Although this system is intuitively appealing, its appropriateness in a given situation depends on costs and benefits relative to alternative supply systems. For many, the capital costs of a suitable roof and a tank are prohibitive. However, the use of steel roofing for reasons other than water collection has been growing rapidly, and for those who already have such a roof the additional costs are less. Also, innovations in construction methods have reduced the cost of tanks (Harrison, 1980; White, Bradley and White, 1972). Nevertheless, determination of the most cost-effective proportions of roof and tank is complicated by the normally large variation in rainfall.

Perrens (1975, 1982a, 1982b) used a water balance model to prepare design curves for domestic rainwater systems for four sites in New South Wales, Australia. We have taken his work further by including cost curves for the determination of economic optima, and by examining the loss of accuracy incurred by using a monthly instead of a weekly time step. For many stations weekly data are not available; in other cases where data are only available in manuscript, using monthly data saves much time in data preparation. We have used as examples two stations with identical mean annual rainfall, but contrasting distributions.

Methods

Simulation of variation in stored water

The simulation program is based on WATBAL (McAlpine, 1970; Keig and McAlpine, 1974), a program developed for soil water budgeting. The available water is represented by a single store (in

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The authors gratefully acknowledge helpful discussions with P. M. Fleming.

0790-0627/89/010011-08$03.00 © 1989 Butterworth & Co (Publishers) Ltd

this application, the storage tank), the capacity of which is assigned at the beginning of a run. Storage varies incrementally, increasing by the amount of rain received on the roof catchment (Catch) in the current interval and decreasing by water used during the interval. Water use is calculated using the storage for the previous interval (N–1), the catch for the current interval (N), and the 'potential' water use, ie, use when the supply is non-limiting:

$$\text{Water Use}_N = \text{Supply Index}_N \times \text{Potential Water Use}$$

where

$$\text{Supply Index}_N = f(\text{Storage}_{N-1} + \text{Catch}_N)$$

Changes in water volume in a tank at Marafa, Kenya, were simulated for the 42 years of available rainfall records at intervals of (a) one week, and (b) one month. For each interval, storage was increased by the rainfall collected and reduced by the amount that a family of six persons would use in that period. When supply was non-limiting, consumption was assumed to be 150 litres per family per day, reducing with declining storage to 30 litres per family per day, due to self-imposed rationing (Figure 1). These values represent the average maximum and minimum rates for 19 sites without piped water in the East African study by White, Bradley and White (1972).

Simulation output for each time interval included the volume collected (Catch), volume used, net storage, and the Supply Index (the amount actually used in the interval expressed as a fraction of the amount that would have been used if the supply had been ample).

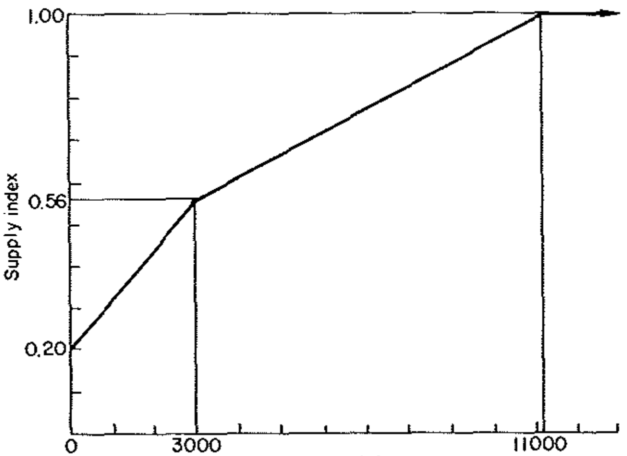

Figure 1. Water use function (applied in the model to storage after catch has been added, but before consumption has been subtracted).

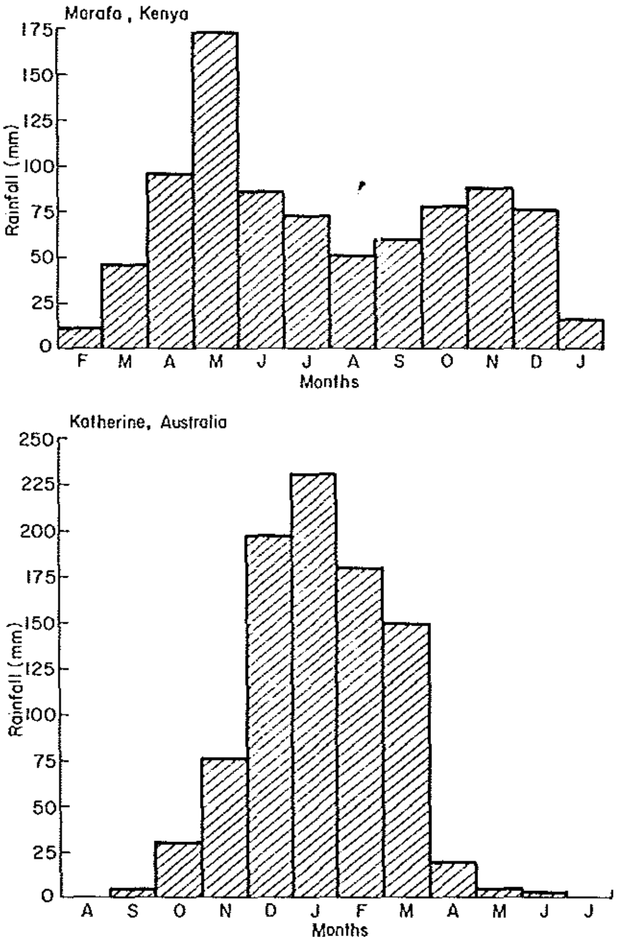

Figure 2. Rainfall distributions for Marafa, Kenya, and Katherine, Australia.

Output for an entire run of 42 years included (a) the number of times the tank was empty in each year (termed 'Failure') and the duration of each failure, (b) the total number of failures in 42 years, (c) the cumulative period of failure as a percentage of the 42 years, and (d) the supply index averaged over 42 years, which can be interpreted as the relative yield of the system.

As shown in Figure 2, Marafa has two rainy seasons (a bimodal distribution). Since most sub-humid/semi-arid tropical regions outside eastern Africa have a single rainy season, a comparison of the influence of rainfall distribution on water system design would contribute to a more general appraisal of this procedure. Katherine, in Australia's Northern Territory (132°E longitude; 14°S latitude), was chosen for comparison because (a) it has a mean annual rainfall similar to Marafa, (b) it has a unimodal distribution (Figure 2) similar to West African stations such as Kano, Nigeria, and (c) daily data were readily available in a computer-compatible form. Katherine data were adjusted to make the mean annual rainfall identical with Marafa and then simulations were carried out as for the African station.

Optimization of roof and tank combinations

Calculation of the most economic combination of tank volume and roof area requires their relative costs. We have used the following costs which were approximate for Marafa in 1987:

45 m^2 galvanized steel roof:	KSh 2 900 (US\$170)
15 kl above-ground ferro-cement tank:	KsH 6 200 (US\$365)

To obtain the cost of other sizes of roof we have assumed cost to be proportional to area. For tanks of different size we have assumed that cost is proportional to surface area, all tanks having the same shape, giving the tank cost curve shown in Figure 3. (This assumption closely approximates the cost–size relationship for three tank types manufactured in Australia.)

The first step in the identification of optimum designs was to simulate the storage changes over the entire period of records for about 100 systematically differing combinations of roof area and tank volume, and to calculate an average failure rate and supply index for each. This was done using weekly time intervals only. Isopleths of failure rate and supply index were then plotted along with those of costs (Figures 5 and 7). Optimum designs were determined graphically using both the criterion of failure rate and that of supply index (Figures 5 and 7).

Figure 4, a simplification of Figure 5 in which only failure rate is considered, illustrates the method. Optimum designs lie on a line which passes through the points of minimum cost on the failure rate isopleths, ie, those points furthest from a higher-cost isopleth and closest to a lower-cost isopleth.

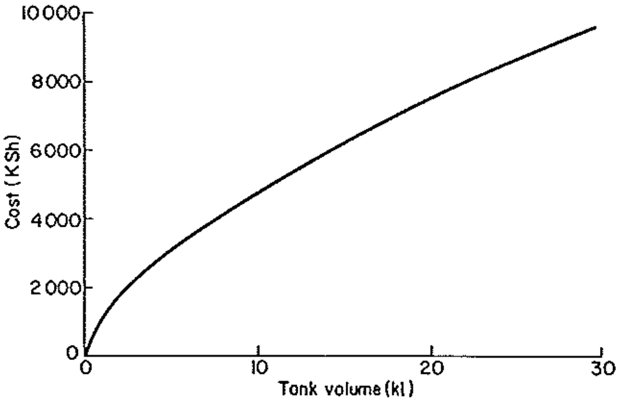

Figure 3. Tank costs.

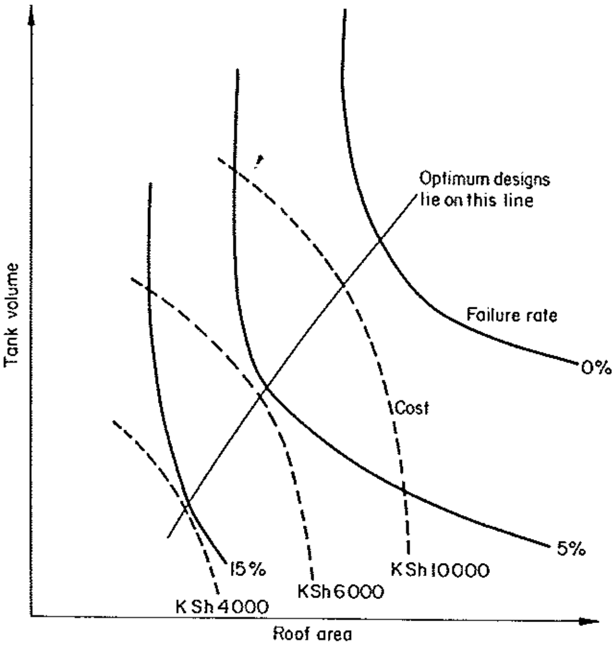

Figure 4. Simplified design curves.

Failure Rate isopleths ———

Cost isopleths - - - - - - -

Results

Design for the bimodal rainfall climate of Marafa

The optimum design that provides a fully adequate supply at all times (average Supply Index = 1.0) is a roof of 100 m^2 and a tank of 25 kl and costs KSh 16 000 (US\$940) (Figure 5). This is the point of minimum cost on the curve of Supply Index = 1; the cost is estimated by interpolation between the KSh 10 000 and 20 000 isopleths. This design, of course, has zero failure rate. Zero failure can still be achieved with the tank size reduced to 12 kl, but yield is reduced by about 15% (Supply Index = 0.85). This is due to the imposition of rationing when storage falls below 11.25 kl. The cost of this system is approximately KSh 13 000 (US\$765), about 20% less than the ideal one.

Less expensive designs with smaller roof area and/or smaller tanks have less yield and carry increased risk of failure (Figure 5). A region of optimum, ie, most cost-effective, configurations is defined by designs maximizing supply index on one side and those minimizing failure rate on the other. For a given average failure risk (or supply index) the optimum (lowest-cost) design can be ascertained from Figure 5. For example, given an average failure rate of 1.5%, a roof of about 70 m^2 and a tank of about 8 kl is optimum. An alternative starting point would be the maximum acceptable cost, eg KSh 10 000 (US\$590). In this case the optimum design (lowest risk of failure) is an 85 m^2 roof and a 9 kl tank.

Improved understanding of the consequences of a given average failure rate in Figure 5 can be gained from analysis of the frequency of failures of different durations (Figure 6). Here, the number of years in 100 years that a failure of a given duration or longer is expected is shown for various average failure rates. For example, for a 1.5% failure rate the tank is expected to be empty for at least one week 20 years in 100, two weeks or longer 14 years in 100, four weeks or longer four years in 100 and never empty for as long as five weeks. Figure 6 indicates that in designs which experience 1.5% average failure rate, the tank never empties in 77% of years, a conclusion quite different from that of being empty for 0.8 weeks per year.

An early design being considered by a development project at Marafa was a 45 m^2 roof and a 15 kl tank. The roof area was that of the standard dwelling

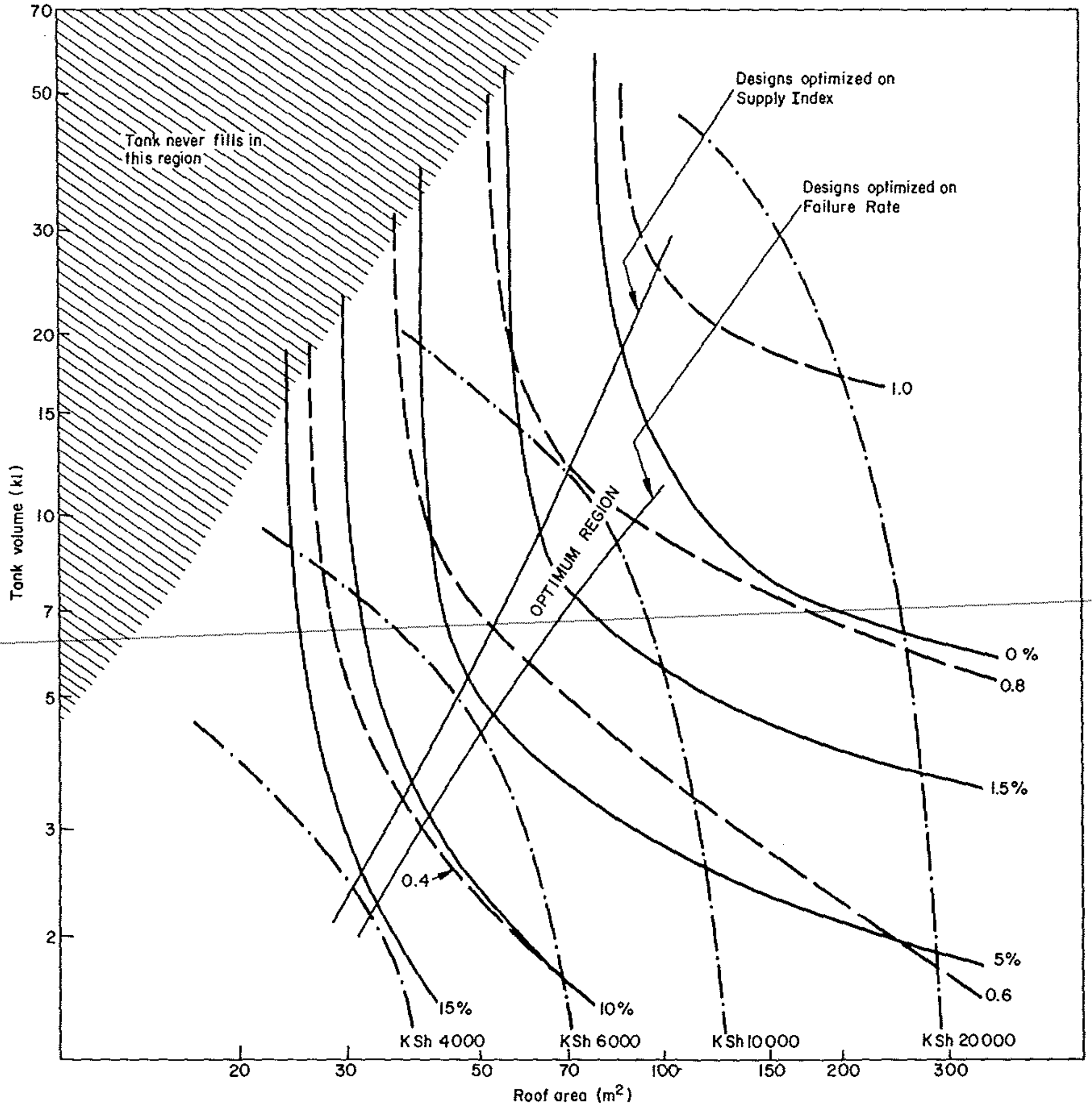

Figure 5. Design curves for Marafa, Kenya.

Failure Rate isopleths ———
Supply Index isopleths — —
Cost isopleths —·—·—·—

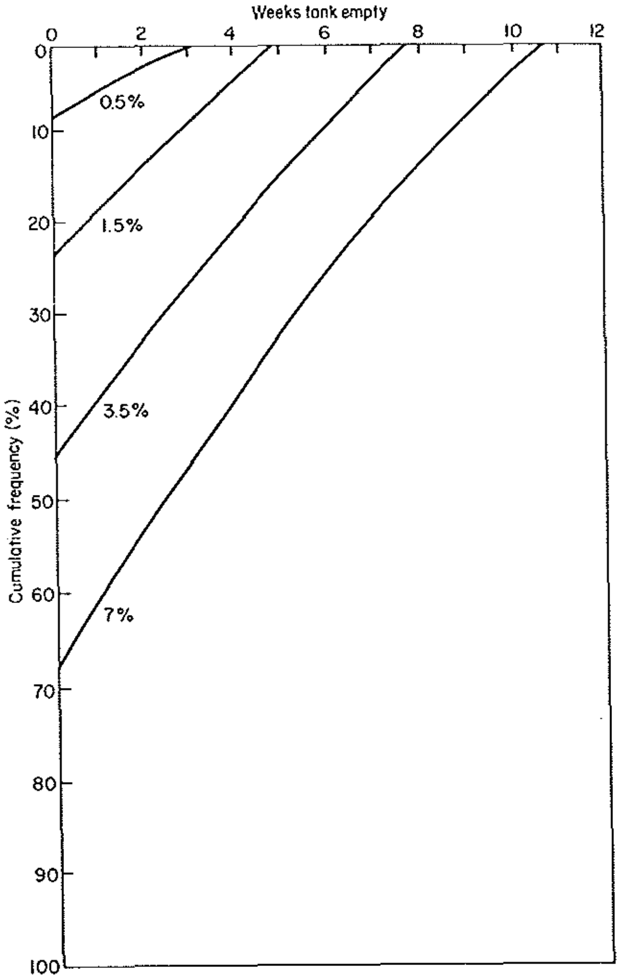

Figure 6. Cumulative frequency distribution of failure durations for various values of average Failure Rate.

and the tank size was deemed ample and 'appropriate'. This design has a failure rate of 3%, and as shown in Figure 5 is far from the optimum region. For the same cost, a 74 m^2 roof and an 8 kl tank reduces the failure risk to less than 1.5%. The frequency of years in which failure occurs drops from 46 to 23% and the maximum duration from eight weeks to five weeks (Figure 6). If, however, a 3% risk is acceptable, the substitution of a 55 m^2 roof and 5 kl tank would reduce the cost by about 35%. Alternatively it might be decided that the roof size be 45 m^2 based on the dwelling size, and the tank size optimized. Using Figure 5 the tank size could be reduced from 15 kl to 7 kl before risk of failure increases significantly (although with 0.04 sacrifice in average supply index, ie, more stringent rationing), a saving of nearly 40% in tank cost (Figure 3).

Design for the unimodal rainfall climate of Katherine

As would be expected from Figure 2, designs for the unimodal Katherine climate require much larger tanks than at Marafa, and thus costs to achieve a given reliability level are higher (Figure 7). A fully adequate supply (Supply Index = 1.0) requires a tank of 55 kl (25 kl at Marafa) and costs KSh 20 000 (US$1 180), 25% higher than at Marafa. For a failure rate of 1.5% the optimum is a roof of 70 m^2 (same as Marafa) and a tank size of about 28 kl (cf 8 kl for Marafa). The cost is about KSh 16 000 (US$940), twice the cost to achieve the same reliability of supply at Marafa. Investment of KSh 16 000 at the bimodal location would provide a fully adequate supply without rationing (Figure 5).

Discussion

Assuming that this method effectively identifies the most economic design, how important a contribution is it likely to be in practice? The decision on whether to collect and store rainwater must take into account capital costs, risk of storage failure and coordination with other supplies. In his Australian study Perrens (1975) showed that the costs of a tank and perhaps some additional roof are small in comparison with the cost of a house, and the cost saving of an optimum design is much less again. In many developing countries, however, the additional cost of materials for a roof catchment system may be as much as the cost of a basic house. In this situation the cost saving of an optimum design could be a deciding factor in adopting a roof catchment system.

How costly is the optimization method? This depends largely on the cost of obtaining rainfall data in computerized form, as it appears that at least 30 years of records are needed. Where daily or weekly records have already been computerized the cost is small, but in some countries these are only available in manuscript. If monthly totals could be used, considerable savings would be made in data procurement, entry and storage. To see the effect of this economy on the simulation output an additional run was made for the period 1957–60 at Marafa using four-weekly (convenient approximation of monthly) calculation intervals.

Use of a monthly calculation interval overestimated the risk of failure two- to threefold (Table 1). This resulted from an overestimation of the

Table 1. Failure of supply (weeks) in four years at Marafa.

	Weekly	Four-weekly	Four-weekly/4
1957	11	36	9
1958	8	24	7
1959	10	20	3
1960	8	24	7

Note: Calculated using actual weekly rainfall totals, four-weekly totals, and weekly values calculated as four-weekly totals/4.

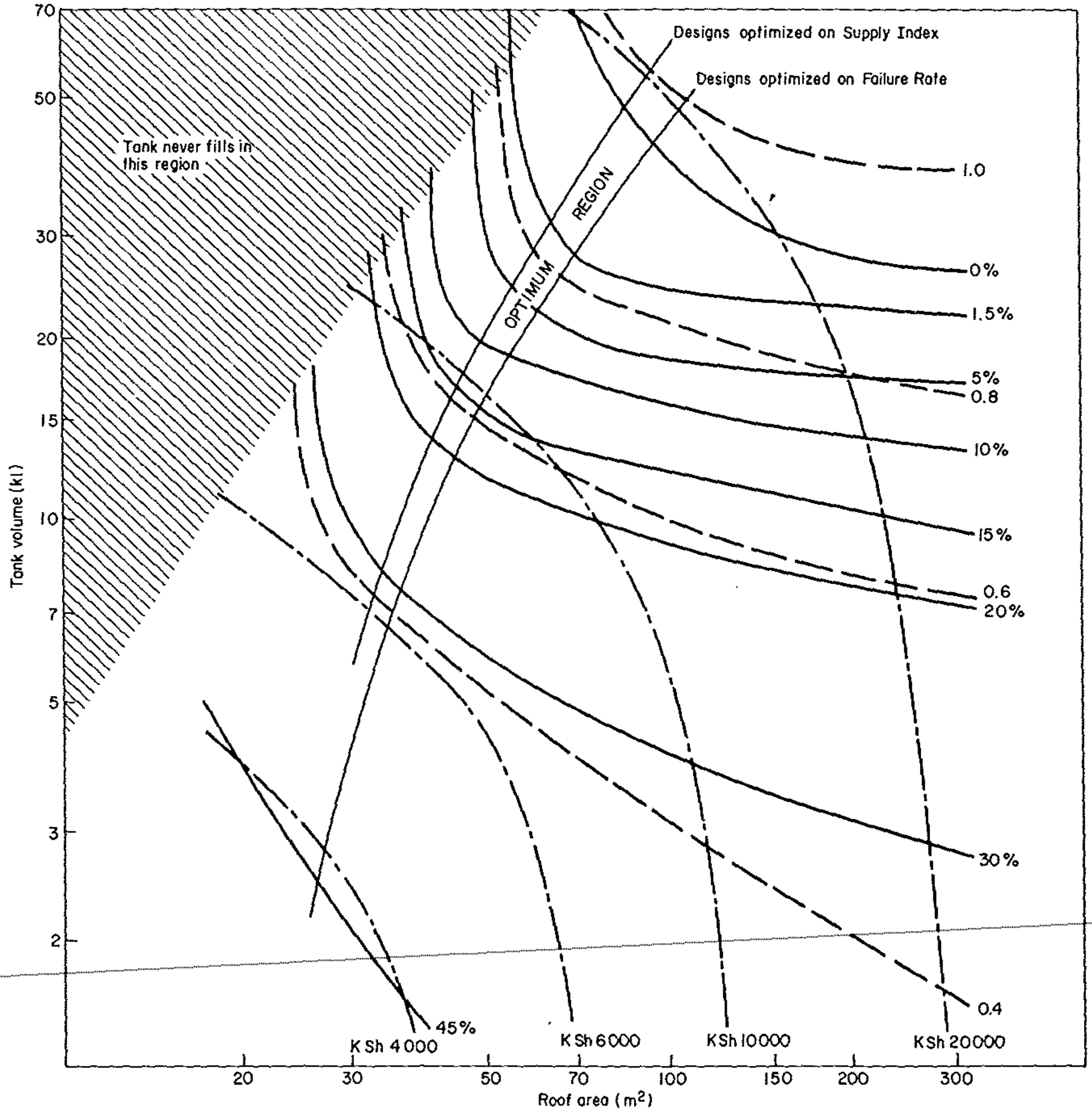

Figure 7. Design curves for Katherine, Australia.

Supply Index relative to storage and consequent underestimation of storage (Figure 8). The model has rainfall (and catch) occurring at the beginning of each period (Figure 8c, d) at which time the Supply Index is calculated for the period (Figure 8b). By extending the period the Supply Index is overestimated due to the higher value of catch and also to the delay in drawing down the storage (see Figure 8b, weeks 13–16).

Since a large component of the error in using 'monthly' rainfall data appears to be due merely to the increased time step, it was of interest to use four-weekly rainfall data but calculate at a weekly time step. Estimates of both Supply Index and storage were much closer to the output using the actual weekly rainfall for 1959 (Figure 8) and estimation of failure rates was in good agreement in three of the four years (Table 1). We conclude that

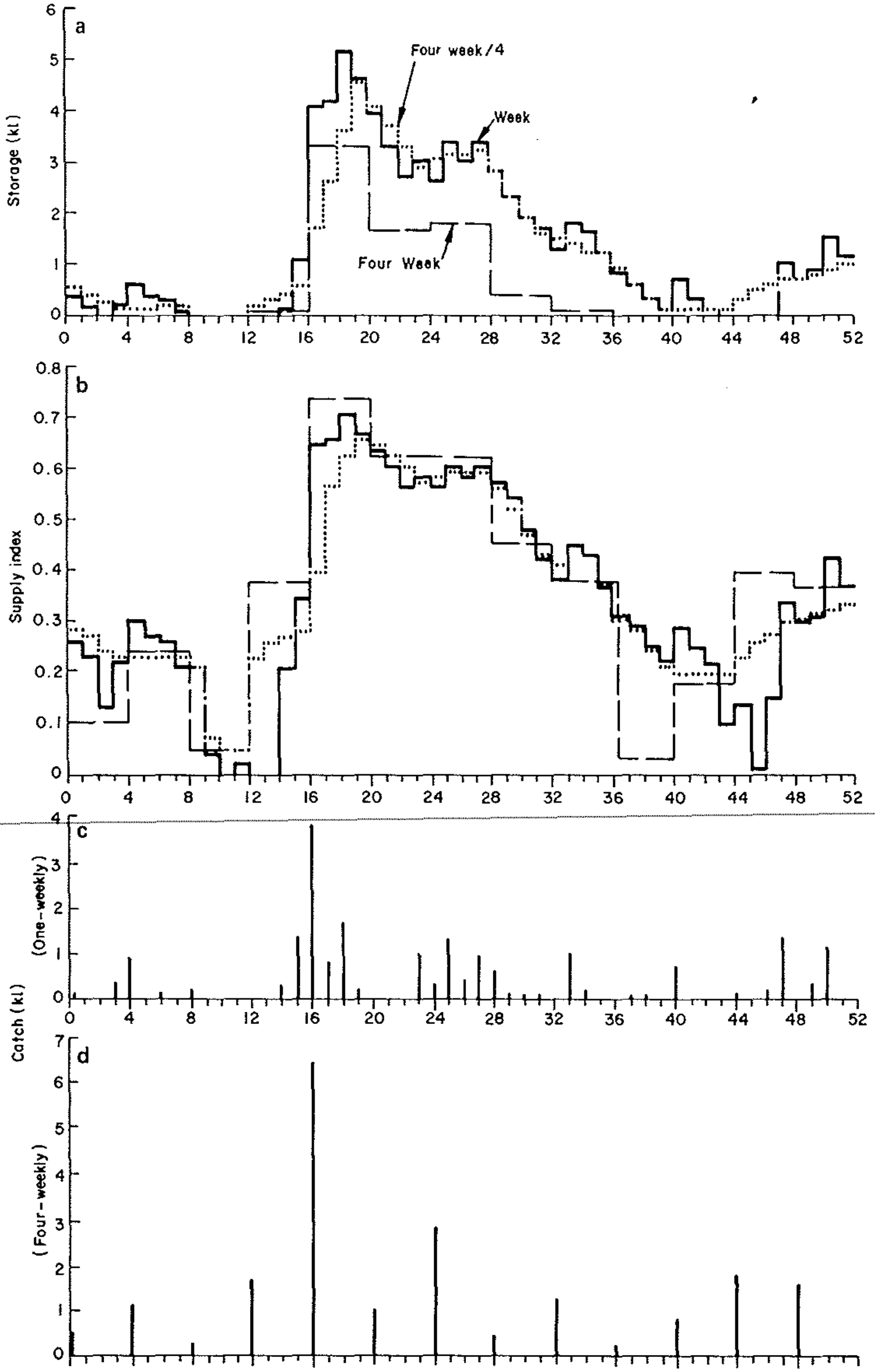

Figure 8. Time course of Storage, Supply Index and Catch for Marafa, 1959, using one-week and four-week calculation intervals.

while substitution of monthly data and a monthly calculation interval is not an acceptable economy, the use of monthly totals divided into four equal parts may be satisfactory.

In deciding what sacrifice in accuracy is acceptable when economizing on detail in the rainfall input, the uncertainties associated with other inputs to the model must be considered. At present it is our definition of the water use function which has least precision. We have relied heavily on generalized data from White, Bradley and White (1972) on usage from non-reticulated sources. From the standpoint of the daily labour costs in acquiring water, the system we are considering is a reticulated system, since water is available at the house. However, because each household has complete control of its own limited supply, we have assumed self-rationing, and usage at the much lower rate reported by White, Bradley and White (1972) for unreticulated supplies from which water must be carried. Fortunately, as can be seen in Figure 5, the proportioning of optimum designs does not vary much over the range of failure rates. It follows that a design will not depart much from optimum if the water use differs from our assumed rates, although naturally the risk of failure will not be the same.

The availability of this design procedure, which permits better understanding of the degree of variability in storage replenishment, may justify further studies of water use behaviour, which is now the major uncertainty in the evaluation of roof catchment systems.

Conclusions

The most appropriate proportioning of roof and tank in a roof catchment water supply can be found using design curves based on risk estimates for a range of designs. This reduces the cost of providing supply at a given risk, and also permits an economic analysis of costs and benefits relative to alternative supplies.

Given an adequate rainfall record and knowledge of consumption rate, the risk estimates can be made with a simple water balance model using a time step not greater than one week. Even when consumption rate cannot be well predicted, optimum proportioning will still be approached.

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