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Feasibility of Rainwater Collection Systems in California

by

David Jenkins • Frank Pearson

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REPORT HIGHLIGHTS

- Collection of rainwater in storage tanks for domestic use is feasible, but only as a partial supply.
- The distribution of rainfall at 13 representative locations in California generates a consistent expression for the yield of a rainwater collection system in terms of annual rainfall at the location, collection area, and storage tank capacity.
- The high cost of large storage tanks needed to sustain even minimal domestic use during the dry summer season indicates smaller tanks and alternate water supplies to provide economically feasible systems.
- Rainwater supply systems are recommended for rural areas only because the concentration of lead in urban rainwater frequently exceeds the limit recommended for drinking water.
- The first flush of rainwater should be diverted away from the storage tank and the water should be periodically disinfected to maintain desired water quality for domestic use.

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FEASIBILITY OF RAINWATER COLLECTION SYSTEMS IN CALIFORNIA

by

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ABSTRACT

The northern California drought of 1975-77 emphasized the need to explore alternatives for water supply. This research examined the feasibility of collecting rainwater for domestic consumption from roof areas into storage tanks. Rainfall records for 13 representative California locations were analyzed to provide a basis for estimating the supply of water from rainwater collection systems. Standard statistical measures of central tendency, distribution and variation, as well as serial correlation, were remarkably consistent. A single relationship emerged which expressed the yield of rainwater supply systems for all locations in terms of annual rainfall, collection area, and storage tank capacity for different levels of system reliability. Because of the high cost of the large storage tank needed for a completely reliable rainwater supply system to sustain even a minimal domestic demand, the most economical supply system will generally involve use of rainwater during the wet season, supplemented from other sources during dry periods.

The concentration of lead in rainwater near urban areas frequently exceeds the recommended limit for drinking water, which would imply that rainwater supply systems are feasible only in rural areas. Microbiological contamination of rainwater results from bird droppings on the collection area, but chlorine disinfection proved effective. Turbidity can be removed to below the limit recommended for drinking water by a process of alum coagulation and settlement, feasible on a household scale.

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CHAPTER ONE

RAINWATER COLLECTION SYSTEM CHARACTERISTICS

Four factors control the performance of rainwater collection systems: the amount of time distribution of rainfall, the amount and time distribution of demand, the available collection area, and the storage volume provided. Of these, collection area and storage volume, and to some extent demand, can be controlled by the system designer. To establish functional relationships between rainfall, demand, collection area, and storage for use in the design of rainwater collection systems, a mathematical model was constructed.

MODEL STRUCTURE Rain falling on a collection area passes to a storage tank. If the tank fills, any of the newly collected water in excess of the storage capacity spills; spilt water is wasted. Then, in response to a demand for water, water is withdrawn from the tank, up to an amount equal to the quantity stored in the tank. Any water not withdrawn remains in the tank.

Each sequence of events—rainfall, collection, spillage, withdrawal—occurs in a definite order over a specific time interval. Rainfall for a time interval is first collected and enters storage, then any spillage occurs if the tank overflows, and finally the demand for water over that time interval is satisfied. This sequence is repeated in successive time intervals through the period of record.

A time interval of one month was adopted. In Chapter Two it is shown that results obtained using a one-month interval were comparable to that obtained with a one-day interval. The effect of using a longer time interval is to slightly underestimate system performance, as shown in Chapter Two.

Also for this work a uniform demand was assumed. This is realistic for in-house uses of water, but for outdoor uses, such as garden watering or filling swimming pools, the seasonal variations in demand must be taken into account by appropriate interpretation of results presented in this study, as discussed later in this chapter.

To simplify the model it is mathematically expedient to normalize model parameters by dividing rainfall, demand, spillage, yield, and storage each by the collection area, and to express these quantities in units of gallons per square foot. Thus we obtain (unit) rainfall; unit demand, i.e., the desired amount of water from the system; (unit) spillage, i.e., the amount of water wasted; and (unit) yield, i.e., the amount of water actually obtained. All these are expressed in terms of gallons per month per square foot of collector area. Likewise, (unit) storage is expressed as gallons per square foot of collector area (1.0 gal/sq ft = 1.604 in). Normalized quantities are implied when we speak of rainfall, demand, spillage, yield, and storage.

In the model, a given historical rainfall record is first normalized, and values of demand and storage selected. Then the yield is computed for each month of record. System performance is characterized by two parameters: percent yield and percent of time that system fails. Percent yield is the total or cumulative yield divided by total demand over the period of record, times 100%. Percent of time the system fails is the number of months for which the yield is less than the demand divided by the number of months of record, times 100%.

Note that since no more than the demand is withdrawn in any time interval the percent yield can never exceed 100%. Indeed, if the demand exceeds the mean annual rainfall supply, the percent yield can never exceed the ratio of mean rainfall supply to demand, times 100%.

For a given rainfall record the system performance is evaluated over a range of values of demand and storage to establish the system characteristics. From these system characteristic curves it is possible to answer design questions, e.g., what storage volume is needed for a given demand? Or what yield will a given storage volume provide for?

Predictions of system performance in the future are based entirely on rainfall amounts and patterns observed in the past. Significantly different system performance is possible if rainfall characteristics of the past are not reproduced in the future. Longer historical records can be expected to produce more reliable indications of future patterns, but the statistical limitations of records of finite length must be kept in mind. For example, if the historical record shows an event to occur 100% of the time then standard statistical procedures would estimate 0% for the standard deviation (average error) of this 100% statistic, indicating absolute certainty. But in truth nothing is certain in nature. We must be wary of operations of fact that can easily result from imprudent interpretation of past events.

RAINFALL RECORDS Records of monthly rainfall for a 40-year period (1937-1976) for each of 13 representative California locations shown in Figure 1 were analyzed statistically. Figure 2 typifies the monthly distribution of rain, being shown here for the city of Oakland, expressed in gallons per square foot per month. Features that recur throughout all the records are the dry California summers with monthly rainfall generally less than one-tenth of that in wet months. There is also a marked variability of rainfall. Thus, the performance of rainwater collection systems not only varies widely according to a seasonal pattern, but also can be expected to fluctuate from year to year, depending on whether the year is relatively wet or dry.

The horizontal broken line on Figure 2 represents the mean annual rainfall, 0.96 gal/sq ft-month. This value is an upper limit to the long-term yield of a collection system regardless of storage volume, although in practical cases with feasible storage volumes the attainable yield is somewhat less.

FIGURE 1 Thirteen study locations in California

SYSTEM PERFORMANCE — CASE STUDY System performance is illustrated here by a case study for Oakland, California. System performance is expressed by two parameters, percent yield and percent of time the system fails. Percent yield (or percent of cumulative demand that is met) and percent of time the system fails were computed by the model for each month of the year and for three levels of demand: 0.5 gal/sq ft-month (less than the supply), 1.0 gal/sq ft-month (approximately equal to the supply), and 1.5 gal/sq ft-month (which exceeds the supply). Results of this study in Figures 3, 4, and 5 were constructed for the three respective demand levels.

In each case the improvement in system performance with increasing storage volume is evident. It is also clear that percent of time the system fails is a more stringent criterion of system performance than percent of cumulative demand met, since the former criterion records total system failure for any month that the yield is not fully met (no matter how slight the deficit), while the actual yield obtained is credited according to the percent yield criterion.

Comparing the three families of curves, it is clear that larger storage volumes are needed to attain the same percentage yield as the demand is increased. However, when the demand exceeds the mean annual rainfall, then no matter how large the storage, it is not possible to satisfy the entire demand. For any particular demand there is a certain storage volume, albeit large, from which no spillage occurs during the period of analysis.

For purposes of rainwater collection system design the year-round average system performance curves are likely to be of greater interest than curves for individual months. Figure 6 shows annual average system performance as a function of demand and storage.

CHARACTERISTIC CURVES FOR 13 REPRESENTATIVE CALIFORNIA LOCATIONS For design purposes, a useful way to portray mean annual system performance is to plot lines of constant percentage yield versus demand and storage volume. Figures 7-19 present such performance curves for the 13 locations in California shown in Figure 1. From these plots one can readily obtain yield as a percentage of demand for given locations, demands, and storage volumes.

PERFORMANCE CHARACTERISTICS FOR TIME-VARYING DEMANDS As mentioned earlier, it may be desired to investigate system performance with a seasonal variation of demand. The preceding analysis assumed demand to be constant throughout the year. To take full account of seasonally varying demand would require a more refined analysis, particularly if the peak demand is exerted in the dry season.

In the extreme case where the system's sole function may be to save wet season rainfall for dry season use, consideration should be given to whether rainfall values below average (for wet season months) tend to occur in runs, i.e., whether serial correlation appears in the record. If no such persistence occurs in the record we might simply compute the storage volume as the total rainfall in the wet season, or the amount of water required for the dry season, whichever is lesser. If strong persistence appears in the record it may be reasonable to compute the supply during a lean wet season as the total of each month's rainfall reduced by the standard deviation of rainfall for that month. These effects are considered in greater detail in Chapter Three.

Generally, however, seasonal variation in demand patterns are so great as to almost preclude preparation of general design curves. Such cases must receive special study. But a preliminary evaluation of the possible range of performance of a system could be obtained from the design curves, by first assuming maximum demand to persist through the year to obtain minimum percent yield, than assuming minimum demand throughout the year to find the maximum possible yield.

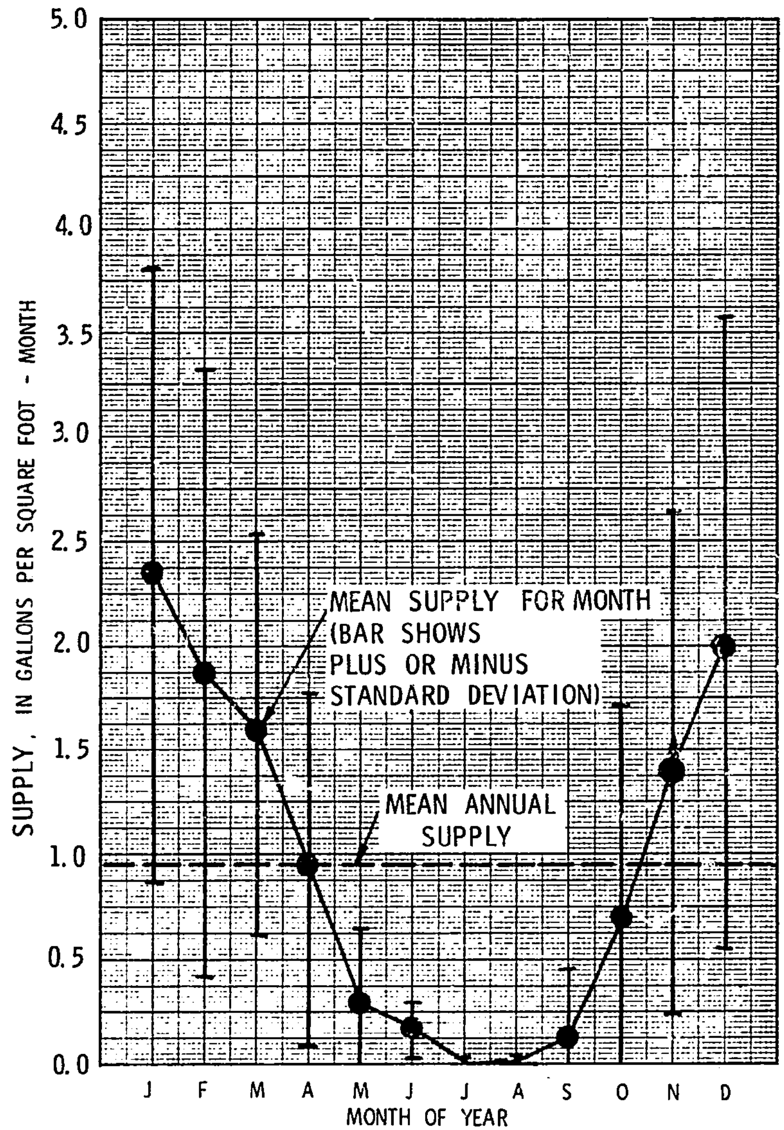

FIGURE 2 *Annual distribution of rainfall supply at Oakland, California*

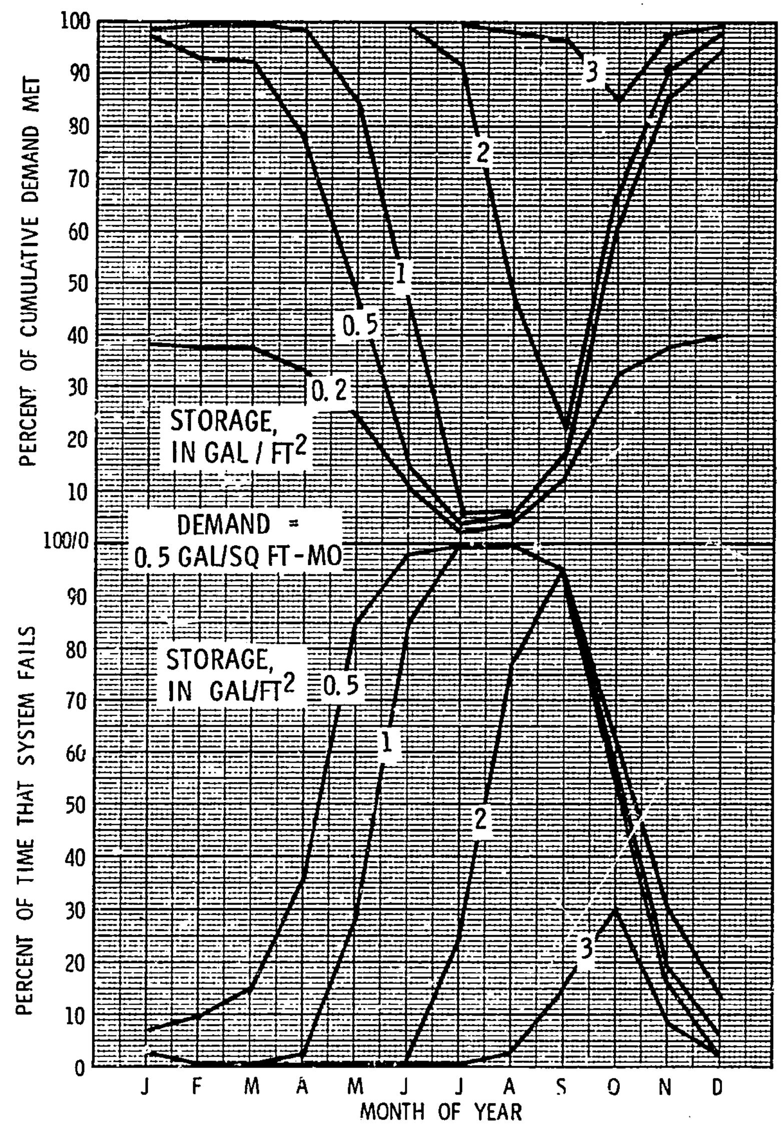

FIGURE 3 *Annual variation of system performance over a range of storage for demand of 0.5 gal/sq ft-month, Oakland*

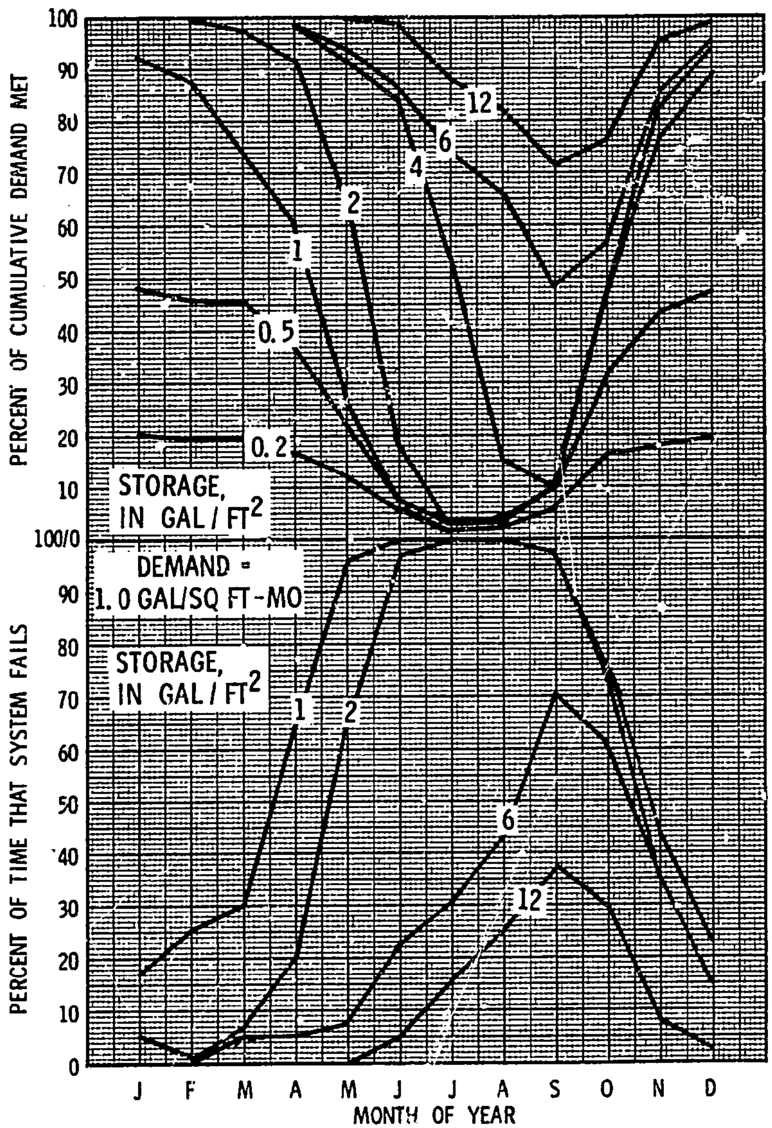

FIGURE 4 *Annual variation of system performance over a range of storage, for a demand of 1.0 gal/sq ft-month, Oakland*

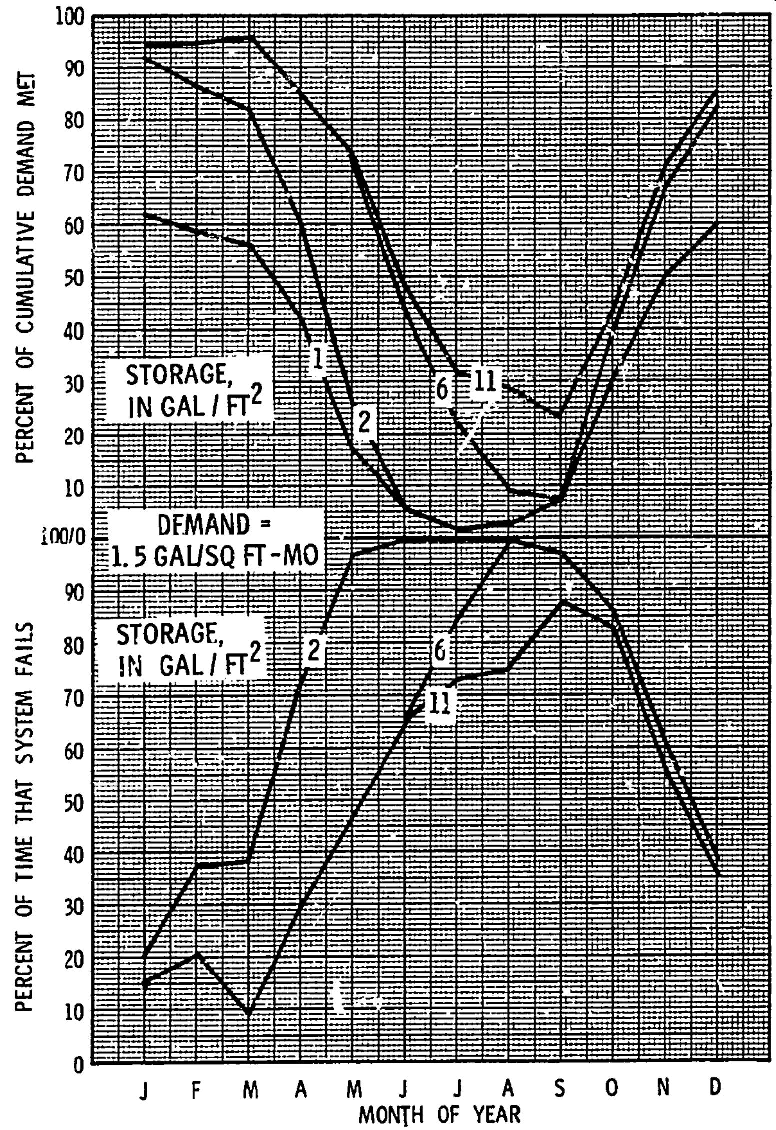

FIGURE 5 *Annual variation of system performance over a range of storage, for a demand of 1.5 gal/sq ft-month, Oakland*

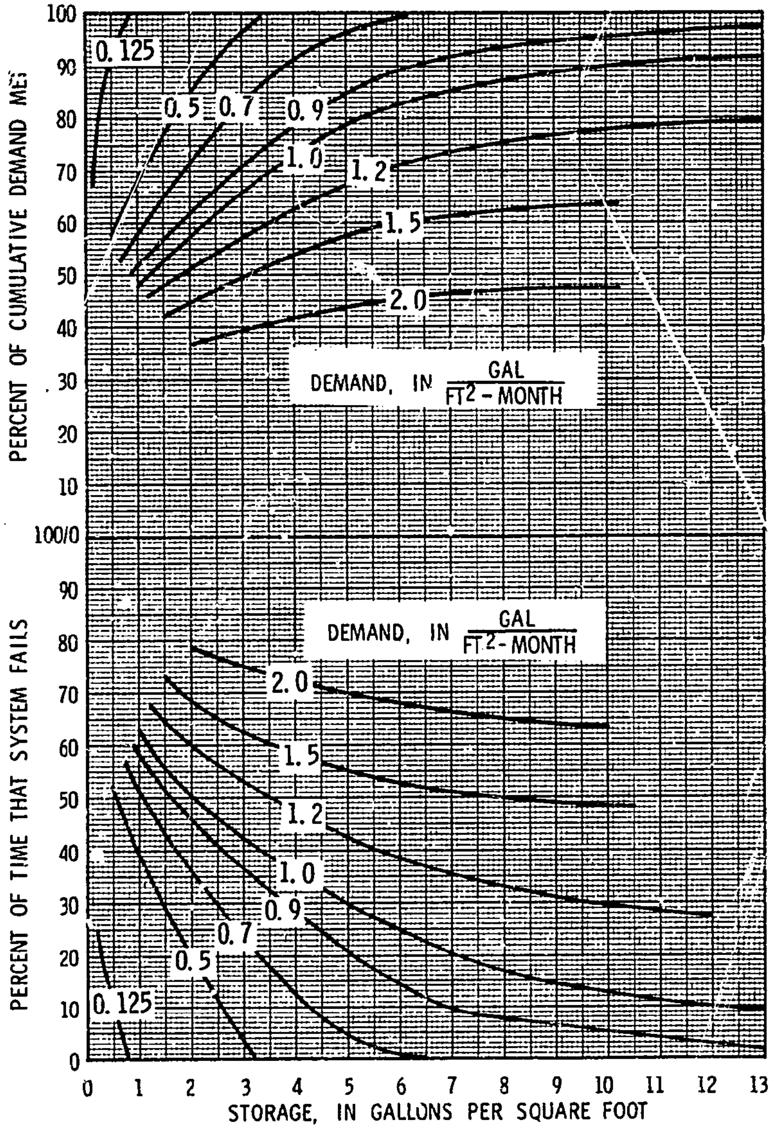

FIGURE 6 *Annual average system performance versus demand and storage, Oakland*

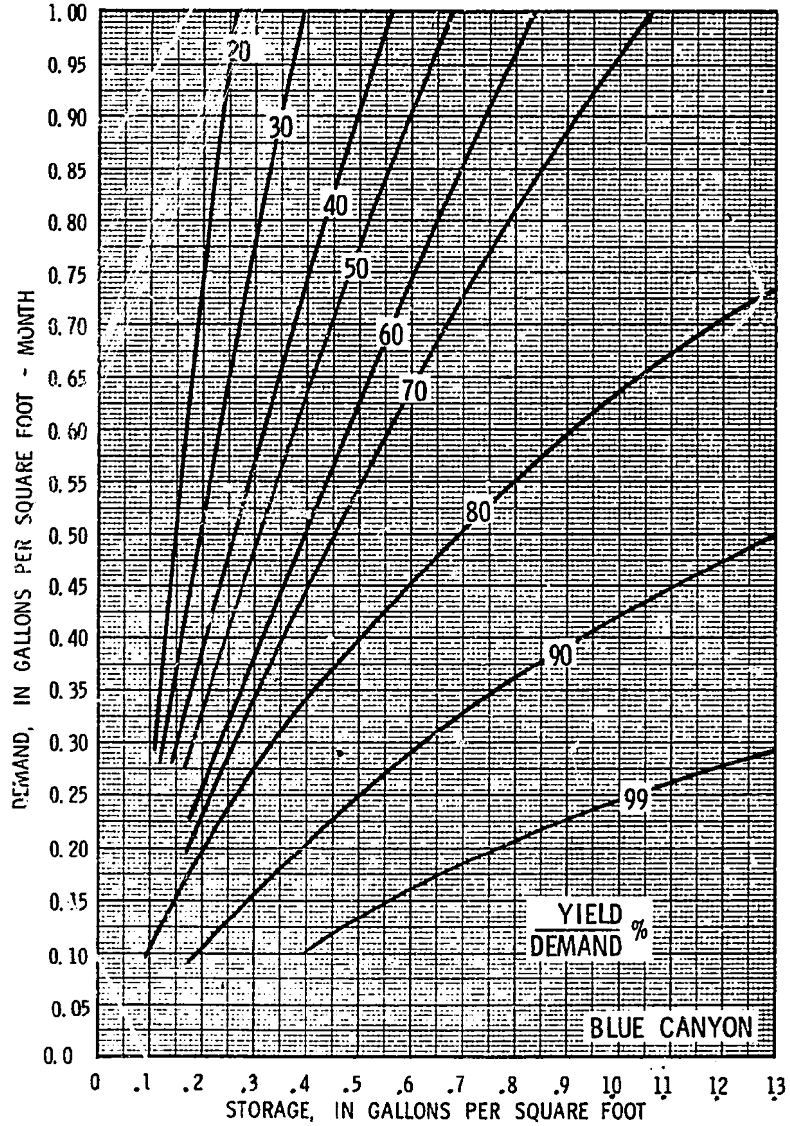

FIGURE 7 *Yield as a percentage of demand versus demand and storage, Blue Canyon, California*

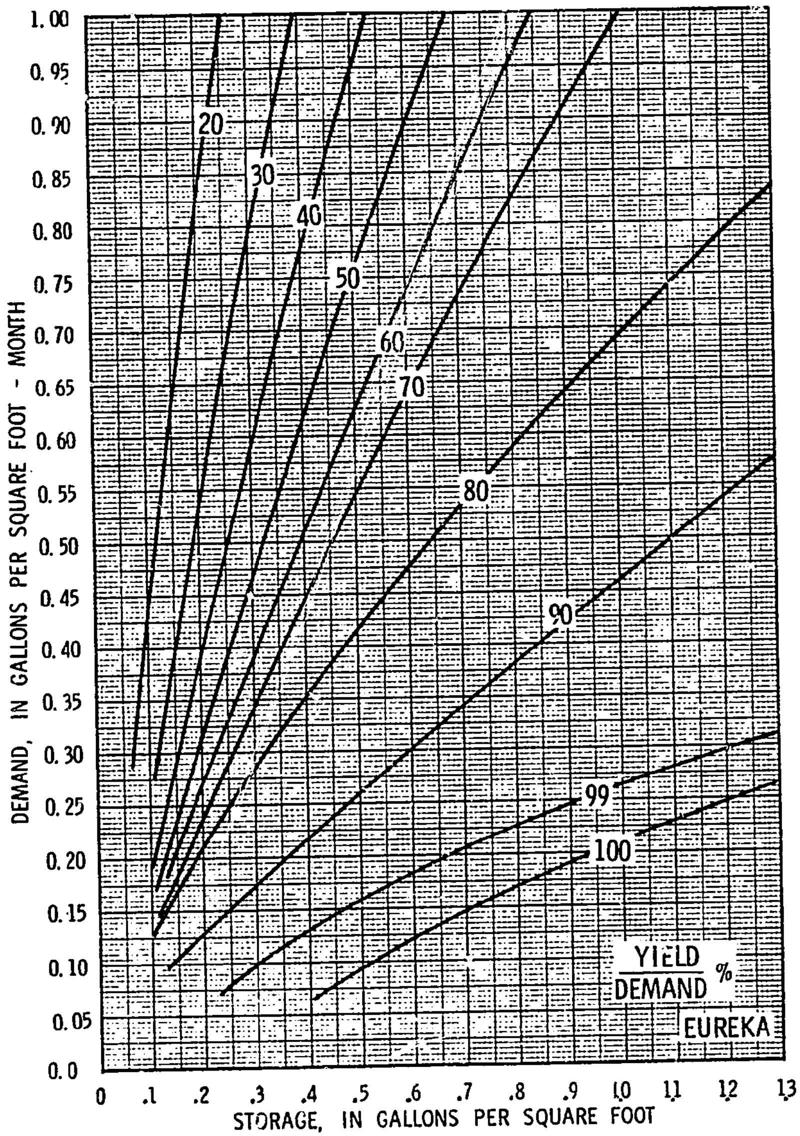

FIGURE 8 *Yield as a percentage of demand versus demand and storage, Eureka, California*

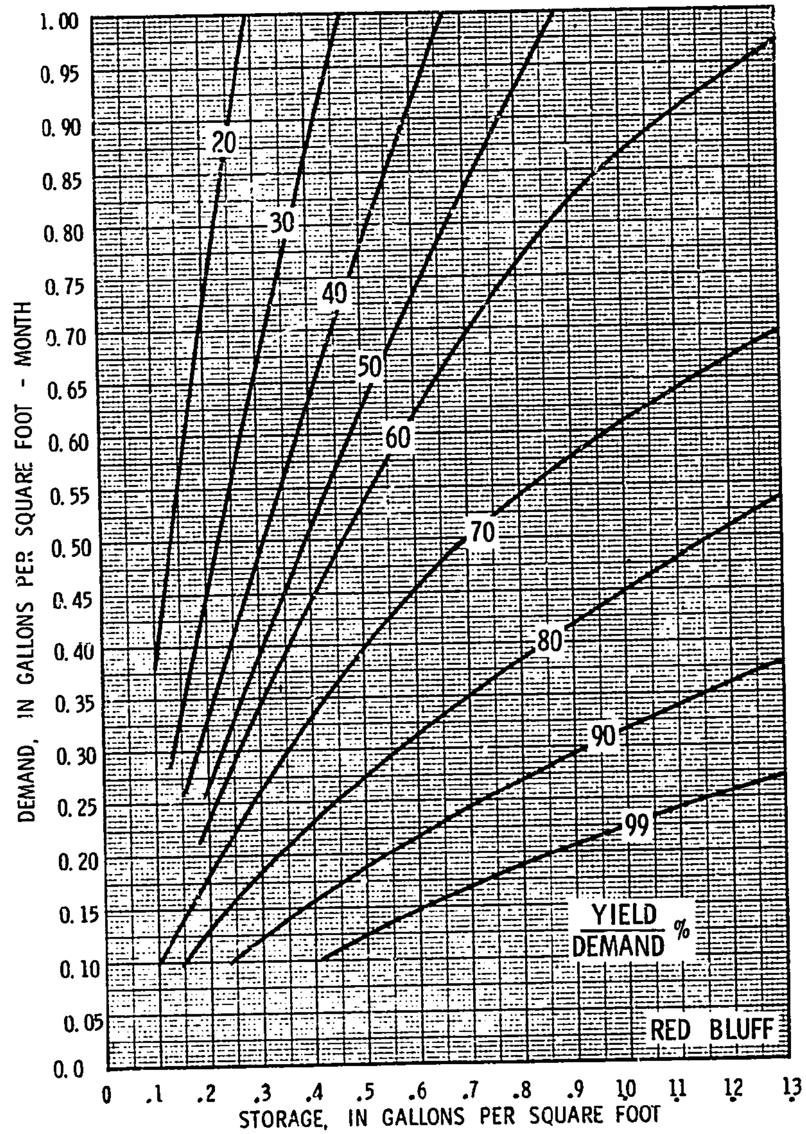

FIGURE 9 *Yield as a percentage of demand versus demand and storage, Red Bluff, California*

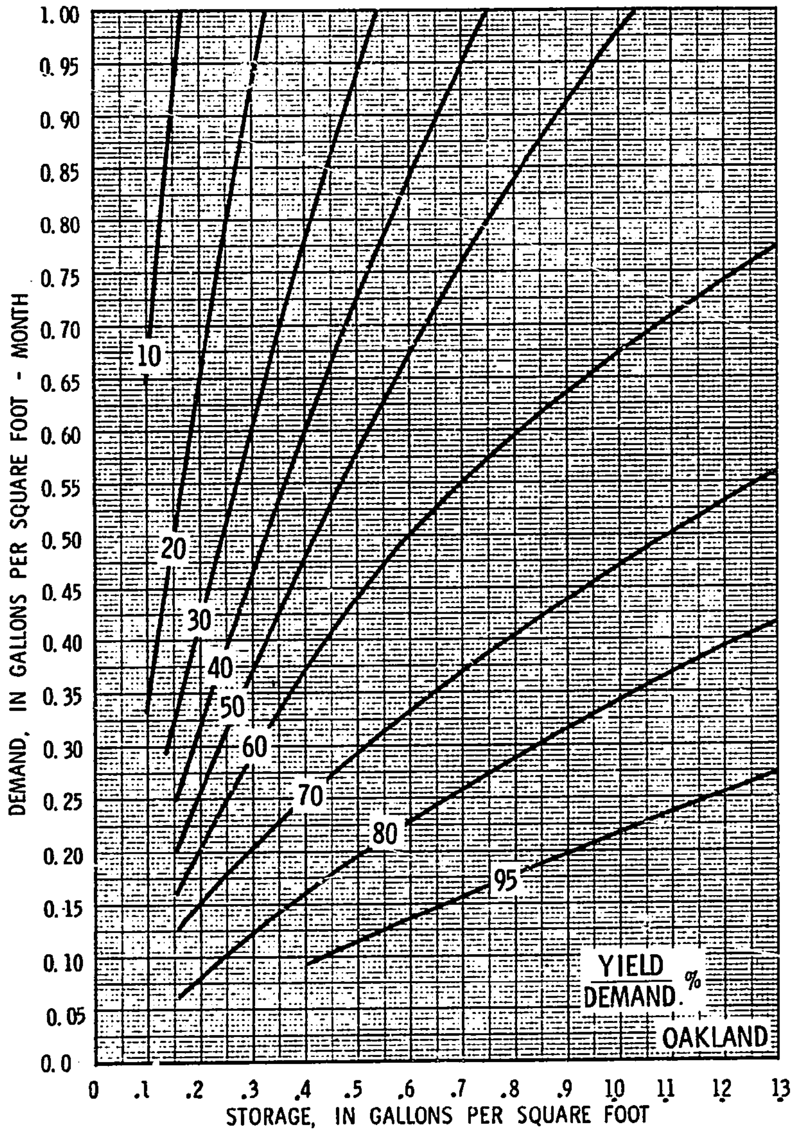

FIGURE 10 *Yield as a percentage of demand versus demand and storage, Oakland, California*

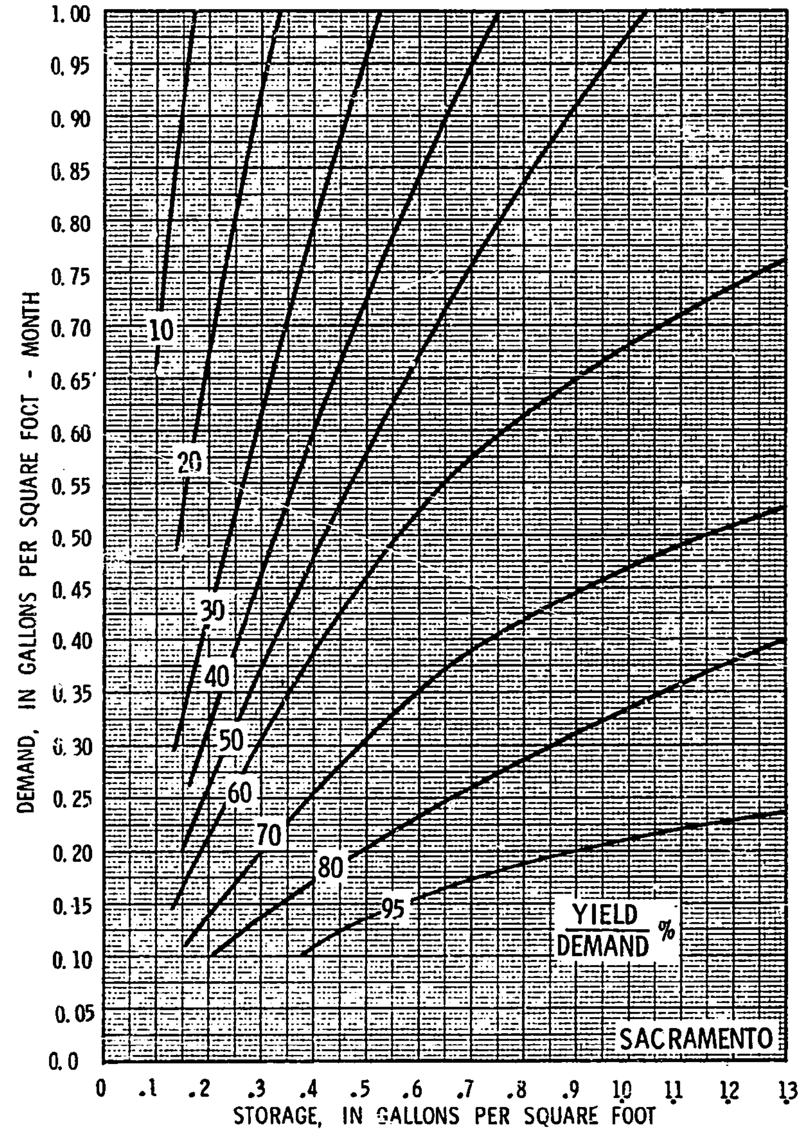

FIGURE 11 *Yield as a percentage of demand versus demand and storage, Sacramento, California*

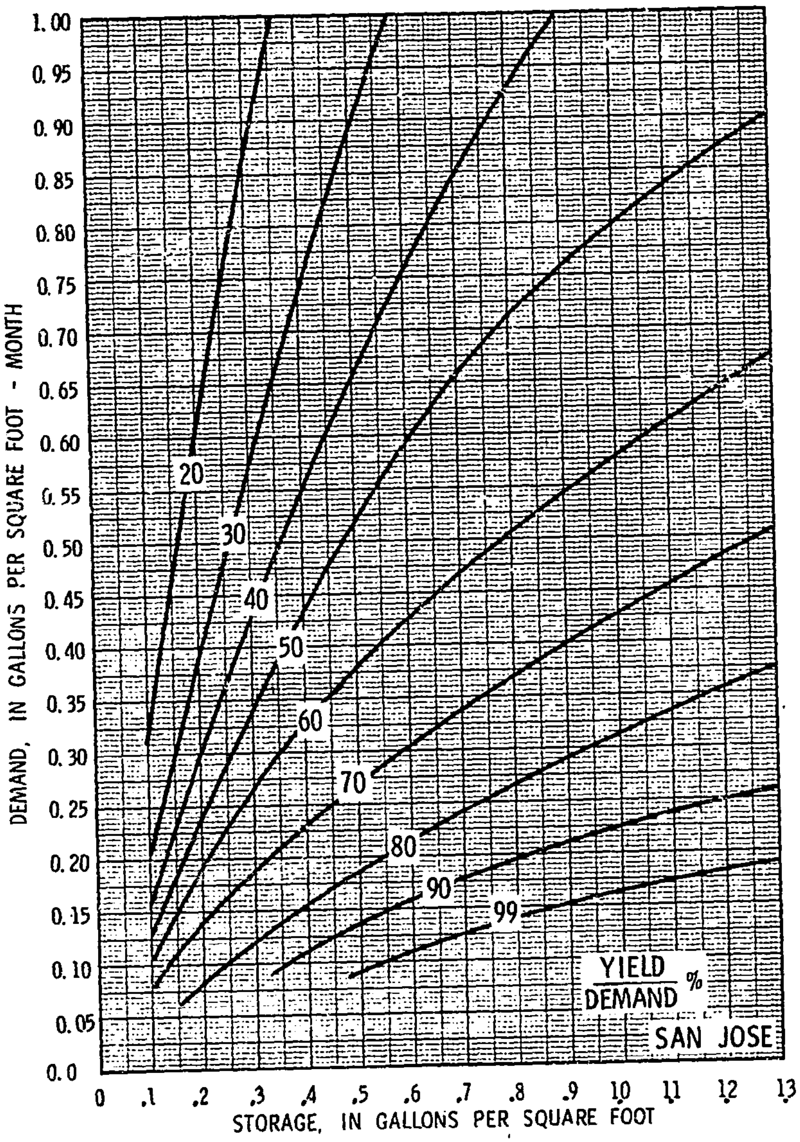

FIGURE 12 *Yield as a percentage of demand versus demand and storage, San Jose, California*

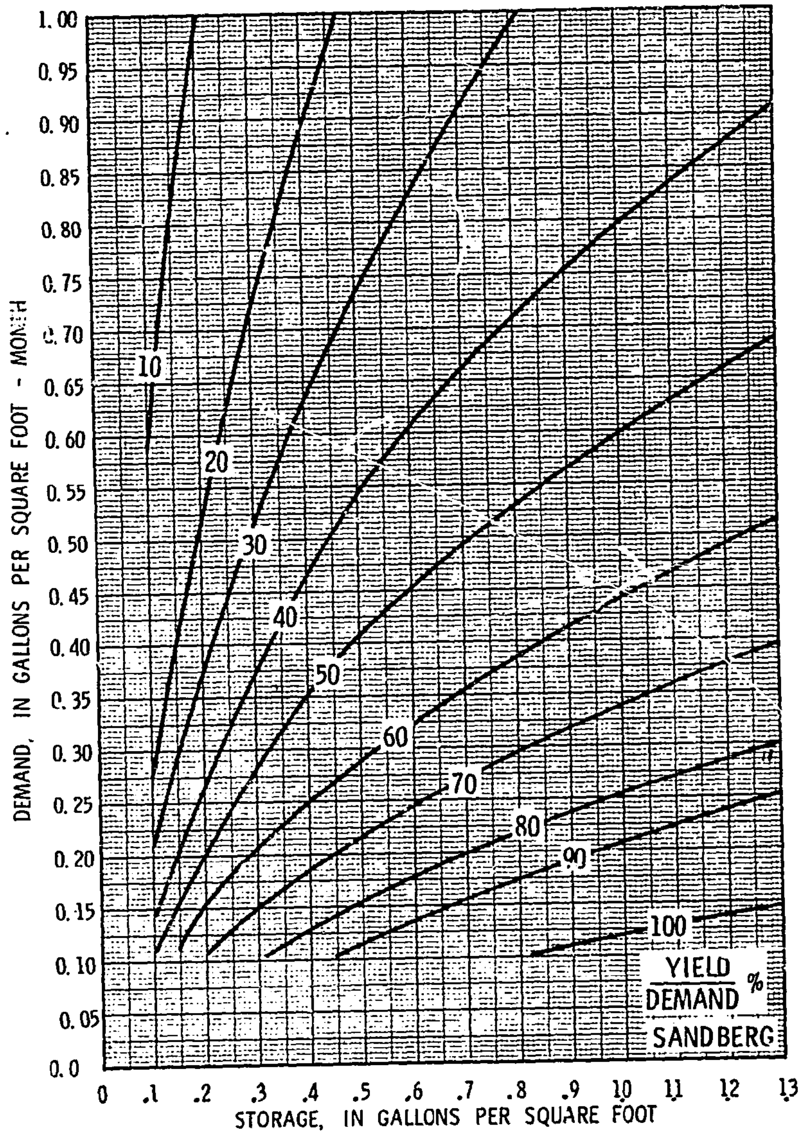

FIGURE 13 *Yield as a percentage of demand versus demand and storage, Sandberg, California*

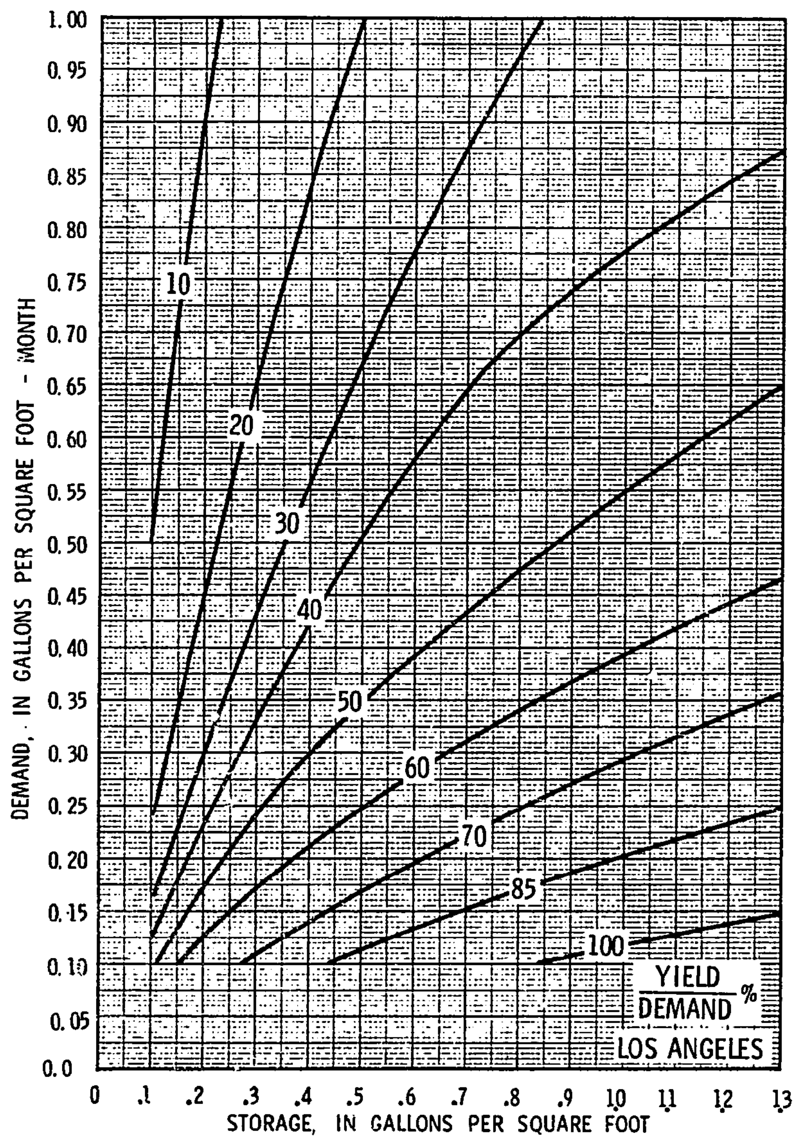

FIGURE 14 Yield as a percentage of demand versus demand and storage, Los Angeles, California

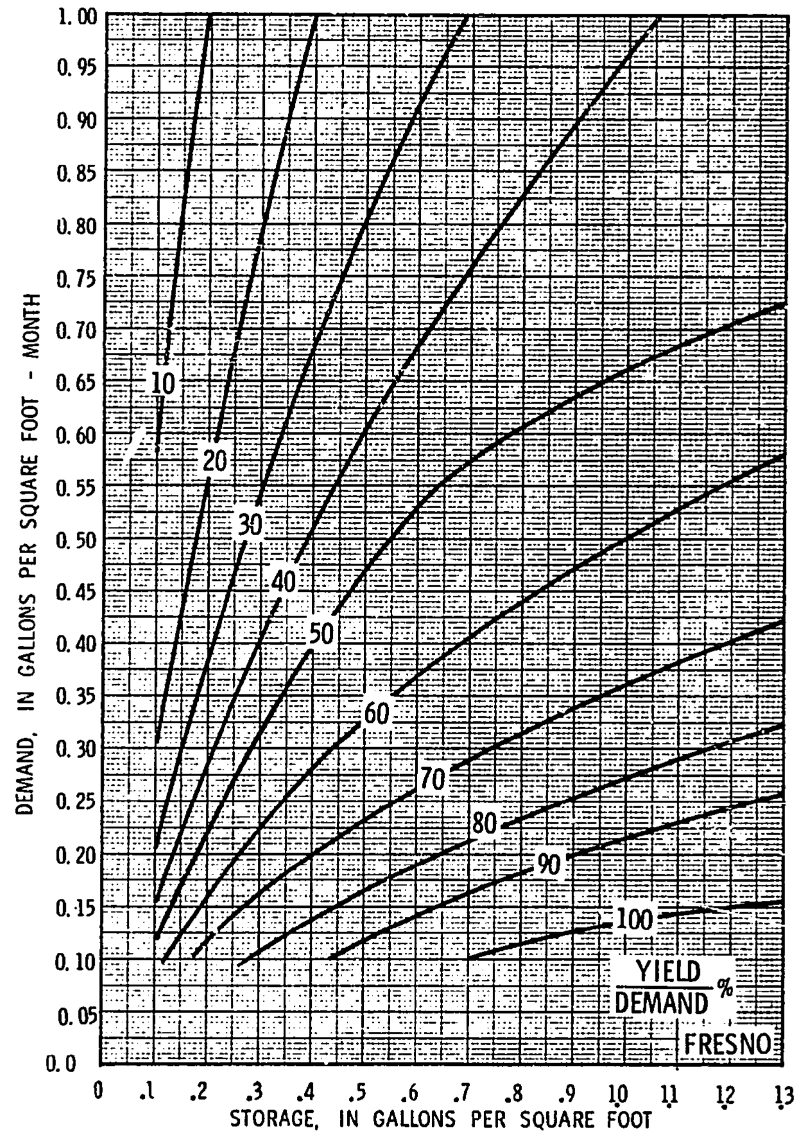

FIGURE 15 Yield as a percentage of demand versus demand and storage, Fresno, California

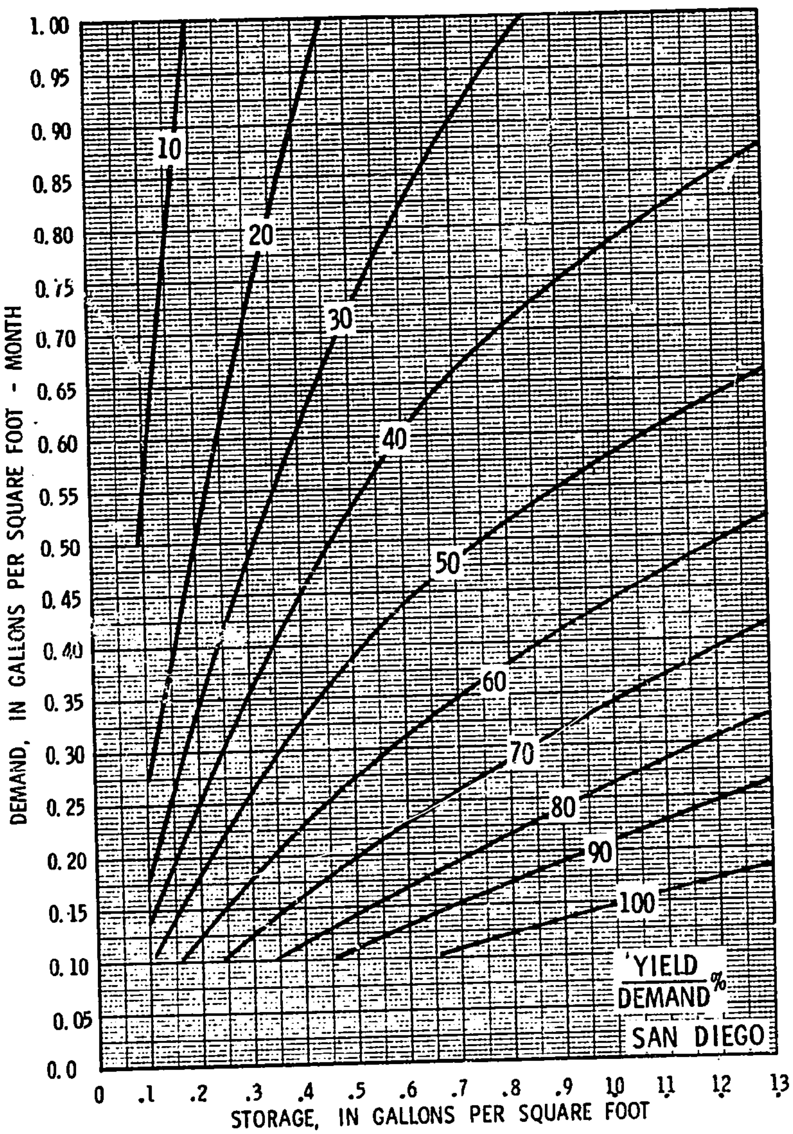

FIGURE 16 *Yield as a percentage of demand versus demand and storage, San Diego, California*

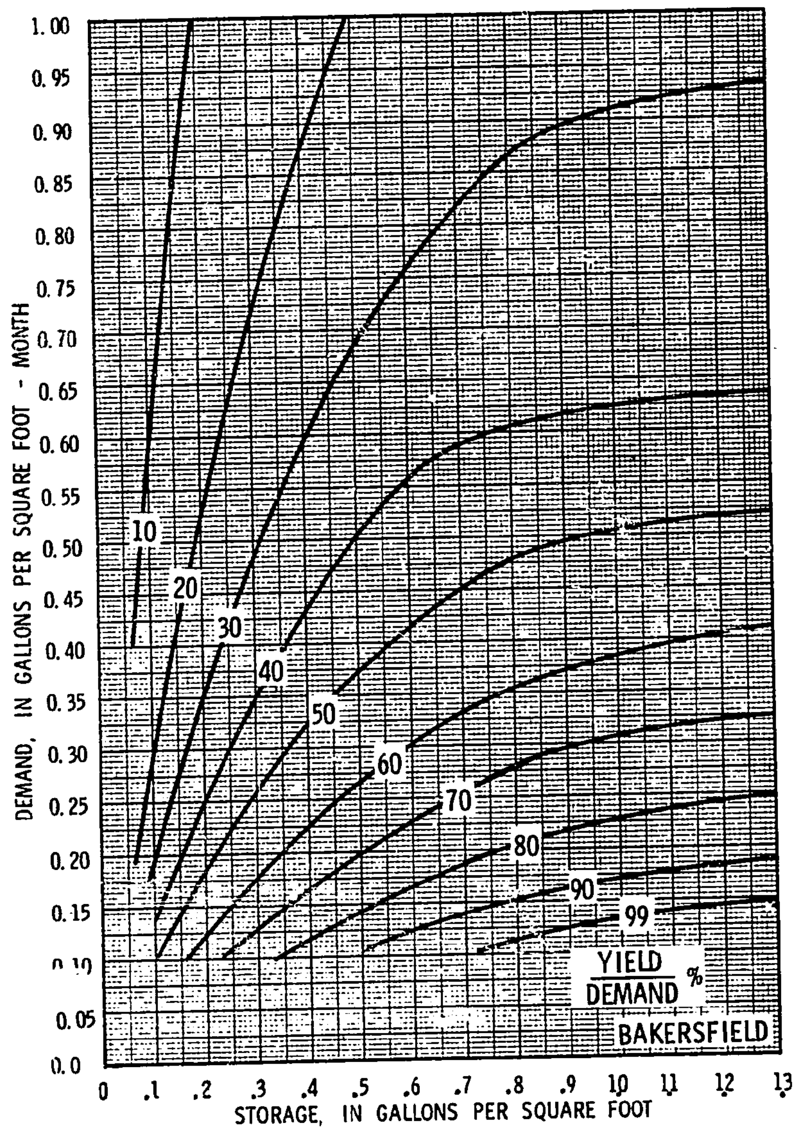

FIGURE 17 *Yield as a percentage of demand versus demand and storage, Bakersfield, California*

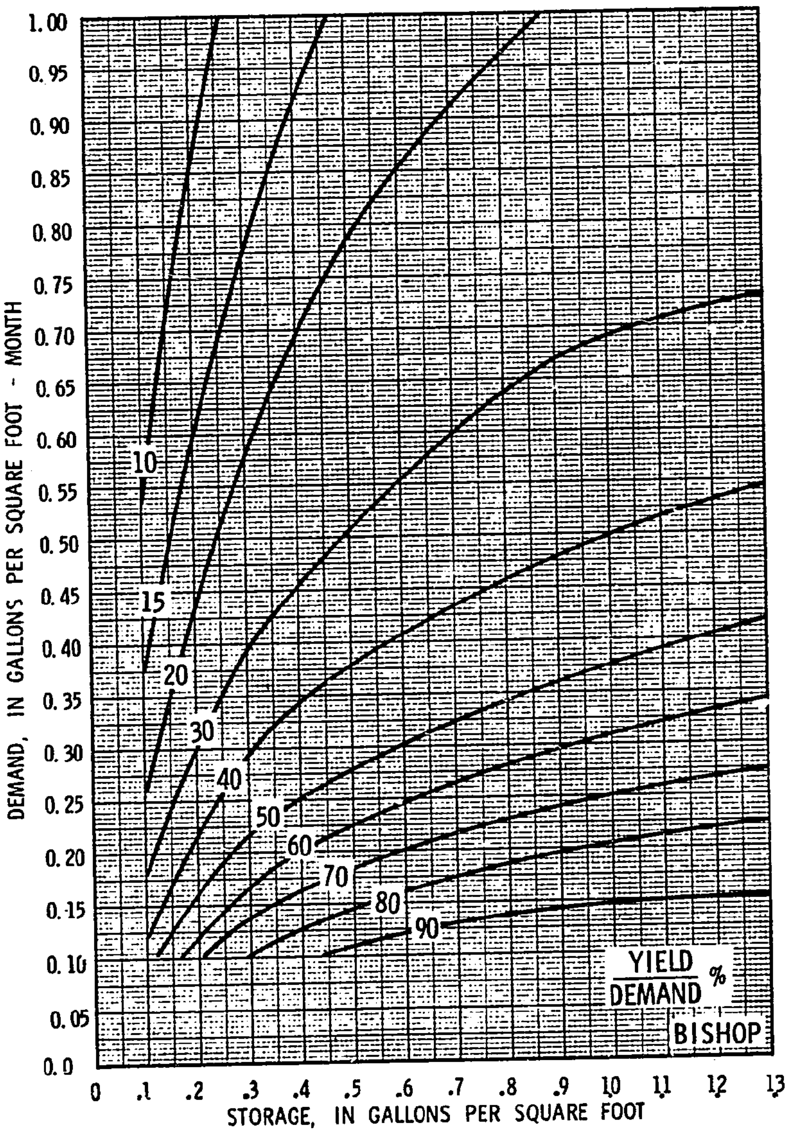

FIGURE 18 *Yield as a percentage of demand versus demand and storage, Bishop, California*

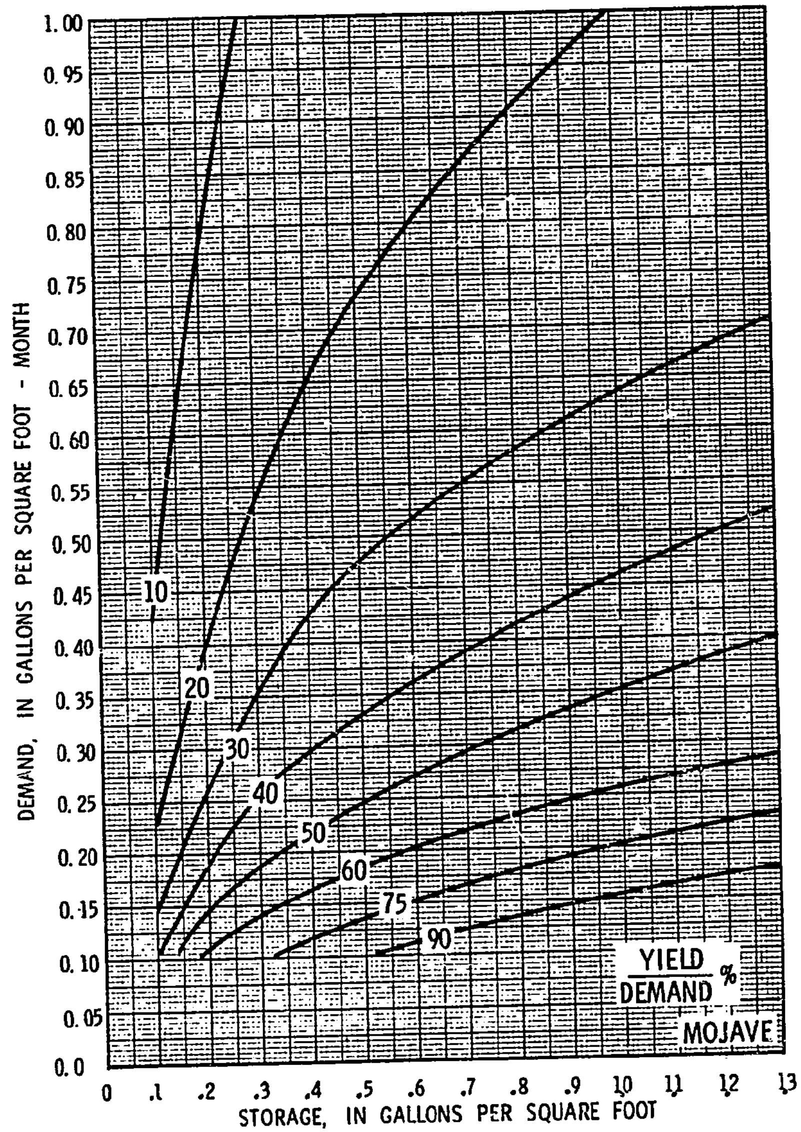

FIGURE 19 *Yield as a percentage of demand versus demand and storage, Mojave, California*

CHAPTER TWO

RAINWATER COLLECTION SYSTEM DESIGN

A digital mathematical model of a physical system in constant change considers the system as a series of events recorded at discrete time intervals. Disparity between such a system and its model can result from the time interval selected for the model being much longer than the frequency of fluctuations in input or response in the natural system.

To illustrate this problem consider an analogous hypothetical situation in which we conjecture that a bank sets an upper limit on checking account balances, and any money deposited in excess of that amount is automatically confiscated by the bank. Also, the bank does not permit overdrafts. In such a situation it would be possible to operate one's checking account without losing money to the bank, if deposits and withdrawals were small compared to the upper limit, and if on the average deposits and withdrawals balanced one another.

But then, suppose the bank in a zealous drive for efficiency sets a limit on the number of deposits and the number of withdrawals per year. An initial limit of 1,000 each per year should not trouble most people, but as the limit is lowered to 100, then 10, then 1 per year people are compelled to deposit and withdraw in ever larger amounts. At some point the deposit will exceed the bank's upper limit so that a part of the deposit spills into the bank's coffers. Then the account holder will never be able to withdraw as much as he deposits.

For a rainwater system the rainwater storage tank corresponds to the analogous bank account, rainfall on the collection area corresponds to deposits to the account, and demands for water correspond to withdrawals from the account. The real situation is represented where the number of deposits and withdrawals are unrestricted, so that there is a continual flow of water (money) into and out of the storage tank (account). The model situation is represented when rainfall (deposits) and water demands (withdrawals) are discretized. As the time interval between discrete transactions of water (money) increases, so may the discretized system perform less efficiently than the continuously varying case. At some sufficiently long time interval where the discretized input or output exceeds the maximum capacity of the storage tank (bank account), operation at full efficiency is impossible. In short, a model discretized over relatively long-time intervals may perform less efficiently than a continuous-response prototype that the model represents.

ALTERNATIVE SYSTEM MODELS The simplest rainwater collection model is as follows: in each time interval rainfall enters storage; then, if storage capacity is exceeded, the storage tank overflows; then, water is withdrawn, up to the demand for that time interval, if sufficient water is available in storage.

Rainfall records are available on a monthly and a daily basis, although considerably more effort is required to process daily data for the purpose of analyzing collection system performance. To evaluate the possible benefits of working with daily data the efficiency of rainwater collection system was estimated from both monthly and daily data. In addition, to narrow any discrepancy between system performances computed from the two sets of data, two modifications to the above-described model were investigated.

The first modification was to subdivide each monthly rainfall record into 30 equal portions and to compute system performance as if the portions each represented rainfall for each of 30 days of that month. This was described as the Yield and Rainfall Distributed (YRD) model for estimating day-by-day performance from monthly rainfall data.

A second device to compensate for an apparent loss of efficiency due to spillage when a longer time interval is used is to assume that the water for the time interval is withdrawn from storage before spillage occurs, the Yield Before Spillage (YBS) model. This modifies the Yield After Spillage (YAS) model described above. The real world lies somewhere between the YAS and YRD assumptions.

In equation form, the YAS model is defined by Equations 1a and 2a, while the YBS model is defined by Equations 1b and 2b. The YRD model is defined in the same way as YAS except that rainfall and demand data are subdivided:

$$S_i = \min (S_{i-1} + R_i, S) - Y_i \tag{1a}$$

$$Y_i = \min (D_i, S_{i-1}) \tag{2a}$$

or

$$S_i = \min (S_{i-1} + R_i - Y_i, S) \tag{1b}$$

$$Y_i = \min (D_i, S_1 + R_i) \tag{2b}$$

where S_i = water in storage at the end of the i-th time period, in inches; R_i = rainfall during the i-th period, in inches; Y_i = yield from system during the i-th period, in inches; D_i = demand from system in the i-th period, in inches; and S = the storage volume provided, in inches. Note that in both models the initial values of S, S_o, may lie in the range zero to S, but is in this model set to zero.

Having selected one of these models for evaluation, a rainfall record from which system performance is to be established is entered in Equations 1 and 2, sequentially for each time interval of the record. System performance is evaluated by Equations 3 and 4:

$$P = \frac{N_D}{N} \text{ X } 100\% \tag{3}$$

$$Q = \frac{\sum_{i=1}^{N} Y_i}{\sum_{i=1}^{N} D_i} \text{ X } 100\% \tag{4}$$

where N_D = number of time intervals of the record for which $Y_i = D_i$; N = total number of time intervals in the record; P = percent of time that the specified demand is met; and Q = percent of specified demand that is met. Comparing P and Q with performance criteria used in Chapter One, it was found that P = 100 = percent of time that system fails, and Q = percent yield = percent of cumulative demand met.

To facilitate presentation of performance characteristics as a function of demand and storage it is convenient to express demand and storage in nondimensional form. Demand divided by the supply of rainfall is a nondimensional demand parameter which lies in the range zero to 100%. Storage divided by a value called "equalizing storage" is also a nondimensional parameter in the range zero to 100%. Equalizing storage is defined as the storage volume required to sustain a uniform yield equal to 100% of the mean rainfall. It is computed as the range of cumulative deviations of rainfall from mean rainfall, or in equation form:

$$S_E = \max_{i=1,N} \left[\sum_{j=1}^{i} \left(R_j - \sum_{k=1}^{N} R_k/N \right) \right] - \min_{i=1,N} \left[\sum_{j=1}^{i} \left(R_j - \sum_{k=1}^{N} R_k/N \right) \right] \tag{5}$$

where S_E = equalizing storage, in inches.

RESULTS For thirteen representative locations in California shown in Figure 1, Table 1 summarizes data on mean rainfall, equalizing storage, and system performance versus demand exerted and storage provided. Locations are ordered according to decreasing mean annual rainfall. For each location, mean rainfall, equalizing storage, and performance data were computed from three different rainfall records: D10 (approximately 10 years of daily rainfall data), M10 (the same 10 years of monthly rainfall data), and M40 (approximately 40 years of monthly rainfall data).

In each case, performance data were computed separately by the two models, YAS and YBS. Performance data according to the YRD model were also computed from the M10 record. (According to the YRD model the specified demand was met 2% to 5% more of the time than indicated by the YBS model, and the YRD and YBS indicated the same percent of the specified demand met, within 1%). The following comments relate to Table 1:

1) Equalizing storage computed from the 10 year record approximates 1.25 times the annual rainfall, as shown in Figure 20.

2) System performance expressed as percent of time that the specified demand is met is lower than performance expressed as percent of specified demand that is met. The reason is that for any time interval the demand is partially but not entirely met the system is considered to have failed with respect to the percent of time criterion, although only partial failure with respect to the percent of specified demand criterion is recorded.

3) System performance computed assuming the yield to be withdrawn after spillage (YAS) is lower than performance computed assuming the yield to be withdrawn before spillage (YBS). This is because the amount of newly collected water that is spilt from storage will be less if the yield is deducted from the newly collected water before it enters storage (YBS).

4) System performance under the YAS assumption is almost identical to that under YBS when daily rainfall records are analyzed, although the difference can be large when monthly records are analyzed. The reason is that when daily records are analyzed the time interval is so small that both the YAS model and the YBS model closely approximate the real-world situation of continuous input to the system and continuous withdrawal. However, when this real-world situation is discretized in relatively large monthly steps, then any observations resulting from the particular assumptions of the model become significant.

5) Under the YAS assumption, the specified demand is met 0% of the time if the demand per unit time interval exceeds the storage volume provided. This effect explains the 0% performance values in Table 1. This does not appear when shorter time intervals are used, e.g., one day.

6) System performance estimated from 10 years of monthly data is comparable, though slightly lower than that estimated from the same period of daily data. The reason is that spillage is greater if an entire month's rain enters storage before withdrawal is made than if water is withdrawn every day.

Table 2 presents system performance data recomputed for storage as a percentage of mean annual rainfall, whereas Table 1 storage was expressed as a percentage of equalizing storage. It is desirable to express demand and storage in terms of mean annual rainfall, which is a readily available data item for any given location, from the practical viewpoint of establishing system performance relationships usable throughout California.

Figure 21 presents performance characteristics for Oakland, California, as computed from 10½ years of daily data (1967-77) using the YAS model, while Figure 22 shows the fraction of demand met as a function of demand and storage capacity for 12 other California locations. For comparison, Figure 23 shows performance data for Oakland, computed for the same period of daily data using the YBS model. Figures 24 and 25 are for the same period, but this time are for data analyzed on a monthly basis using YAS and YBS models. Figures 26 and 27 are for the 40½ years of monthly data (1937-77) using YAS and YBS models. In each figure (Figs. 21-27) is plotted Equation 6, which envelopes the 100% performance contours, thereby providing a suitable basis for designing the capacity of storage tanks to reliably sustain a given demand:

$$\frac{D}{R} = 0.8 \left(\frac{S}{R}\right)^{0.8} \tag{6}$$

where R = annual rainfall, in inches; D = annual demand for water, in inches, $\geq$ R; and S = storage provided, in inches.

Note that Equation 6 generally overestimates the storage needed to sustain a given demand (or underestimates the demand that a given storage will maintain) as is necessary in order to establish statewide validity. This margin of overdesign might be considered a safety factor against statistical vagaries in future rainfall records possibly not reflecting historical patterns on which this design procedure was based. However, some economy of design will often result from using Figures 7-19 or Figures 21-22 to size storage tanks, rather than Equation 6, especially if some deficit in the supply of water can occasionally be tolerated.

To convert Equation 6 into a form more readily usable for system design it was noted that the daily yield of the system, in gallons = annual demand, in inches X collection area, in square feet X 7.4805/(12 X 365.25). Also the storage volume in gallons = storage, in inches X collection area, in square feet X 7.4805/12. Substituting these conversions, Equation 7 is obtained:

$$Q = 0.002\ A^{0.2}\ R^{0.2}\ V^{0.8} \tag{7}$$

where Q = system yield, in gallons per day; A = collection area, in square feet; and V = storage volume, in gallons. Equation 7, which is valid throughout California, is constrained by the condition that D $\leq$ R, which converts to Equation 8:

$$Q \geq 0.0017AR \tag{8}$$

Figure 28 presents the design relationships expressed by Equations 7 and 8.

An example problem illustrating the use of Figure 28 is to design a storage tank fed by a 2500 square foot roof in Oakland to maintain a reliable supply of 30 gallons per day (gpd). First enter the collection area, 2500 sq ft, and the annual rainfall, 18.7 inches, in the left side of Figure 28 (or Equation 8) to obtain the average supply of rainfall = 0.0017 X 2500 X 18.7 = 79 gpd, which exceeds the required yield of 30 gpd. Next, follow across to the right side of Figure 28 (or use Equation 7) for the required storage volume = $[30/(0.002 \times 2500^{0.2} \times 18.7^{0.2}]^{1/0.8}$ = 11,300 gal or approximately 14 ft square by 8 ft deep. The percentage utilization of rainfall is 100% X 30/79 = 38%.

Costs for construction of such a tank including a pump may approximate $3,000 under favorable conditions, corresponding to a cost of water of approximately $30 per thousand gallons, discounting at 10% over a 30 year life. This is 70 times the price of municipal water in Oakland, so that roof water is unlikely to be economically feasible where a public supply or suitable groundwater is available.

An approach likely to reduce costs is to design a storage tank for less than 100% reliability, sizing the tank equal to the capacity of a large tanker truck that would be relied upon to refill the storage tank in the event of a dry period. For example, if a tanker truck of 2000-gallon capacity is available to transport water, the design problem is to estimate how much trucked water would be needed.

Again assume a 2500-square foot roof in Oakland, and a demand of 30 gpd. It is required to compute the percentage reliability of a 2000-gallon rainwater storage tank, which is equivalent to 2000 X 12/(2500 X 7.4805) = 1.28 inches over the roof area. First compute demand/rainfall = 30/79 = 0.38, and storage/rainfall = 1.28/18.7 = 0.068. Now refer to Figure 21 for Oakland. From the design point indicated by a solid black circle in the upper and lower parts of Figure 21, it is seen that rainwater will provide approximately 75% of the demand.

Costs are now reduced. A prefabricated 2000-gallon tank costs approximately $1,000 installed with a pump, which reduces the cost of rainwater to approximately $13 per thousand gallons. If 2000 gallons of trucked water costs $50, the average price of water is 0.75 X 13 + 0.25 X 25 = $16 per thousand gallons. However, it is noted that, even if total reliance were placed on trucked water, a storage tank of the same capacity as the truck would still be necessary, so it is reasonable to regard the rainwater system as almost free.

TABLE 1

SYSTEM PERFORMANCE FOR SPECIFIED STORAGE/EQUALIZING STORAGE

Station	Record Type*	Mean Rain (in./yr)	Equaliz Storage (in.)	System Performance: % Time Specified Demand Is Met			System Performance: % of Specified Demand That is Met		
Demand / Mean Rainfall (%)				10	100	100	10	100	100
Storage / Equalizing Storage (%)				1	1	10	1	1	10
Yield After or Before Spillage ?				A B	A B	A B	A B	A B	A B
A: Blue Canyon	D10	66.88	87.75	91/91	34/37	64/64	91/91	39/41	65/65
WSOG	M10	66.87	84.79	81/93	0/35	39/51	89/97	12/57	61/69
	M40	66.06	164.74	92/98	0/42	61/68	96/99	21/58	73/79
B: Eureka	D10	38.93	43.12	91/91	38/41	64/65	91/91	42/45	66/67
WSO CI	M10	38.92	41.25	81/94	0/40	42/54	89/97	11/60	62/70
	M40	39.67	48.09	81/92	0/44	47/59	89/96	12/61	64/72
C: Red Bluff	D10	21.10	25.09	84/85	29/32	59/60	85/85	32/35	60/61
WSO AP	M10	20.88	25.53	73/88	0/33	38/48	83/93	11/53	59/64
	M40	21.92	55.95	92/98	0/39	59/66	95/99	21/56	70/77
D: Oakland	D10	18.71	25.26	78/79	28/30	58/58	79/79	31/33	59/59
WSO AP	M10	18.70	24.07	66/80	0/33	38/48	77/87	11/51	55/63
	M40	18.34	33.89	76/86	0/37	51/60	82/90	14/52	62/69
E: Sacramento	D10	17.55	25.76	81/81	29/32	59/59	81/81	32/34	59/60
WSO CI	M10	17.54	25.22	74/86	0/30	36/49	81/90	12/51	59/64
	M40	18.17	41.65	82/91	0/36	53/60	88/95	18/53	66/73
F: San Jose	D10	14.30	16.90	80/80	26/28	59/57	80/80	28/31	58/58
	M10	14.29	16.26	67/21	0/35	38/47	76/86	9/51	54/62
	M40	13.67	33.51	83/91	0/36	54/62	88/95	18/52	66/74
G: Sandberg	D10	14.25	17.32	71/71	18/20	46/46	71/71	20/22	47/47
WSO	M10	14.25	16.63	58/70	0/26	27/43	68/78	9/40	43/54
	M40	12.56	66.21	98/100	0/32	71/76	88/100	28/48	79/82
H: Los Angeles	D10	11.14	17.56	71/71	19/21	51/51	71/71	21/23	52/52
WSO AP	M10	11.14	17.00	55/70	0/30	37/50	69/78	10/41	50/58
	M40	12.54	62.87	95/99	0/36	70/74	97/99	26/47	77/80
I: Fresno	D10	10.69	17.70	81/81	28/30	61/61	81/81	29/31	61/62
WSO AP	M10	10.69	16.65	66/77	0/37	48/58	78/85	12/51	59/67
	M40	10.22	23.93	77/86	0/38	56/63	84/92	17/52	66/73
J: San Diego	D10	8.98	11.82	75/75	19/21	53/54	75/75	21/23	54/55
AP	M10	8.98	11.23	62/75	0/33	34/51	73/83	9/46	51/62
	M40	9.61	40.05	94/99	0/36	68/72	97/99	26/51	76/81
K: Bakersfield	D10	5.78	7.22	76/76	21/24	57/58	76/76	23/25	58/58
WSO AP	M10	5.76	6.59	63/77	0/39	41/57	70/81	9/51	55/66
	M40	5.96	19.88	90/96	0/40	67/72	91/96	23/54	75/81
L: Bishop	D10	5.41	14.76	97/97	27/28	63/63	97/97	29/30	64/64
WSO AP	M10	5.39	14.30	92/97	0/28	48/53	95/98	17/46	63/67
	M34	5.41	16.99	95/98	0/28	51/57	98/100	21/46	65/70
M: Mojave	D10	5.08	11.81	91/91	22/23	59/57	91/91	23/25	58/58
	M10	5.08	11.48	80/90	0/26	44/54	88/95	14/42	56/64
	M29	4.62	16.33	89/94	0/30	58/65	92/96	20/45	67/72

* D10 = 10 Year Daily Record, M10 = 10 Year Monthly Record, M40 = 40 Year Monthly Record.

TABLE 2

SYSTEM PERFORMANCE FOR SPECIFIED/STORAGE ANNUAL RAINFALL

Station	Record Type*	System Performance							
		% of Time That Specified Demand is Met				% of Specified Demand That is Met			
Demand/Mean Rainfall(%)		50	50	100	100	50	50	100	100
Storage/Mean Ann.Rain(%)		2	20	2	20	2	20	2	20
Yield After or Before Spillage		A B	A B	A B	A B	A B	A B	A B	A B
A: Blue Canyon WSO G	D10	60/61	96/96	41/43	71/71	62/63	96/96	44/46	72/72
	M10	0/62	93/97	0/37	50/59	38/74	96/98	19/58	68/76
	M40	0/58	99/100	0/40	55/62	34/70	100/100	16/57	68/75
B: Eureka WSO CI	D10	64/65	98/98	46/47	74/74	66/67	98/98	49/51	75/76
	M10	0/65	97/99	0/42	56/64	38/75	98/99	19/61	71/79
	M40	0/62	94/97	0/44	3/67	39/75	96/98	19/62	72/80
C: Red Bluff WSO AP	D10	56/57	96/96	37/39	67/67	57/58	96/96	39/41	67/68
	M10	0/56	92/95	0/36	48/57	35/70	95/97	18/54	64/71
	M40	0/54	97/100	0/38	51/60	33/69	99/100	15/55	64/73
D: Oakland WSO AP	D10	50/51	91/92	33/35	64/64	51/52	92/92	36/38	65/65
	M10	0/50	89/93	0/34	47/55	33/65	92/96	16/52	62/64
	M40	0/52	84/93	0/38	52/61	32/64	90/96	16/53	63/71
E: Sacramento WSO CI	D10	52/53	91/92	34/36	64/64	53/54	92/92	36/38	65/65
	M10	0/53	86/91	0/32	44/54	34/68	92/95	17/52	62/69
	M40	0/53	90/98	0/36	49/56	31/65	95/99	15/52	62/70
F: San Jose	D10	49/50	92/92	33/34	64/64	50/51	92/93	35/37	65/65
	M10	0/53	87/94	0/36	48/55	32/65	91/96	16/53	63/69
	M40	0/50	94/100	0/85	49/57	30/63	97/100	14/51	61/69
G: Sandberg AP	D10	37/38	84/85	23/24	55/56	39/40	85/85	25/26	56/57
	M10	0/40	78/86	0/26	43/54	27/56	84/89	14/41	54/63
	M40	15/42	99/100	0/17	52/62	35/51	100/100	9/39	65/72
H: Los Angeles WSO AP	D10	36/37	81/82	22/23	56/56	37/38	82/82	24/25	56/57
	M10	0/40	75/82	0/31	44/55	26/52	67/87	13/42	55/62
	M40	19/40	99/81	0/25	44/53	31/46	81/89	5/39	34/61
I: Fresno WSO AP	D10	47/48	89/90	31/32	64/65	48/49	90/90	32/34	65/65
	M10	0/51	85/90	0/38	54/62	32/63	89/93	16/52	64/71
	M40	0/49	89/96	0/37	51/60	28/61	94/98	14/51	62/70
J: San Diego AP	D10	40/41	87/87	24/26	62/62	41/42	88/88	26/28	63/63
	M10	0/46	83/90	0/33	50/62	28/58	87/93	14/47	61/70
	M40	0/33	82/89	0/18	50/57	26/46	87/93	12/40	59/67
K: Bakersfield WSO AP	D10	44/45	92/92	28/30	66/66	45/46	92/92	29/31	66/67
	M10	0/52	86/94	0/41	55/63	30/63	92/96	15/53	66/74
	M40	0/40	94/92	0/32	54/62	19/55	89/84	0/48	64/71
L: Bishop WSO AP	D10	40/41	99/100	22/24	59/59	42/43	79/100	25/26	60/60
	M10	0/34	96/100	0/27	43/48	27/58	99/100	13/44	59/63
	M40	0/32	83/89	0/27	39/48	29/58	90/94	12/44	56/63
M: Mojave	D10	33/34	86/86	20/21	53/54	35/36	86/86	21/23	54/54
	M10	0/34	79/86	0/26	40/51	24/54	85/89	12/41	53/61
	M40	0/31	77/83	0/27	42/51	27/52	83/88	8/41	53/61

*D10 = 10 Year Daily Record, M10 = 10 Year Monthly Record, M40 = 40 Year Monthly Record.

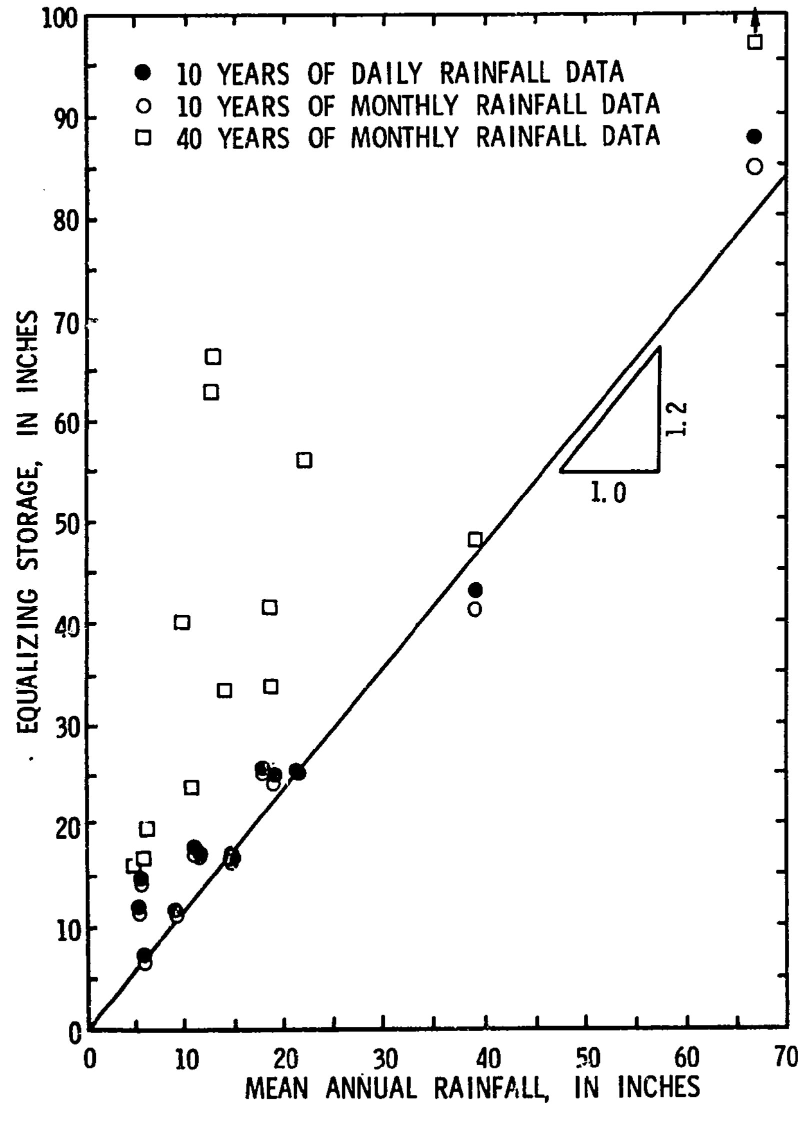

FIGURE 20 *Equalizing storage versus mean annual rainfall for 13 California locations*

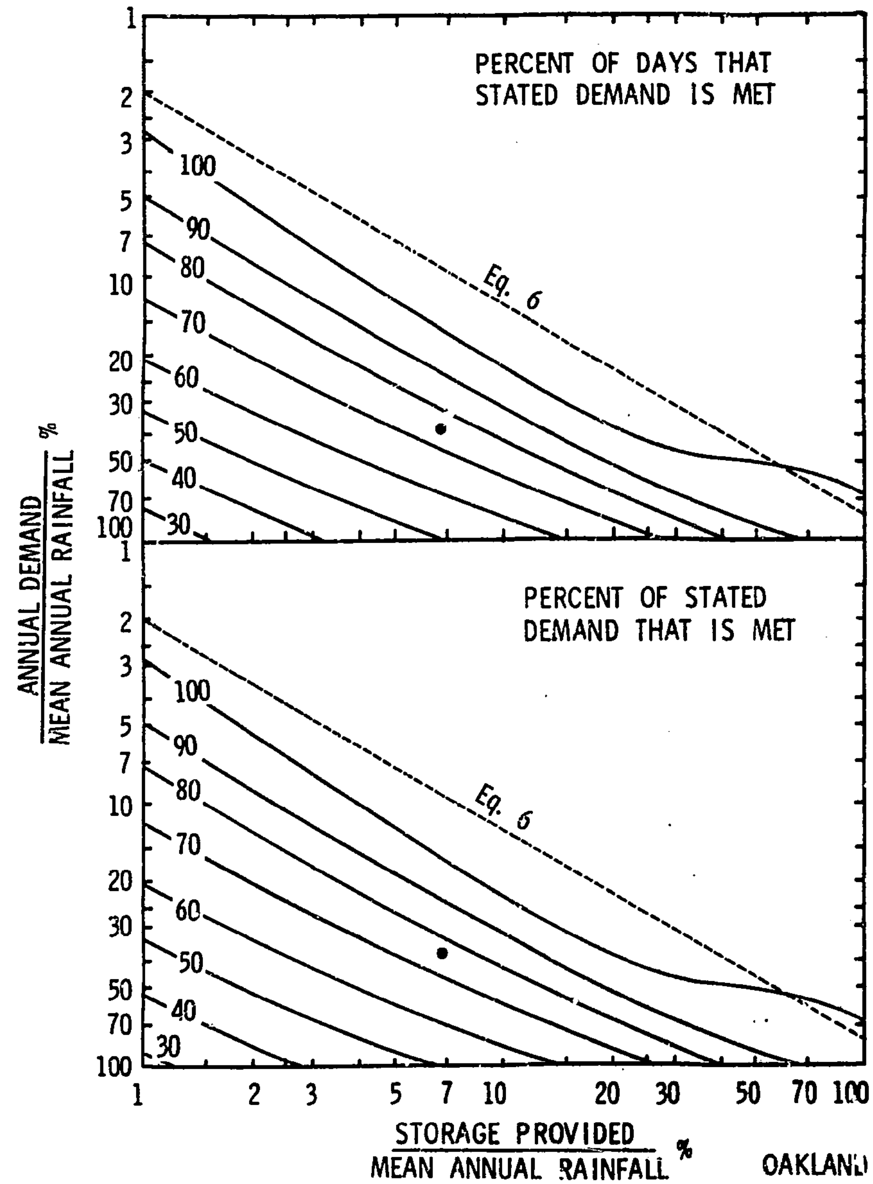

FIGURE 21 *Rainwater collection system performance versus demand and storage for Oakland, California*

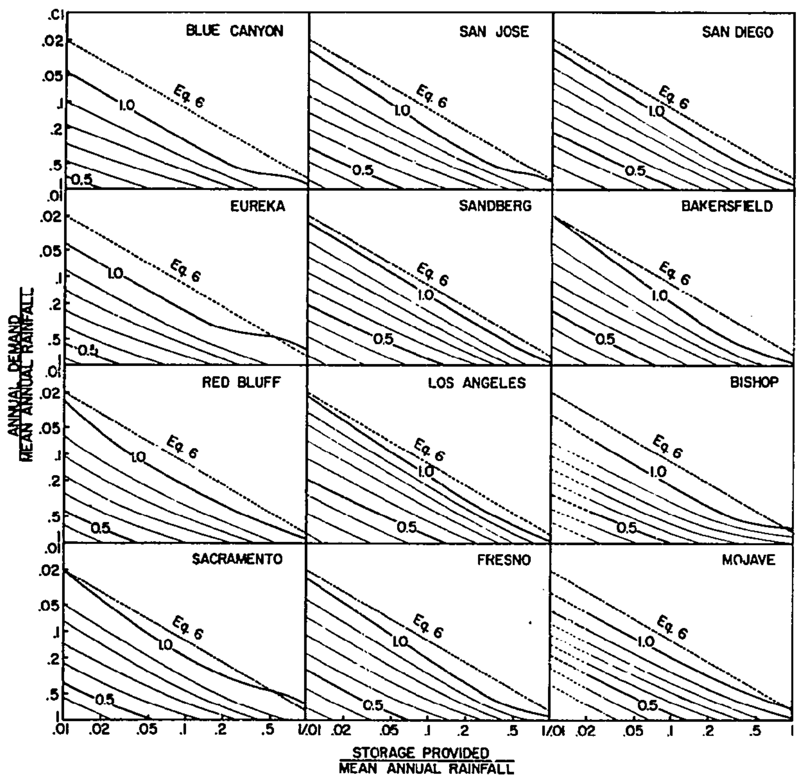

FIGURE 22 *Fraction of demand that is met by rainwater collection systems for 12 California locations*

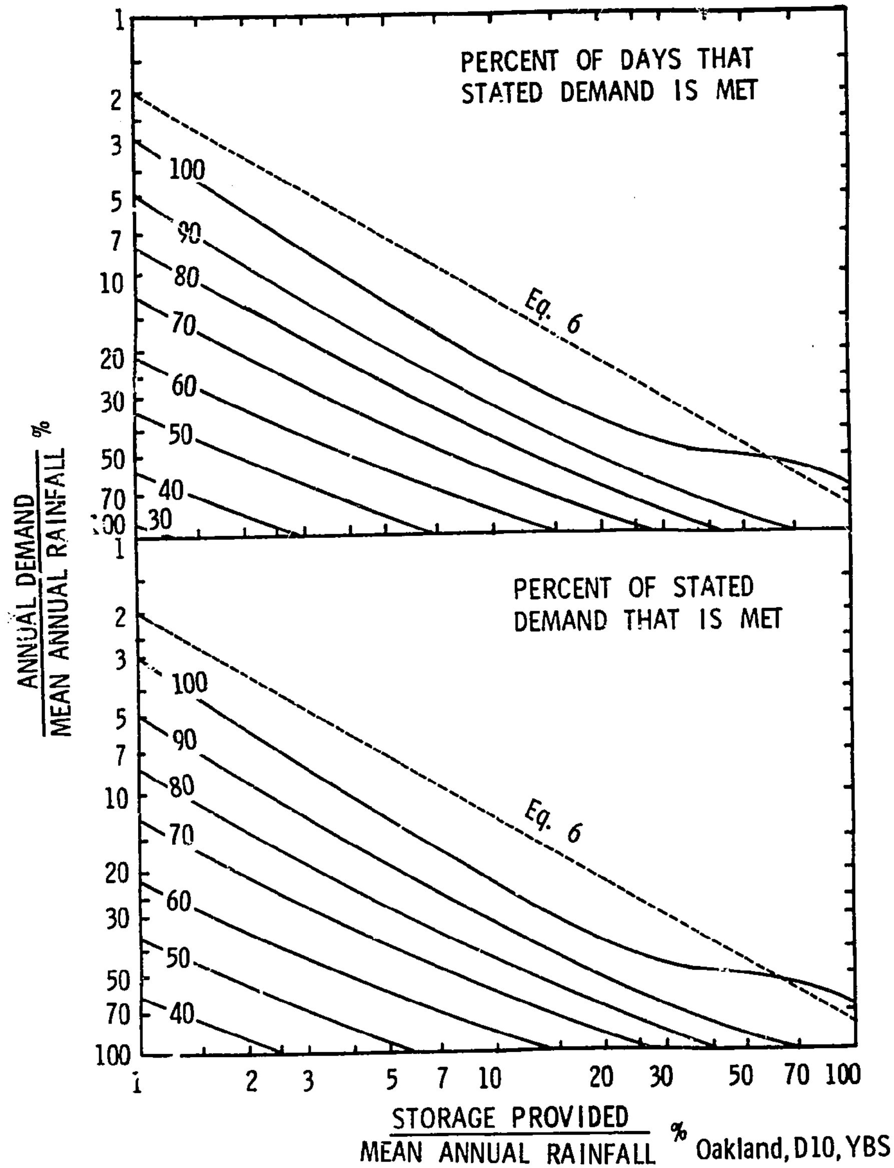

FIGURE 23 *System performance versus storage and demand at Oakland, computed by the YBS model from 10 years of daily rainfall data*

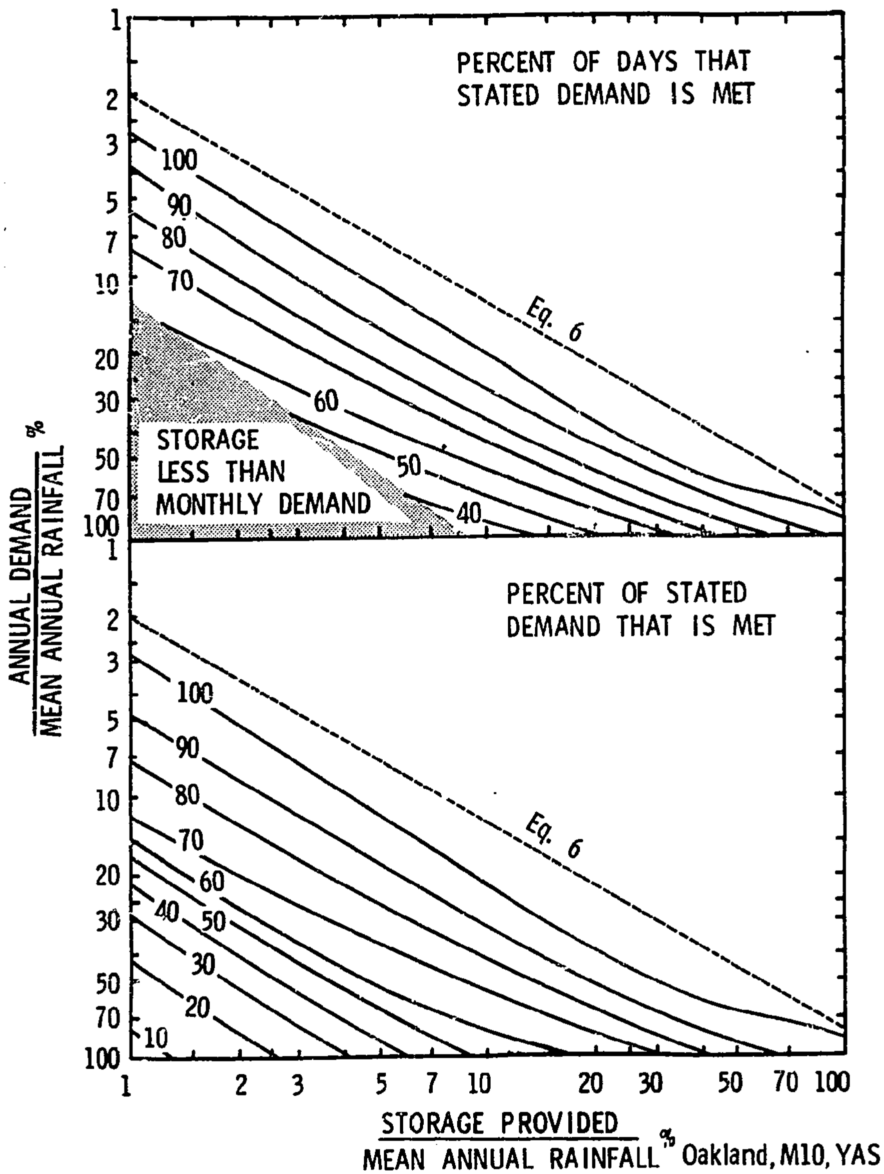

FIGURE 24 *System performance versus storage and demand at Oakland, computed by the YAS model from 10 years of monthly rainfall data*

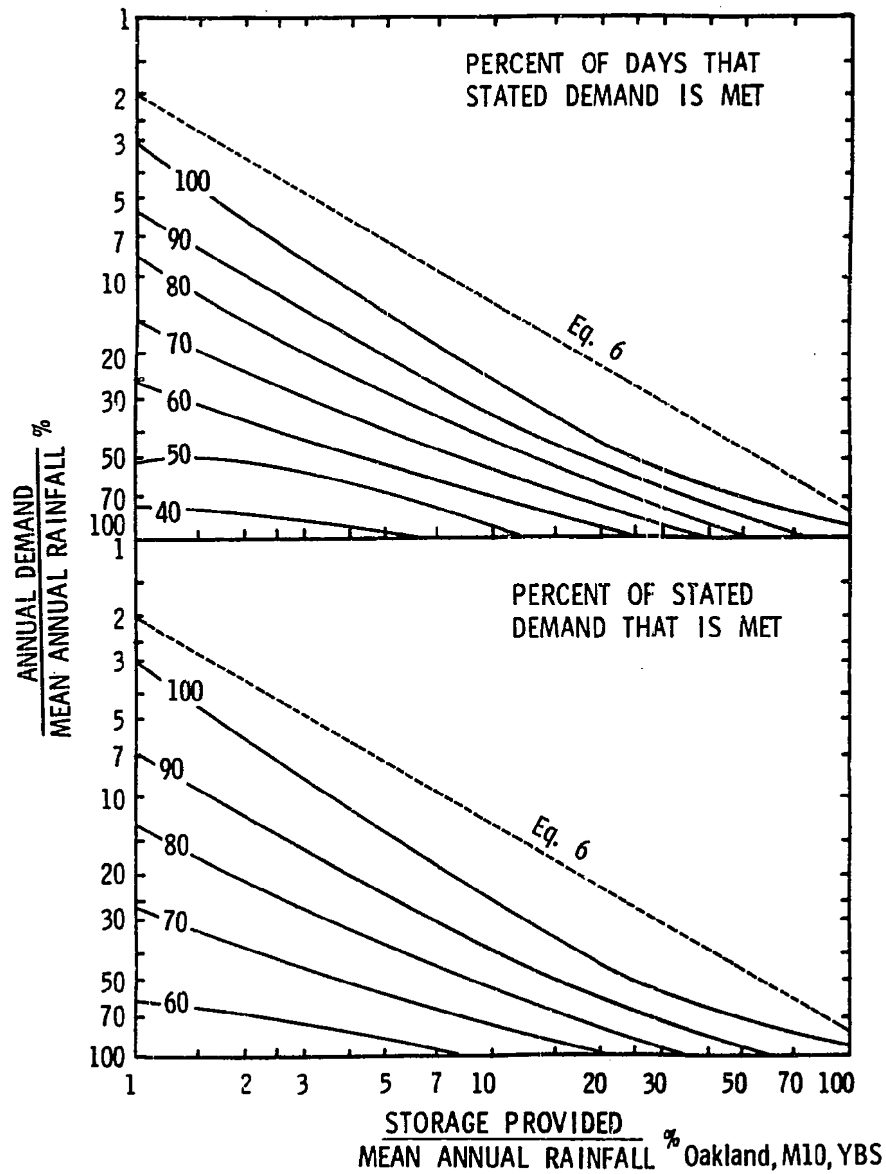

FIGURE 25 *System performance versus storage and demand at Oakland, computed by the YBS model from 10 years of monthly rainfall data*

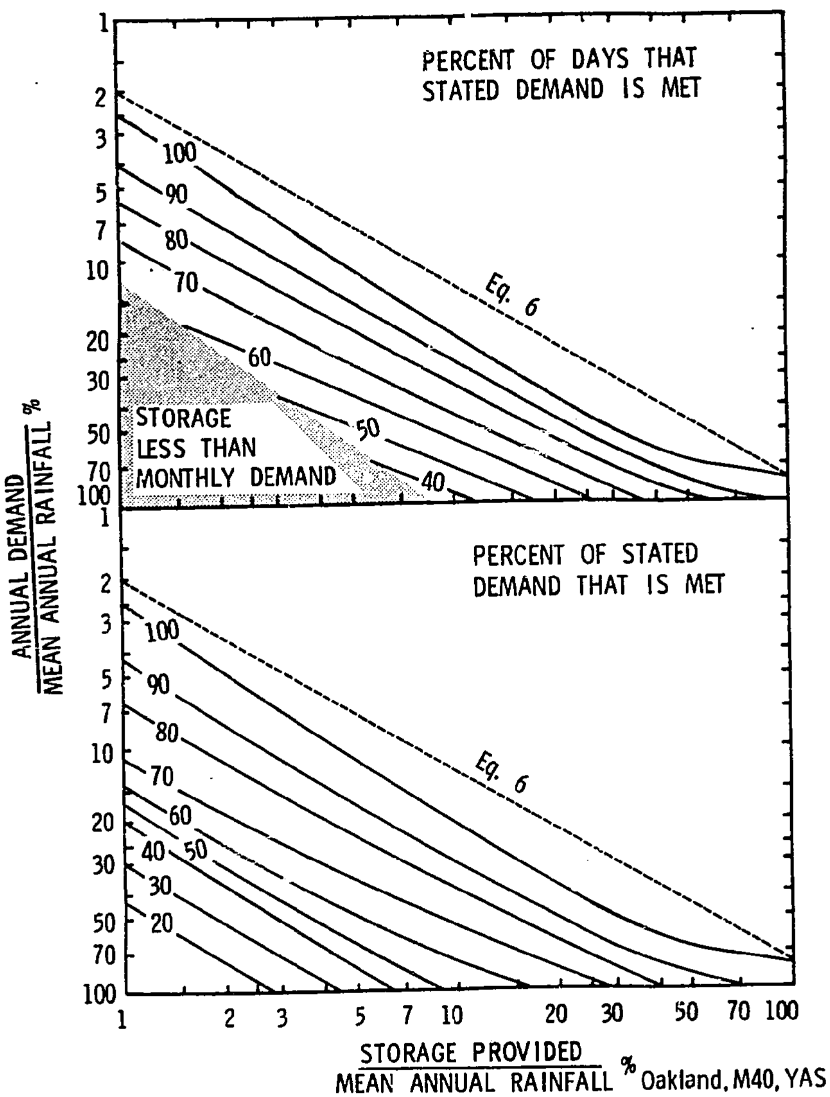

FIGURE 26 *System performance versus storage and demand at Oakland, computed by the YAS model from 40 years of monthly rainfall data*

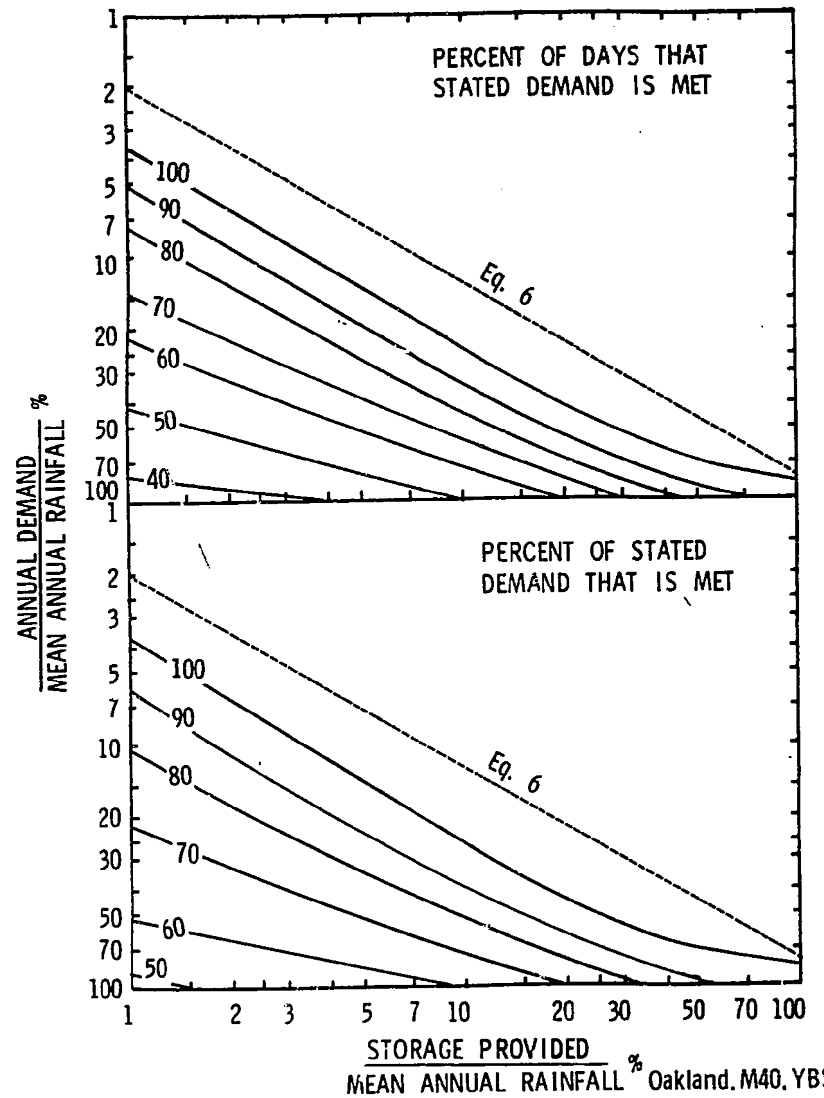

FIGURE 27 *System performance versus storage and demand at Oakland, computed by the YBS model from 40 years of monthly rainfall data*

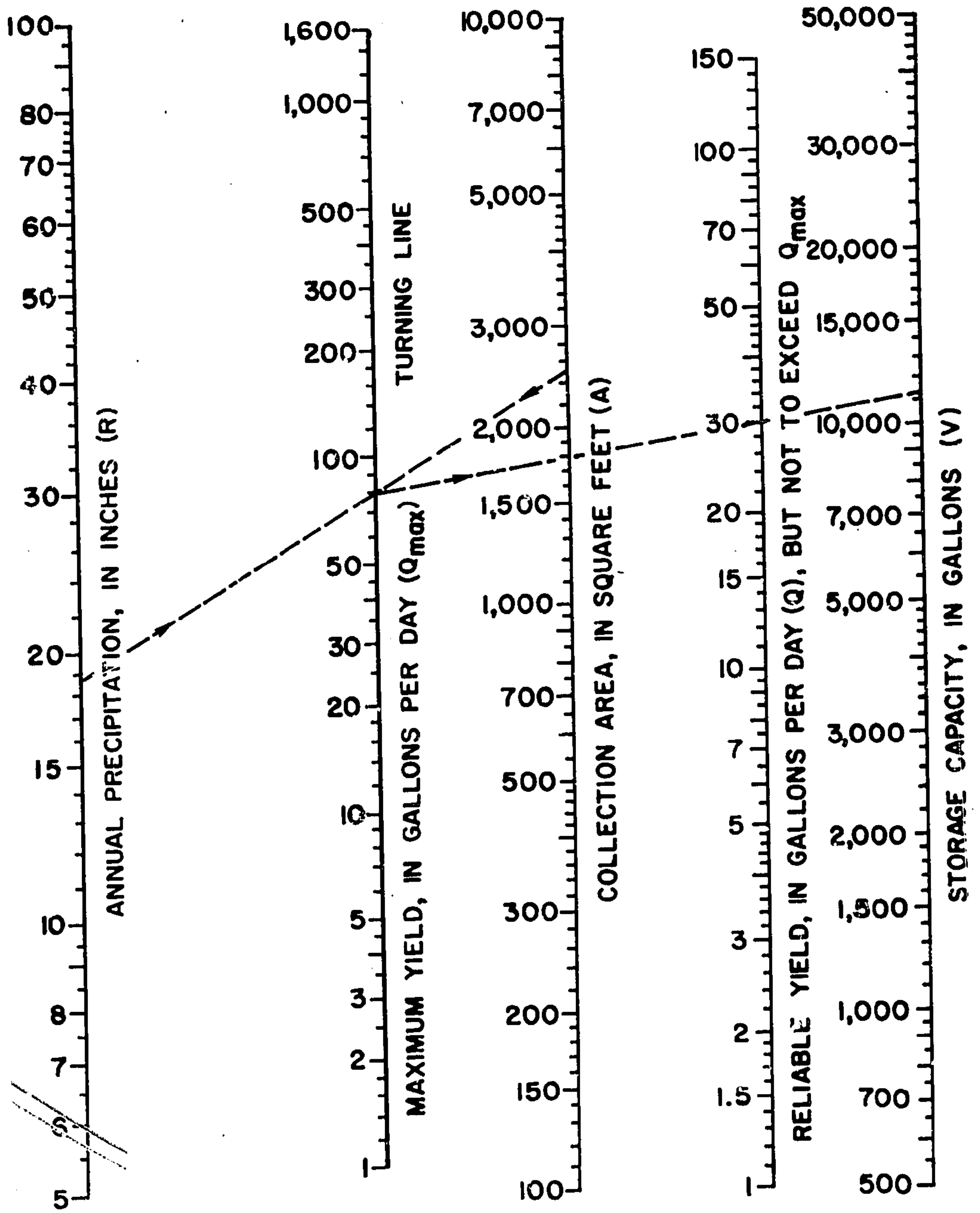

FIGURE 28 Rainwater collection system design graph

CHAPTER THREE

STATISTICAL INTERPRETATION OF SYSTEM PERFORMANCE

STATISTICAL CHARACTERIZATION OF RAINFALL RECORDS Although the mean annual precipitation at the California locations studied varies from 66 inches at Blue Canyon to only 5 inches at Mojave, there is a consistent pattern of relatively wet winters and dry summers that persists in all 13 locations throughout the state. This persistent annual distribution of precipitation manifests in a consistent pattern of rainwater collection system performance, as shown in Figures 21 and 22.

The purpose of this part of the study was to examine certain nondimensional statistical characteristics of 40 years of monthly precipitation records at the 13 selected California locations, for consistency between stations. If no statistically significant difference exists between stations it will be reasonable to regard a single set of nondimensional statistics as representative of all the locations studied, which are representative of all the major climatological regions of the state. The implications of this set of statistics with respect to the performance of rainwater collection systems can then be examined. Specifically, the tool of synthetic hydrology can be used to generate a simulated record of precipitation over as long a period as desired, for the purpose of evaluating long-term vs. short-term system performance. The storage required to reliably maintain a specified yield over a long period will generally be greater than if the system is to operate over only a brief period.

The following statistical parameters were selected to describe monthly precipitation at each of the 13 locations:

Monthly proportion of annual total rain

Coefficient of variation of monthly rain

Coefficient of skewness of monthly rain

Lag-one serial correlation coefficient of monthly rain

These statistics are presented in Figures 29-32 and in Tables 3-6. Note particularly the strong seasonal trend of mean annual rainfall (Figure 29 and Table 3), the higher variability of rainfall in summer than in winter (Figure 30 and Table 4), and the highly skewed distribution of summer rainfall (Figure 31 and Table 5) due to a large number of summer months entirely without rain together with a few summer months during the period of record when considerable rain fell. Finally, note from Figure 32 and Table 6 that no significant serial correlation occurs for summer rainfall, although there is a slight tendency for persistence to occur in the winter, such that abnormally wet winter months tend to occur in runs, and likewise for winter months with rainfall less than average for those months.

The positively skewed distribution of rainfall, particularly summer rainfall, suggests that the log-normal distribution may provide a better model for monthly rainfall in California than the normal distribution. Figures 33-36 and Tables 7-10 present statistics of the base-10 logarithms of monthly rainfall, zero rainfall having been transformed to 0.01 inches per month before taking logarithms. These statistics display similar trends to statistics of data prior to log-transformation, leaving open the question of whether monthly rainfall data conform better to a normal or log-normal distribution, or some other distribution.

Table 11 presents the chi-squared statistic for goodness of fit of rainfall data for any month and for each of the 13 stations to the normal distribution, while Table 12 shows values of chi-squared for goodness of fit to the log-normal distribution. It can be seen that there is no significant difference at the 5% level ($F = 24.9$) between the distribution of the data and the normal distribution in 16 cases out of 156, and no significant difference from the log-normal distribution in 47 cases out of 156. A significant difference at the 95% level ($F = 53.4$) occurs in 88 cases for the normal distribution and 65 cases for the log-normal distribution. To convey the goodness of fit visually, exceedance plots for Oakland are shown as Figures 37 and 38 for fit to the normal distribution.

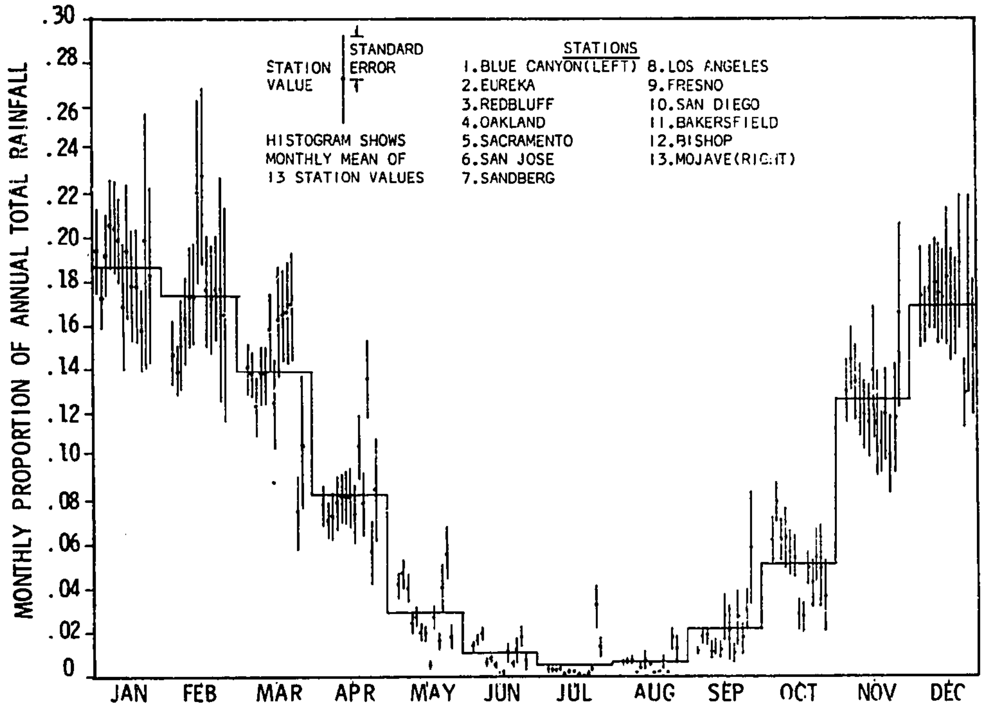

FIGURE 29 *Monthly proportion of annual total rainfall for 13 stations based on records 1937-76*

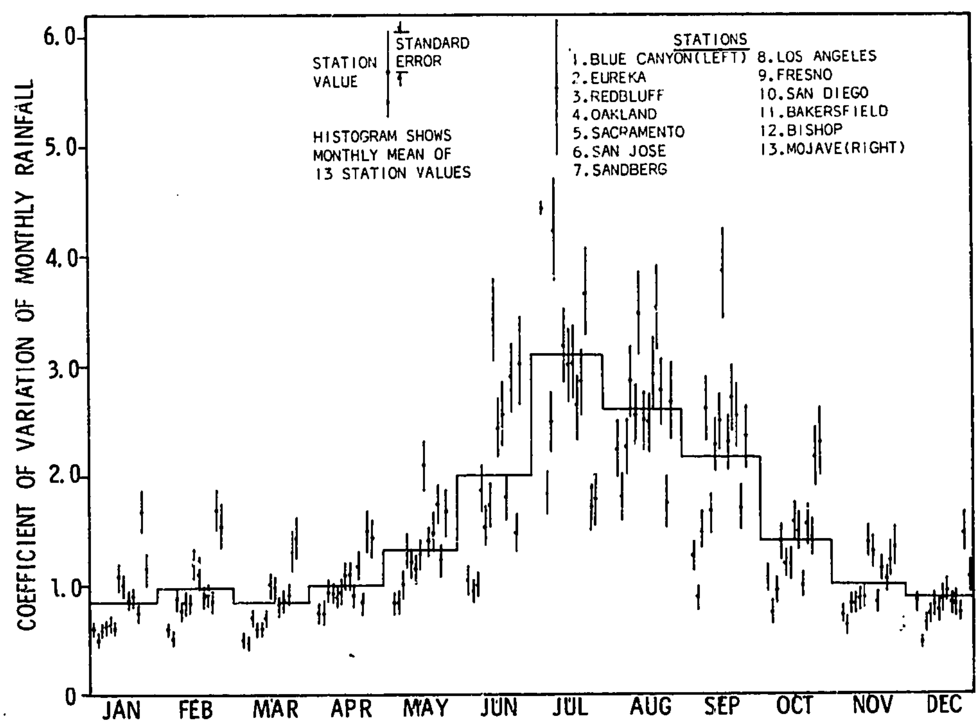

FIGURE 30 *Coefficient of variation of monthly rainfall for 13 stations based on records 1937-76*

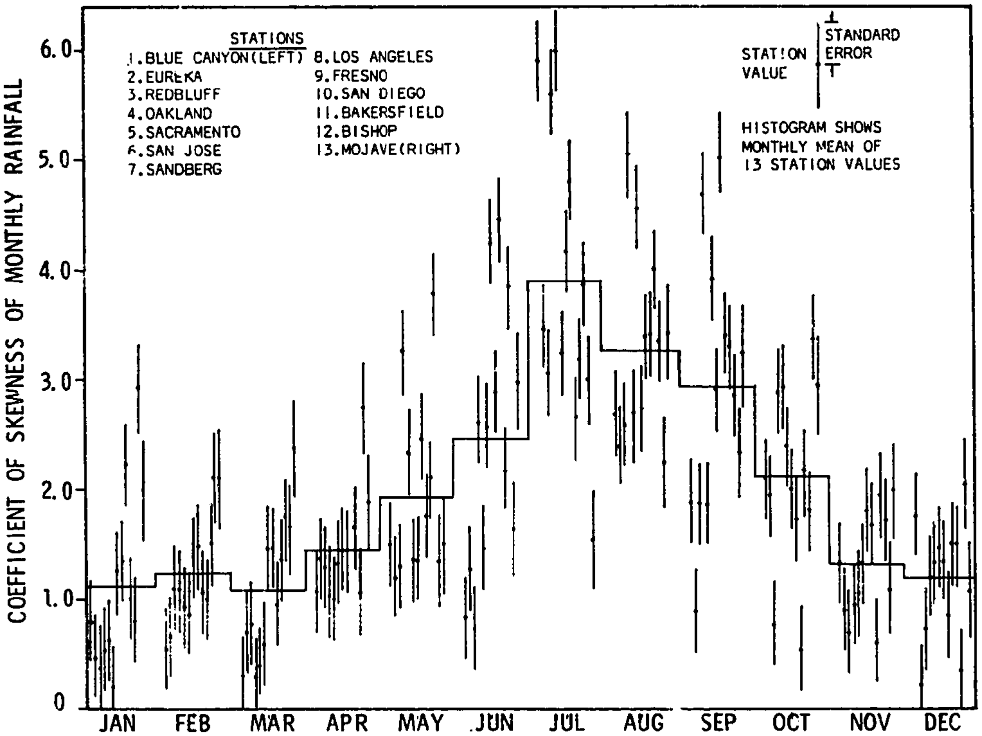

FIGURE 31 *Coefficient of skewness of monthly rainfall for 13 stations based on records 1937-76*

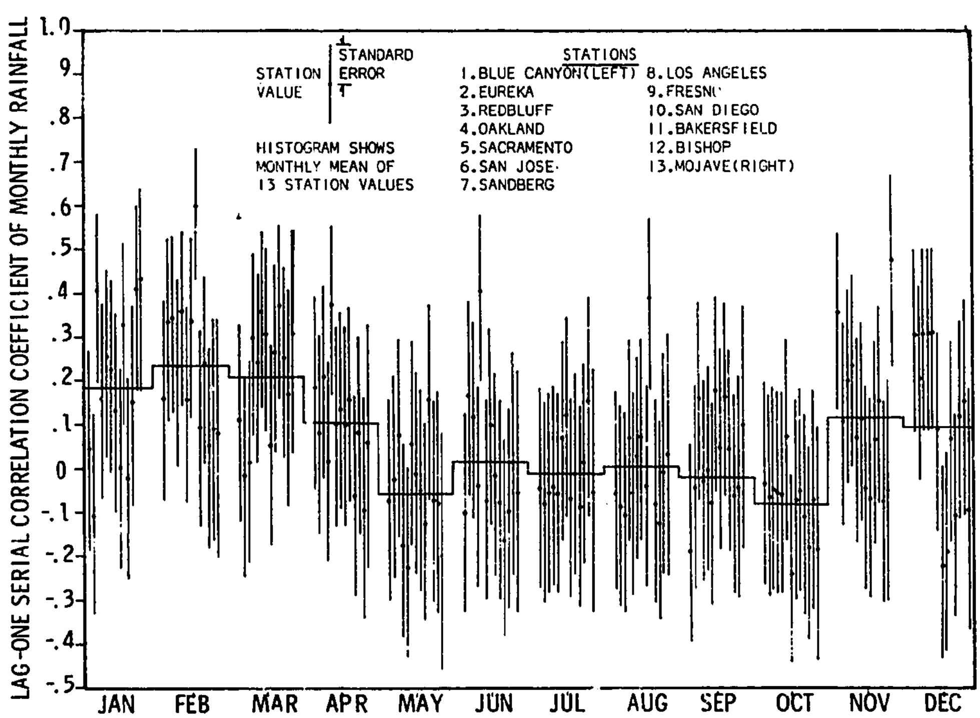

FIGURE 32 *Lag-one serial correlation coefficient of monthly rainfall for 13 stations based on records 1937-76*

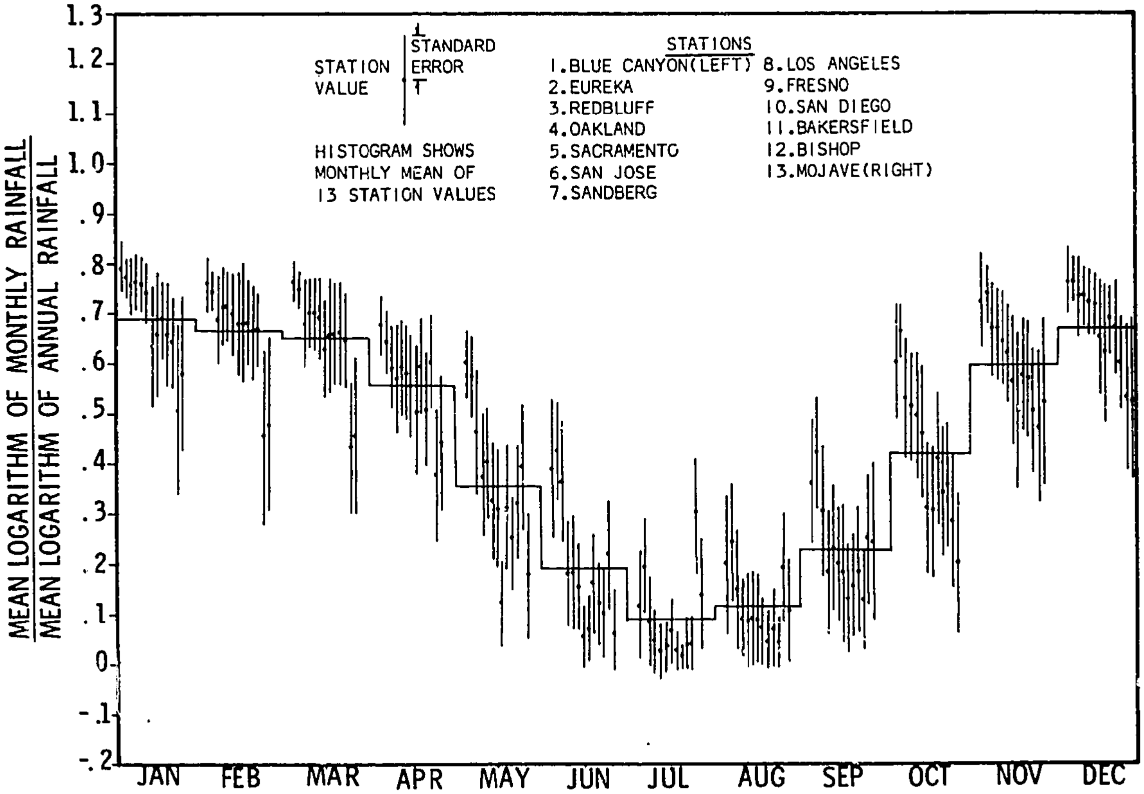

FIGURE 33 *Mean log monthly rainfall, log base being mean log of annual rainfall for 13 stations based on records 1937-76*

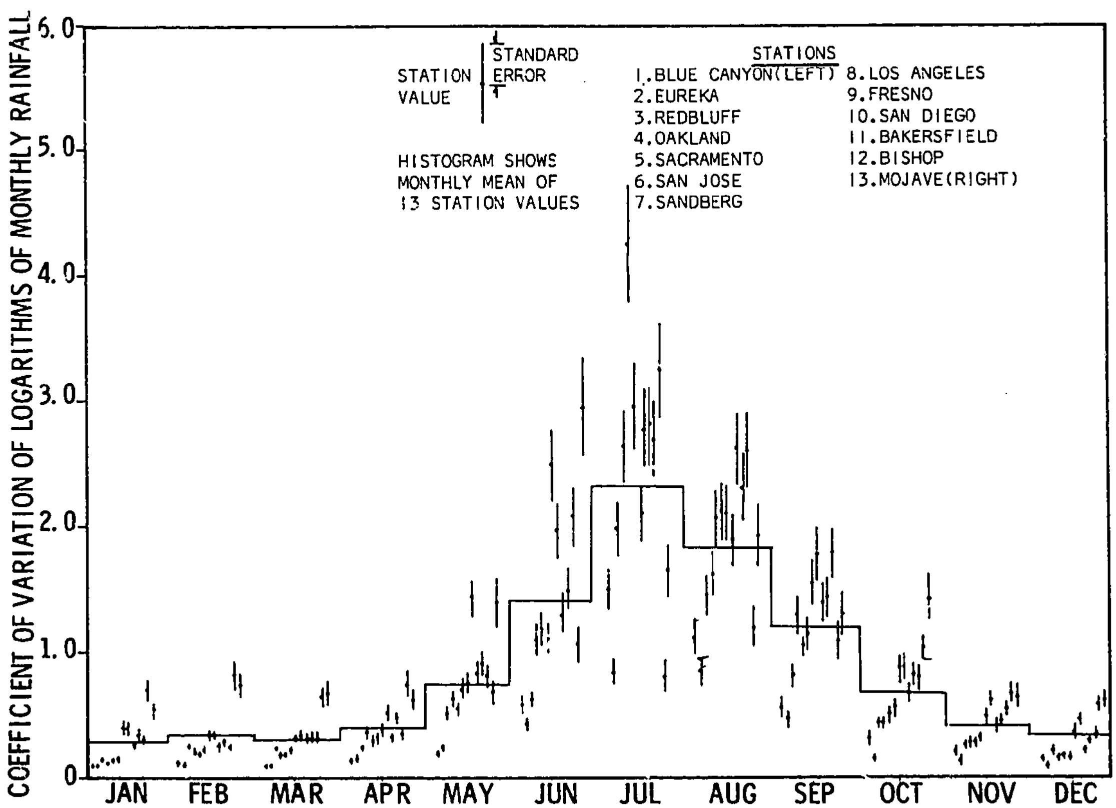

FIGURE 34 *Coefficient of variation of logarithms of monthly rainfalls for 13 stations based on records 1937-76*

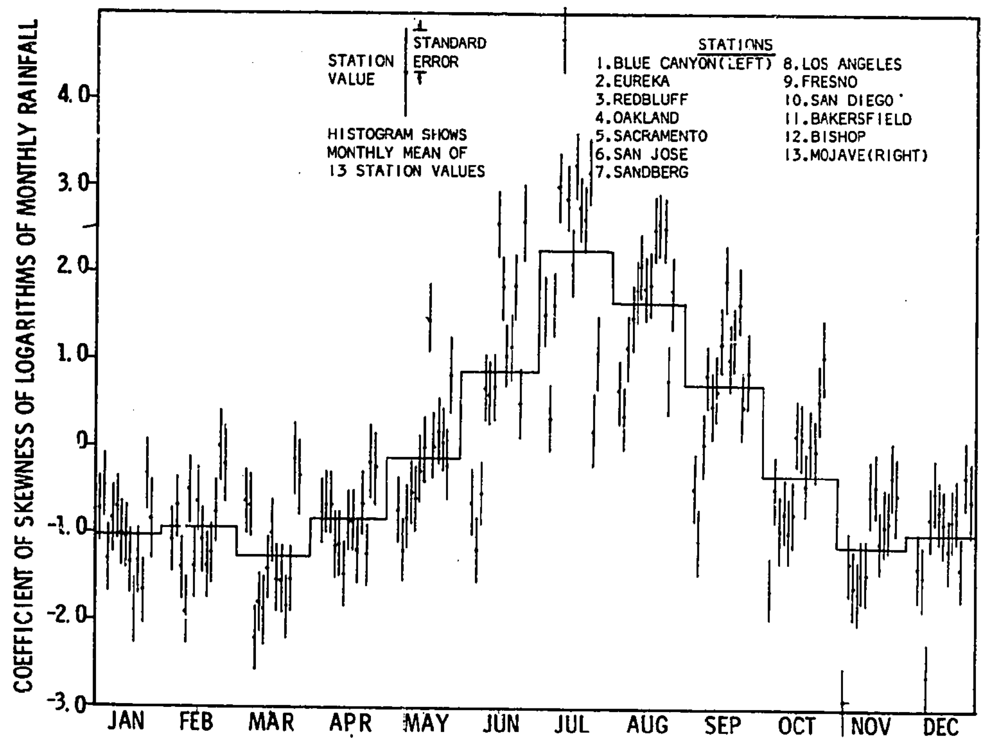

FIGURE 35 *Coefficient of skewness of logarithms of monthly rainfalls for 13 stations based on records 1937-76*

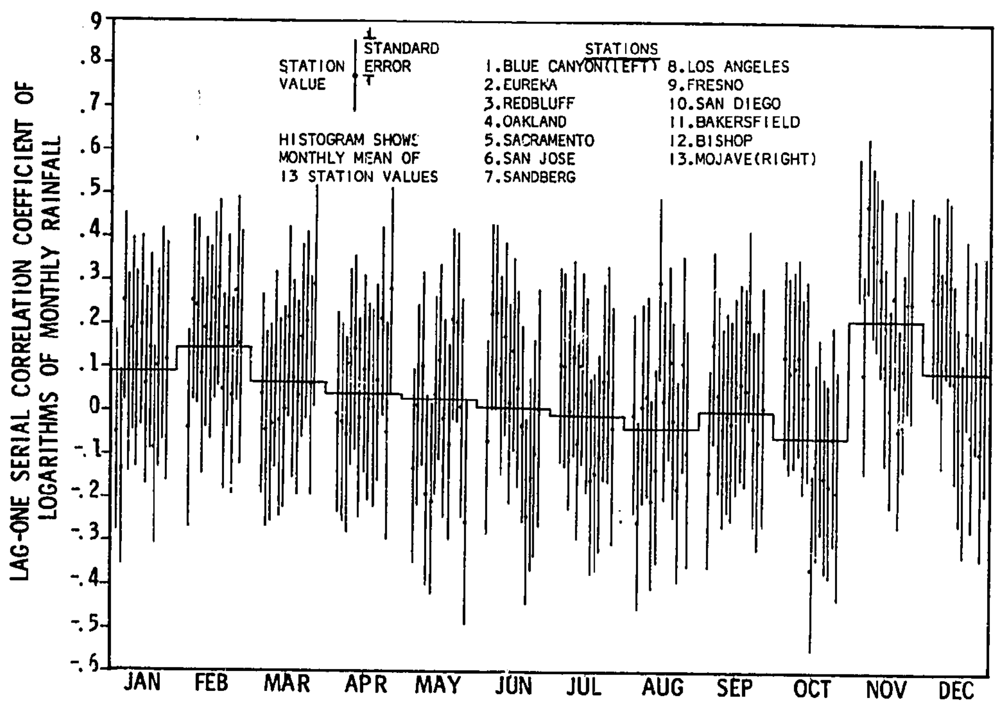

FIGURE 36 *Lag-one serial correlation coefficient of logarithms of monthly rainfall for 13 stations based on records 1937-76*

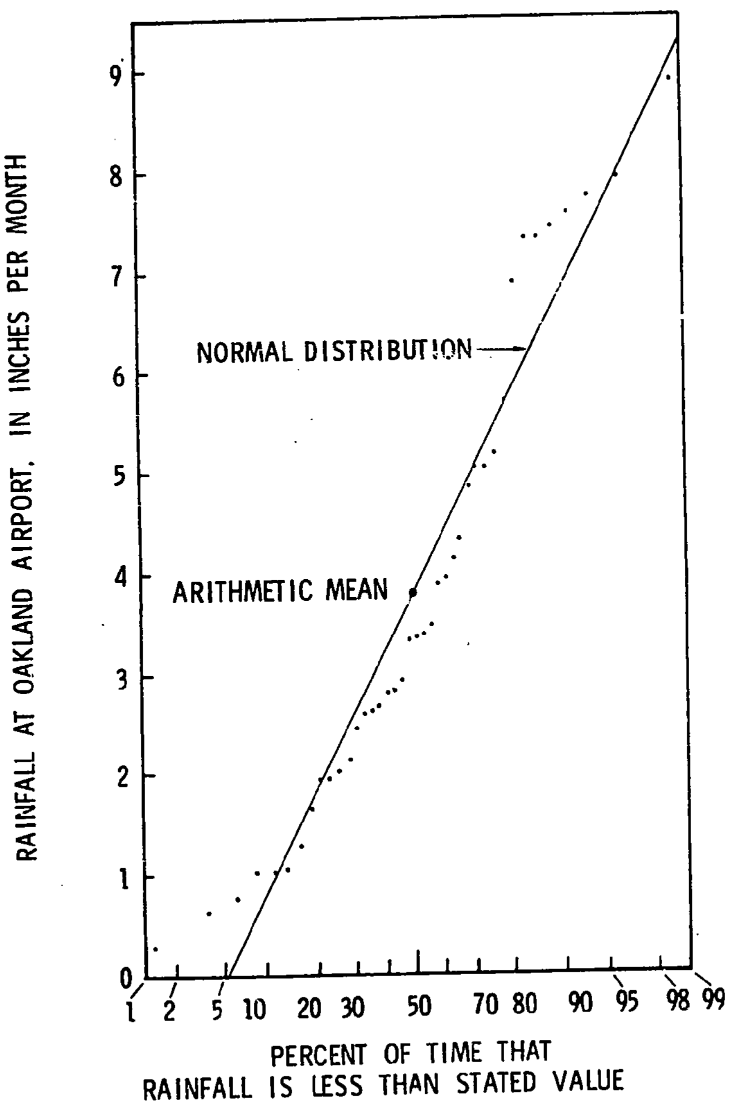

FIGURE 37 *Comparison of January rainfall at Oakland Airport to normal distribution, based on records 1937-76*

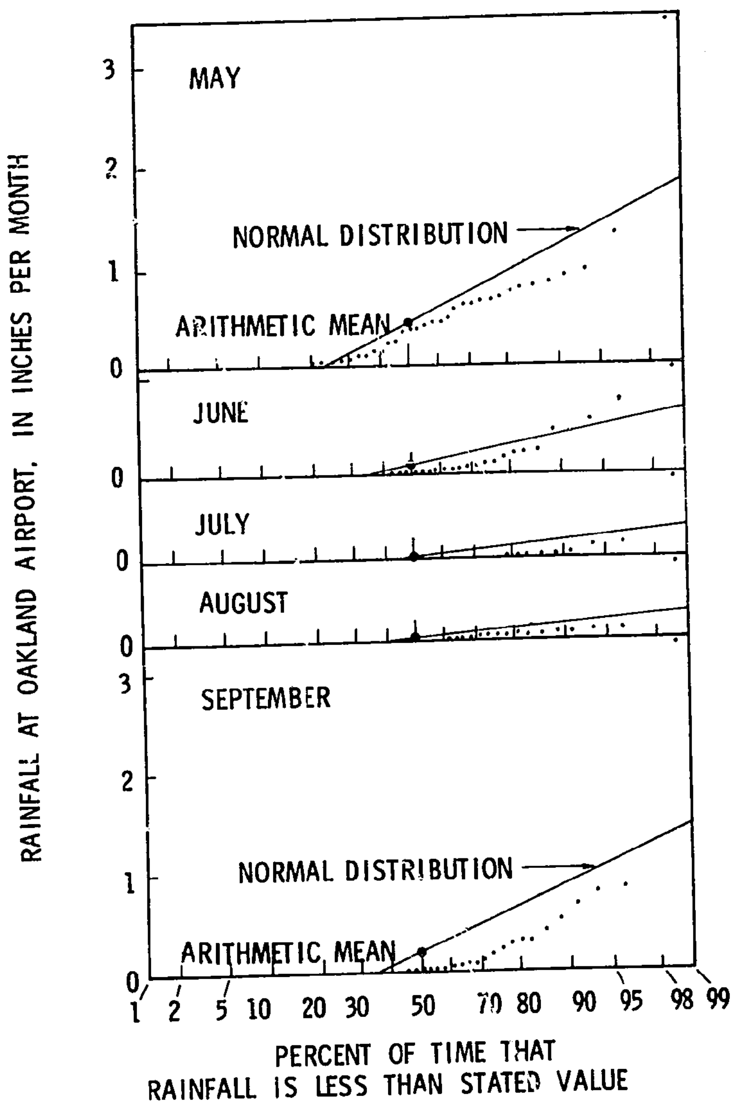

FIGURE 38 *Comparison of May, June, July, August, and September rainfalls at Oakland Airport to normal distribution, based on records 1937-76*

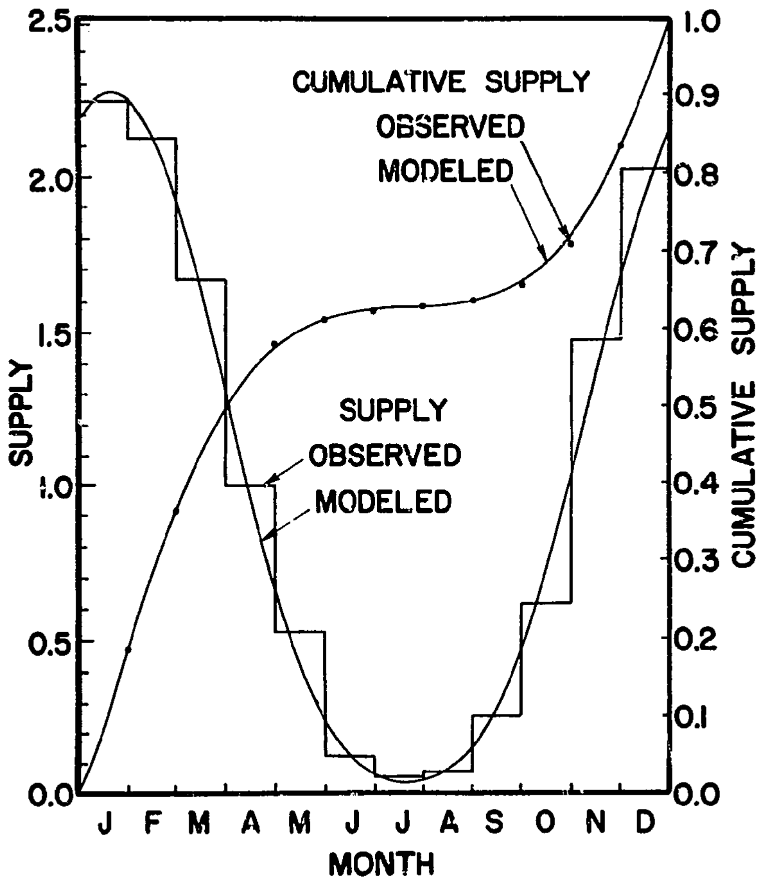

FIGURE 39 *Monthly mean rainfall as a proportion of mean rainfall*

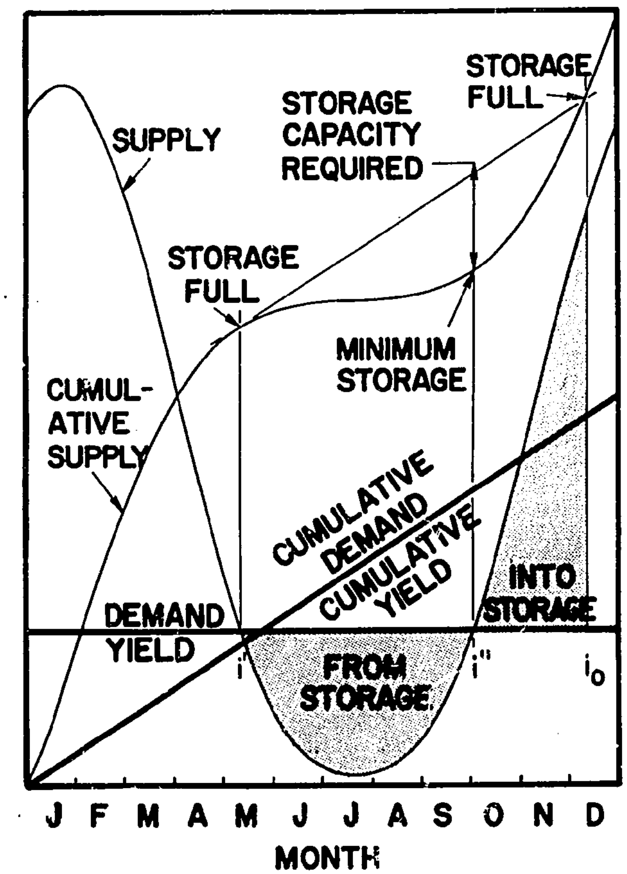

FIGURE 40 *Supply-demand-storage relationships for a 100% reliable system*

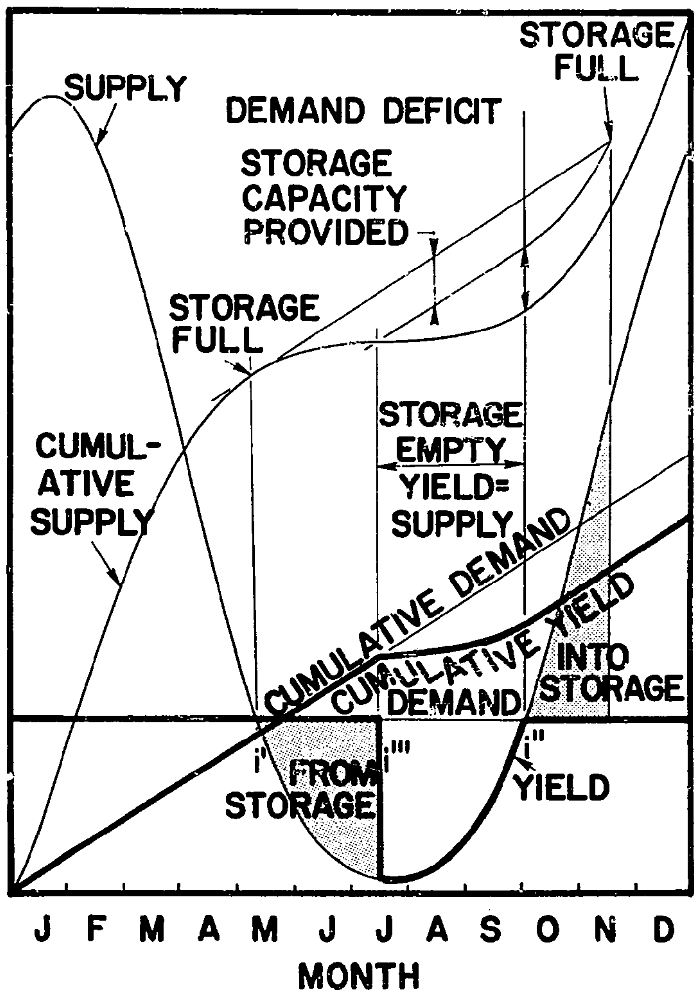

FIGURE 41 Supply-demand-yield-storage relationships for a system less than 100% reliable

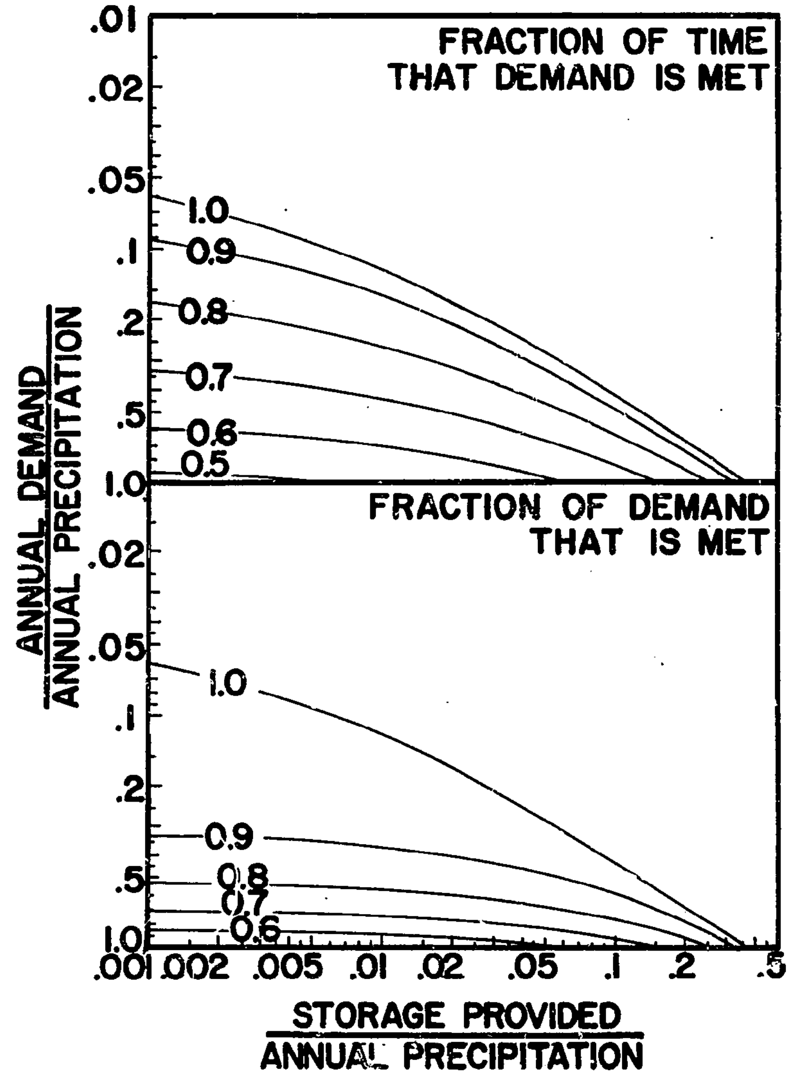

FIGURE 42 Reliability of rainwater systems vs. demand and storage ignoring variability of rainfall in any month

TABLE 3

MONTHLY PROPORTION OF ANNUAL TOTAL RAINFALL

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Blue Canyon	.194	.147	.141	.078	.042	.014	.003	.006	.011	.062	.130	.173
Eureka	.173	.139	.138	.071	.047	.016	.003	.007	.018	.079	.144	.164
Red Bluff	.192	.151	.123	.073	.040	.019	.003	.007	.018	.062	.134	.177
Oakland	.206	.163	.138	.079	.024	.007	.002	.002	.011	.063	.126	.179
Sacramento	.205	.173	.138	.082	.027	.007	.001	.004	.013	.056	.119	.175
San Jose	.199	.173	.158	.082	.020	.005	.001	.007	.012	.054	.116	.173
Sandberg	.169	.221	.125	.082	.019	.002	.002	.005	.027	.028	.139	.182
Los Angeles	.194	.229	.162	.074	.005	.002	.001	.002	.020	.027	.115	.170
Fresno	.179	.177	.165	.105	.027	.011	.000	.002	.010	.049	.106	.108
San Diego	.178	.172	.166	.079	.016	.005	.001	.006	.027	.042	.119	.188
Bakersfield	.158	.177	.170	.136	.040	.012	.003	.002	.017	.054	.101	.129
Bishop	.199	.177	.075	.057	.056	.018	.032	.017	.030	.049	.118	.174
Mojave	.183	.165	.107	.085	.018	.007	.013	.012	.058	.036	.165	.150
Mean	.187	.174	.139	.083	.029	.010	.005	.006	.021	.051	.126	.169

TABLE 4

COEFFICIENT OF VARIATION OF MONTHLY RAINFALL

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Blue Canyon	.613	.600	.509	.741	.831	1.054	4.427	2.246	1.261	1.063	.734	.841
Eureka	.507	.518	.481	.756	.853	.960	1.835	1.811	.881	.753	.636	.482
Red Bluff	.598	.871	.699	.943	1.010	1.018	2.488	2.265	1.488	.966	.824	.669
Oakland	.623	.778	.603	.941	1.324	1.862	4.248	2.856	2.612	1.381	.828	.731
Sacramento	.656	.845	.618	.895	1.215	1.544	5.535	2.549	1.667	1.188	.880	.821
San Jose	.615	.838	.709	.933	1.144	1.715	3.181	3.478	2.274	1.186	.914	.768
Sandberg	1.084	1.188	1.020	1.090	1.279	3.422	3.016	2.506	2.493	1.575	1.395	1.079
Los Angeles	1.008	1.122	.977	1.096	2.098	2.429	3.030	2.479	3.851	1.505	1.309	.946
Fresno	.877	.901	.815	.927	1.409	2.575	2.632	2.928	2.309	1.011	.826	.835
San Diego	.906	.919	.887	1.172	1.480	1.806	2.849	3.543	2.725	1.561	1.154	1.025
Bakersfield	.754	.856	.927	.827	1.741	2.886	3.669	2.770	2.541	1.438	1.068	.748
Bishop	1.676	1.683	1.321	1.499	1.223	1.475	1.714	1.765	1.706	2.175	1.233	1.487
Mojave	1.160	1.550	1.421	1.427	1.649	3.024	1.792	2.686	2.346	2.318	1.364	1.075
Mean	.852	.975	.845	1.019	1.327	1.983	3.109	2.606	2.166	1.394	1.013	.885

TABLE 5

COEFFICIENT OF SKEWNESS OF MONTHLY RAINFALL

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Blue Canyon	.805	.554	.307	1.065	1.503	.827	5.891	2.676	1.882	2.082	1.323	1.753
Eureka	.487	.664	.705	1.373	1.195	1.262	3.467	2.391	.874	1.948	.909	.213
Red Bluff	.375	1.094	.772	1.285	1.290	.737	3.056	2.583	1.865	.776	.690	.721
Oakland	.553	1.092	.292	1.035	3.240	2.606	5.600	5.053	4.684	2.869	.956	1.196
Sacramento	.622	.935	.390	1.012	2.337	1.475	5.991	2.697	1.854	2.921	1.055	1.335
San Jose	.211	.876	.593	1.336	1.347	2.582	3.229	4.569	3.811	2.386	1.325	1.470
Sandberg	1.241	1.389	1.471	1.458	1.358	4.255	4.163	2.739	2.891	1.998	1.809	1.351
Los Angeles	1.362	1.491	1.480	1.440	2.467	2.895	4.798	3.380	5.073	1.722	1.683	.841
Fresno	2.228	1.071	.957	1.465	1.757	4.458	2.641	3.407	3.303	.550	.608	1.507
San Diego	1.028	1.007	1.358	1.639	2.094	2.186	3.189	3.986	3.297	2.173	1.941	1.490
Bakersfield	.805	1.508	1.725	1.067	3.770	3.840	3.856	3.349	2.844	1.802	1.715	.348
Bishop	2.925	2.111	1.641	2.747	1.347	1.634	2.989	2.230	2.321	3.377	1.090	2.032
Mojave	1.988	2.106	2.386	1.881	1.495	2.971	1.538	3.427	3.224	2.961	1.976	1.082
Mean	1.125	1.223	1.083	1.446	1.938	2.441	3.878	3.268	2.925	2.120	1.314	1.180

TABLE 6

LAG-ONE SERIAL CORRELATION COEFFICIENT OF MONTHLY RAINFALL

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Blue Canyon	.044	.158	.110	.183	-.074	-.105	-.043	-.054	-.186	-.034	.354	.304
Eureka	-.109	.335	-.019	.080	-.023	.166	-.081	-.088	-.046	.065	.108	.207
Red Bluff	.406	.341	.016	.210	.073	.117	-.058	-.107	.161	-.048	.188	.307
Oakland	.161	.230	.298	.019	-.175	-.043	-.042	.070	-.031	-.057	.233	.308
Sacramento	.253	.357	.241	.377	-.227	.407	-.059	-.059	-.005	-.057	.069	.309
San Jose	.223	.155	.357	.099	.057	-.076	.068	.025	-.081	.070	.112	.089
Sandberg	.133	.335	.307	.138	-.010	.100	.123	.070	.177	-.241	-.045	-.222
Los Angeles	.005	.601	.057	.102	-.051	-.017	-.070	-.040	.047	-.073	-.070	-.191
Fresno	.323	.092	.265	.156	-.128	-.074	-.013	.392	.159	-.050	.066	.069
San Diego	-.023	.238	.372	-.064	.158	-.166	-.088	.083	.045	-.109	.153	-.108
Bakersfield	.148	.049	.255	.080	-.076	-.087	.012	-.123	-.061	-.179	-.075	.119
Bishop	.407	.090	.172	-.095	-.080	.015	.153	.010	-.044	-.073	-.051	.152
Mojave	.432	.077	.309	.055	-.202	-.055	-.054	.031	.100	-.183	.475	-.601
Mean	.185	.235	.211	.103	-.058	.013	-.012	.003	-.018	-.080	.117	.096

TABLE 7

MEAN LOG OF MONTHLY RAINFALL/MEAN LOG OF ANNUAL RAINFALL

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Blue Canyon	.793	.759	.783	.676	.600	.388	.117	.199	.365	.603	.723	.763
Eureka	.773	.746	.748	.642	.576	.425	.196	.243	.422	.664	.738	.765
Red Bluff	.758	.689	.680	.593	.463	.365	.085	.150	.303	.530	.671	.731
Oakland	.763	.712	.701	.569	.375	.180	.046	.090	.183	.513	.658	.735
Sacramento	.760	.717	.699	.594	.403	.183	.025	.087	.231	.496	.645	.722
San Jose	.743	.698	.691	.580	.326	.157	.037	.090	.197	.461	.621	.717
Sandberg	.636	.681	.628	.555	.308	.055	.066	.088	.181	.309	.564	.651
Los Angeles	.661	.681	.654	.505	.122	.072	.027	.069	.130	.305	.503	.623
Fresno	.693	.682	.658	.595	.311	.162	.017	.047	.155	.411	.576	.690
San Diego	.660	.665	.662	.506	.252	.119	.039	.071	.183	.343	.568	.670
Bakersfield	.644	.676	.644	.605	.322	.101	.039	.043	.128	.358	.505	.602
Bishop	.508	.454	.430	.377	.394	.219	.299	.192	.249	.283	.474	.532
Mojave	.580	.477	.457	.439	.177	.060	.138	.107	.242	.200	.521	.525
Mean	.690	.664	.649	.557	.356	.191	.087	.114	.228	.421	.597	.671

TABLE 8

COEFFICIENT OF VARIATION OF LOGARITHMS OF MONTHLY RAINFALL

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Blue Canyon	.104	.120	.090	.152	.187	.586	1.508	1.163	.567	.315	.215	.145
Eureka	.088	.097	.089	.176	.245	.416	.836	.853	.475	.141	.137	.102
Red Bluff	.148	.254	.236	.268	.515	.621	1.981	1.460	.817	.431	.272	.217
Oakland	.137	.211	.191	.378	.630	1.117	2.644	1.628	1.292	.431	.278	.162
Sacramento	.145	.191	.200	.306	.545	1.194	4.263	2.063	1.053	.496	.287	.183
San Jose	.166	.234	.236	.325	.720	1.128	2.956	2.125	1.159	.563	.327	.176
Sandberg	.401	.330	.321	.390	.766	2.495	2.109	2.116	1.563	.869	.484	.372
Los Angeles	.392	.362	.358	.525	1.446	1.971	2.786	1.802	1.782	.882	.631	.465
Fresno	.260	.266	.335	.336	.830	1.306	2.824	2.630	1.410	.675	.415	.220
San Diego	.343	.307	.338	.481	.917	1.494	2.701	2.323	1.443	.820	.448	.304
Bakersfield	.322	.252	.335	.364	.816	2.082	3.251	2.614	1.807	.801	.559	.361
Bishop	.720	.822	.646	.758	.685	1.068	.819	1.197	1.105	1.033	.683	.593
Mojave	.535	.743	.690	.634	1.395	2.957	1.647	1.931	1.312	1.425	.650	.626
Mean	.289	.344	.313	.392	.745	1.419	2.333	1.847	1.214	.683	.414	.340

TABLE 9

COEFFICIENT OF SKEWNESS OF LOGARITHMS OF MONTHLY RAINFALL

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Blue Canyon	-.732	-1.078	-.637	-.740	-.731	-.629	1.529	.646	-.473	-1.649	-2.912	-.853
Eureka	-.469	-.697	-.671	-.656	-1.193	-1.184	.324	.341	-1.091	-.476	-1.327	-1.477
Red Bluff	-1.298	-1.409	-2.214	-.669	-.818	-.544	1.645	1.158	.031	-.959	-1.593	-2.620
Oakland	-.849	-1.910	-1.819	-1.138	-.522	.682	3.013	1.481	.833	-.755	-1.674	-.802
Sacramento	-.711	-.518	-1.893	-1.127	-.618	.614	4.699	1.794	.489	-.972	-1.435	-.514
San Jose	-1.022	-1.370	-1.413	-1.470	-.286	.689	2.859	2.082	.652	-.788	-1.440	-.739
Sandberg	-1.054	-.647	-.988	-.866	-.011	2.572	2.116	1.838	1.206	.154	-.548	-.853
Los Angeles	-1.332	-1.105	-1.522	-.855	1.464	1.846	3.248	1.876	1.930	.108	-.445	-1.187
Fresno	-1.901	-1.381	-1.542	-1.201	.023	1.042	2.750	2.506	1.026	-.435	-1.111	-.836
San Diego	-1.336	-1.227	-1.850	-.657	.187	1.148	2.625	2.579	1.239	.053	-.900	-.717
Bakersfield	-1.686	-.752	-1.537	-1.227	.066	1.850	3.161	2.506	1.671	-.044	-.848	-1.383
Bishop	-.332	-.011	-.155	-.171	-.211	.498	.184	.783	.453	.552	-.330	-.326
Mojave	-.858	-.203	-.355	-.234	.830	2.595	1.078	1.795	.868	1.050	-.504	-.601
Mean	-1.045	-.947	-1.277	-.847	-.140	1.860	2.249	1.645	.680	-1.320	-1.164	-.993

TABLE 10

LAG-ONE SERIAL CORRELATION COEFFICIENT OF LOGARITHM OF MONTHLY RAINFALL

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Blue Canyon	-.050	-.041	.037	-.005	-.132	-.065	.116	-.004	-.134	.132	.417	.268
Eureka	-.137	.251	-.045	-.026	.014	.226	.107	-.250	.157	.094	.093	.258
Red Bluff	.253	.242	-.029	-.057	.103	.228	.006	.016	.046	.107	.480	.106
Oakland	.091	.086	.099	.107	-.190	.087	.130	.040	-.036	.132	.389	.309
Sacramento	.184	.188	-.026	.142	-.210	.175	-.070	-.198	-.005	.043	.359	.286
San Jose	.101	.159	.004	-.018	.038	.019	.106	-.132	-.022	.075	.310	.076
Sandberg	.196	.028	-.014	-.139	-.115	-.092	-.185	.075	-.190	-.543	-.120	-.258
Los Angeles	.061	.282	.076	.024	-.015	.054	-.154	.028	.072	-.121	.011	-.108
Fresno	.139	.048	.035	.009	-.075	-.029	-.138	.119	.058	-.054	.269	.190
San Diego	-.087	.191	.168	.068	.212	-.240	-.101	-.014	.213	-.148	-.034	-.047
Bakersfield	.103	.034	.208	.216	.207	-.151	.072	-.175	-.037	-.166	.102	.141
Bishop	.186	.273	.060	-.049	.010	-.012	.095	.116	-.067	-.058	.254	-.087
Mojave	.114	.153	.286	.279	-.251	.009	-.035	-.090	.012	-.178	.257	.096
Mean	.089	.146	.067	.042	.031	.010	-.004	-.036	.005	-.053	-.214	.095

TABLE 11

VALUES OF CHI-SQUARED FOR GOODNESS OF FIT OF DISTRIBUTION OF MONTHLY RAINFALL TO NORMALITY

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Blue Canyon	24*	17*	22*	25*	30	64	452	235	76	44	17*	45
Eureka	44	35	33	31	28	30	91	116	36	23*	17*	8*
Oakland	18*	32	20*	35	53	72	391	293	144	57	32	18*
Oakland	36	40	20*	26	51	141	511	341	312	49	32	26
Sacramento	42	36	18*	28	63	247	578	370	187	62	27	30
San Jose	42	44	15*	35	65	136	544	450	186	39	29	23*
Sandberg	106	87	42	40	103	448	424	349	320	171	102	42
Los Angeles	82	38	34	49	216	315	423	314	282	176	87	32
Fresno	32	32	22	18	78	166	551	449	266	89	38	33
San Diego	64	39	32	47	64	163	481	396	449	155	39	38
Bakersfield	12*	52	32	30	111	448	611	451	322	86	49	21*
Bishop	30	101	66	46	73	93	75	89	133	163	86	94
Mojave	36	86	44	56	158	348	201	198	176	161	49	34

*Indicates no significant difference at 5% level
Indicates significant difference at 95% level

TABLE 12

VALUES OF CHI-SQUARED FOR GOODNESS OF FIT OF DISTRIBUTION OF MONTHLY RAINFALL TO LOG-NORMALITY

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Blue Canyon	8*	18*	14*	22*	21*	37	263	189	28	31	28	38
Eureka	14*	26	20*	34	21*	38	73	55	33	8*	16*	14*
Red Bluff	10*	24*	26	14*	31	51	460	273	78	30	20*	35
Oakland	16*	36	25*	28	50	150	512	348	225	22*	19*	27
Sacramento	14*	17*	29	22*	32	194	647	452	135	36	13*	19*
San Jose	10*	33	20*	24*	62	159	578	453	186	44	17*	15*
Sandberg	14*	11*	18*	24*	59	512	451	461	320	87	23*	22*
Los Angeles	26	16*	33	30	219	421	548	394	316	100	37	51
Fresno	12*	14*	28	15*	72	202	565	547	268	63	47	25*
San Diego	14*	25*	31	25*	106	278	546	454	244	72	24*	17*
Bakersfield	28	26	26	31	64	456	613	547	344	78	41	44
Bishop	137	71	31	54	39	107	68	125	119	107	49	22*
Mojave	16*	41	48	29	156	351	204	228	129	156	58	29

*Indicates no significant difference at 5% level
Indicates significant difference at 95% level

From these data it is concluded that the distribution of data is slightly better described by the log-normal distribution than by the normal distribution, except that during the summer neither distribution is satisfactory. But since rainfall in the six summer months from May to October accounts for less than one-eighth of the annual total on the average, little error is introduced in computing overall system performance if either normality or log-normality is assumed for the distribution of monthly rainfall in the summer.

Our final consideration with respect to statistical characterization of monthly rainfall in California deals with the degree of persistence of wet spells and dry spells. From Figures 32 and 36 a slight tendency is observed for wet spells to persist from month to month in the winter (November-April), though not in the summer. Now, by considering the serial correlation (autocorrelation) coefficient over lag periods greater than one month, the possibility of protracted spells of wet weather (or dry weather) can be investigated.

Table 13 presents for each of 13 California locations the number of months out of twelve that an autocorrelation statistically significant at the 5% level (one-tailed test) occurred between the rainfall in any month and the rainfall n months before, where n ranges from 1 to 18. If the records are truly uncorrelated then a statistically significant positive correlation should be observed in approximately 5% of the cases, and a significant negative correlation should occur about 5% of the time. Thus, for 13 locations and 12 months and 18 lag periods the number of statistically significant autocorrelation coefficients expected in 2 X 0.05 X 13 X 12 X 18 = 281. In fact, the total at the bottom right corner of Table 13 is approximately the same at 296, indicating no overall tendency for significant serial correlation to occur.

TABLE 13

NUMBER OF MONTHS OUT OF 12 THAT AUTOCORRELATION COEFFICIENT IS SIGNIFICANT AT 5% LEVEL

LAG IN MONTHS	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	TOTAL
Blue Canyon	1	0	3	1	1	0	1	1	2	2	1	1	1	0	2	2	2	1	22
Eureka[a]	1	0	0	1	2	2	1	1	1	0	1	0	1	2	3	3	1	3	23
Red Bluff[a]	2	0	0	0	1	1	0	1	3	1	0	1	0	1	2	5	3	1	22
Oakland[a]	1	0	0	1	1	1	0	1	1	2	1	0	0	2	0	3	2	6	22
Sacramento[a]	3	0	0	2	0	1	0	1	2	1	1	0	1	2	1	2	1	1	19
San Jose[a]	1	0	0	0	0	1	0	3	3	0	1	0	2	2	2	3	3	2	23
Sandberg[a]	1	1	1	2	1	0	0	1	1	0	2	0	0	1	1	0	1	4	17
Los Angeles[a]	1	0	0	0	1	2	2	0	3	2	1	3	1	1	2	2	5	6	32
Fresno[a]	1	0	0	0	0	1	1	0	2	0	1	2	1	4	2	1	2	4	22
San Diego[a]	1	0	0	0	0	2	4	1	1	0	1	1	0	0	3	1	1	4	20
Bakersfield[a]	0	0	4	1	2	1	1	0	0	1	4	1	0	1	1	2	0	2	21
Bishop[b]	2	2	1	1	2	2	0	1	1	0	1	0	1	0	3	3	2	3	25
Mojave[c]	2	2	2	2	1	1	2	3	2	3	0	1	0	0	2	0	4	3	28
TOTAL	17	3	11	11	12	15	12	14	22	12	15	10	8	16	24	27	27	40	296

[a]Critical correlation coefficient for 38 D.F. = 0.308 at 5% level.

[b]Critical correlation coefficient for 31 D.F. = 0.344 at 5% level.

[c]Critical correlation coefficient for 26 D.F. = 0.374 at 5% level.

From the preceding statistical characterization of monthly rainfall in California the following may be concluded:

1) Annual rainfall is consistently distributed through the year in spite of variations in total annual rainfall between locations. Rainfall in the six winter months from November through April accounts for 88% of the annual total, on the average.

2) Winter rainfall is less variable than summer rainfall and conforms satisfactorily to both the normal distribution and log-normality, slightly better to the latter. Summer months frequently have no rain but occasionally they are quite wet, leading to a poor fit to either the normal or the log-normal distribution, or to any other commonly used statistical distribution. However, since rainfall in the six summer months from May through October averages less than one-eighth of the annual total, precise modeling of the distribution of summer rainfall is not critical to the overall characterization of rainwater collection systems.

3) Winter rainfall exhibits a slight tendency toward short wet spells or dry spells, although these do not persist for more than two months.

HOW RAINFALL STATISTICS DETERMINE COLLECTION SYSTEM PERFORMANCE This section examines the effect on rainwater collection system performance of the three major statistical characteristics evaluated in the previous section, i.e., seasonal variation of mean rainfall, variability of rainfall in a given month, and the degree of persistence or autocorrelation in the record.

Seasonal Variation — The histogram in Figure 39 represents the mean for 13 locations of the ratio of monthly mean rainfall to mean rainfall, in short, the rainfall supply. Solid circles represent the cumulative monthly proportion of the annual total rainfall. As shown by the curves, this mean seasonal distribution of rainfall may be closely modeled by an emperical equation whose functional form is:

$$R_i = f(i) = 12\,\{0.198 + 0.165 \cos\left(\frac{\pi}{6}\left[i - \frac{2}{3}\right]\right)\}^{1.64} \qquad (9)$$

in which R = monthly mean rainfall as a proportion of mean rainfall; and i = month number, e.g., 0.5 for mid-January. According to Equation 9, the wettest time of the year is at $i = 2/3$, and the driest time of the year is at $i = 20/3$. No account was made of differences in the number of days per month in developing Equation 9.

Having established the seasonal variation of the mean supply of rain, the performance of a rainwater supply system is now examined as if this seasonal variation were exactly repeated year after year. That is, for present purposes we ignore the variability and serial correlation of each month's rain, in order to establish system performance relations in terms of the mean distribution of annual rain, f(i). System performance relates to the reliability with which a given demand for water can be drawn from storage into which rainwater from the collection area delivers. Storage is required if the uniform demand exceeds the minimum supply, equal to 4.5% of the mean supply according to Equation 9. Increasing storage is needed as the demand increases to 100% of the mean supply.

Figure 40 depicts graphically the relationships between supply, demand, and storage for a 100% reliable rainwater supply system, expressed in equation form by:

$$D = f(i') = f(i'') \qquad (10)$$

$$S = D(i'' - i') - \int_{i'}^{i''} f(i)\,di \qquad (11)$$

where D = demand as a fraction of mean rainfall; i' and i'' are the times of year when demand equals supply or the falling and rising limbs of the supply curve, respectively; and S = storage capacity used as a fraction of mean annual rainfall. Storage is completely refilled at $i = i_0$ where $f(i')\,(i_0 - i') = \int_{i'}^{i_0} f(i)\,di$.

If the storage volume actually provided S' is less than the value computed from Equation 11, not all of the demand will be satisfied as shown in Figure 41. Then:

$$P = 1 - \frac{i'' - i'''}{12} \tag{12}$$

$$Q = 1 - D\,(i'' - i''') + \int_{i''}^{i'''} f(i)di \tag{13}$$

where S' = storage volume provided as a fraction of mean annual rainfall; i''' = the value obtained for i'' if S' substitutes for S in Equation 11; P = fraction of time that demand is met; and Q = fraction of total annual demand that is met. Resulting calculated values of P and Q appear in Figure 42, which express the effect of the mean annual distribution of rainfall on the performance of a rainwater collection system.

Variability of Rainfall — Since rainfall varies about its mean with some degree of randomness, there is likely to occur in any given period a series of months for which rainfall is consistently below the mean. This situation is obviously more critical from the viewpoint of supply system performance than the case where the mean annual distribution of rainfall is sustained year after year. Theory of storage[1] predicts that the storage required where rain is uniformly distributed through the year but each month's rain varies about the mean is:

$$S'' = \sqrt{\frac{\pi}{24}}\,(CV)N^{0.5} \tag{14}$$

where S'' = mean storage required as a fraction of mean annual rainfall; CV = coefficient of variation of rainfall; and N = the length of record, in years.

No statistical theory is available to directly describe storage requirements where mean rainfall varies seasonally and also in each month varies about the monthly mean. To study this problem we resort to simulation techniques whereby desired statistical characteristics are used to generate a synthetic record of rainfall which is then analyzed to determine storage requirements.

Consider the distribution of values computed sequentially by the expression:

$$x = y + \varepsilon z \tag{15}$$

where ε is a normally distributed random deviate with zero mean and unit variance. Since ε has zero mean εz also has zero mean, so that the mean value of x is equal to y. Also, the variance of y is zero so that the variance of x is equal to that of εz, or unity times z, or simply z. Thus, by Equation 15 it is possible to generate an indefinite series of values, x, with a specified mean, y, and a specified standard deviation, z. If for each month's simulation the respective mean rainfall and its standard deviation are substituted, a series of synthetic monthly rainfall values may be simulated. This procedure was used to generate the 68 year synthetic rainfall record shown in Figure 43. Note that, although the use of a log-normal distribution to generate monthly rainfalls would permit a slightly better fit to the distribution of historical rainfall, a log-normal distribution was not used because log-transformed rainfalls cannot be expressed as a proportion of annual totals, to obtain non-dimensional annual distribution.

The performance of rainwater collection systems in simulated rainfall was evaluated for various combinations of storage volume and demand. Using mean data for 13 California locations (the bottom lines in Tables 3 and 4), system performance curves based on a 1024-year synthetic rainfall record were prepared and are shown in Figure 44. Values shown here differ less than one percent from values computed from a 120-year record, and are similar to those computed directly from individual 40-year historical rainfall records, Figures 21 and 22.

Note that storage volumes computed considering variability of monthly rainfall (Figure 44) exceed those based on a predictable rainfall for any month (Figure 42). For example, to supply a demand equal to 25% of the annual rainfall 90% of the time requires a storage of 3.5% of the annual rainfall according to Figure 44, but only 2.8% of the annual rainfall according to Figure 42.

Persistence of Rainfall — It is seen that the storage volume required to smooth fluctuations in rainfall supply increases with the variability of rainfall for any month. Another effect is that with an increasing degree of persistence in the record (i.e., with increasing length and severity of dry spells and wet spells in the record) the storage volume needed to smooth supply fluctuations increases.[1]

Some degree of persistence in winter rainfall in California is apparent from Figure 32, although summer rain appears to lack serial correlation entirely. The question faced is whether wet-season serial correlation affects storage requirements. This question is studied by examining records of synthetic rainfall. To include the effect of serial correlation Equation 15 is modified to:[1]

$$x_i = y + r\ (x_{i-1} - y) + \varepsilon z\ (1 - r^2)^{0.5} \tag{16}$$

where n_{i-1} is the previously generated value of n, and r is the lag-one serial correlation coefficient between successive values of x. Using Equation 16, two 120-year synthetic rainfall records were generated for r = 0.1 and r = 0.2, and reliability curves were calculated. These curves did not differ by more than one percent from those shown in Figure 44, which confirms Fiering and Jackson's suggestion that storage requirements are not strongly dependent on statistical parameters other than the mean and standard deviation.[1]

A more sensitive test of the effect of serial correlation on storage requirements is to compare curves based on uncorrelated and serially correlated data of mean storage volume needed for a 100% reliable supply as a function of length of record, as shown in Figure 45. This figure demonstrates that the storage volume required to meet a demand 100% of the time increases with the length of record. In contrast, data used in preparation of Figure 44 showed that storage volumes required to meet a demand with less than 100% reliability could be estimated from quite a short rainfall record. Storage volumes needed to meet 100% of the demand are shown in Figure 45 to be slightly higher where the record is serially correlated than for an uncorrelated record, being approximately 5% higher for a correlation of r = 0.1, and 10% higher for a correlation of 0.2. Since the mean serial correlation in the historical rainfall record is only 0.07 (Table 6), the effect of this slight correlation on storage can be ignored, and on the basis of Figure 45 it can simply be considered that the storage volume needed to meet a demand of 100% of the supply is directly proportional to the length of the period over which the system operates. For systems where occasional shortage of water can be tolerated the length of the design period is immaterial.

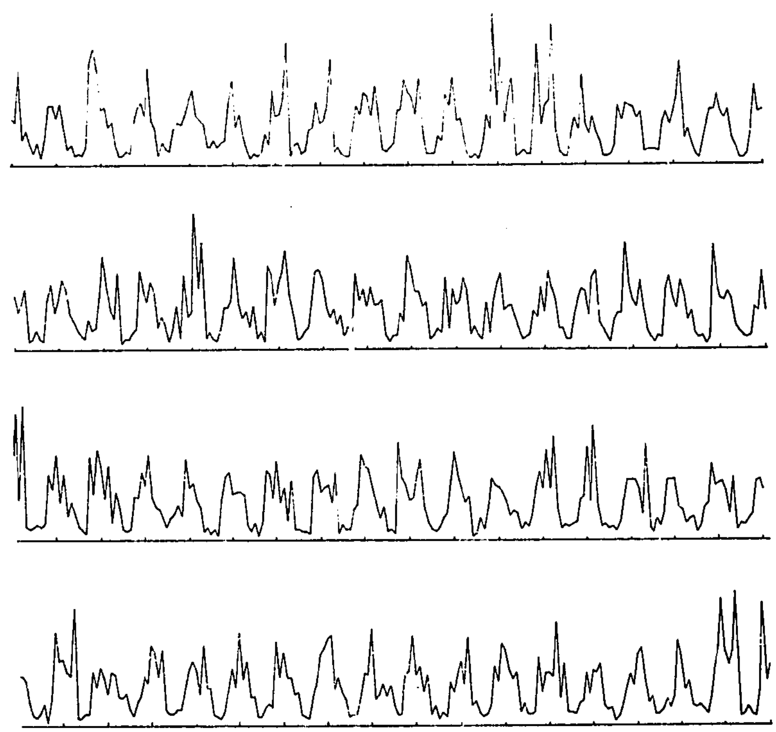

FIGURE 43 Sixty-eight year dimensionless record of rainfall for California locations

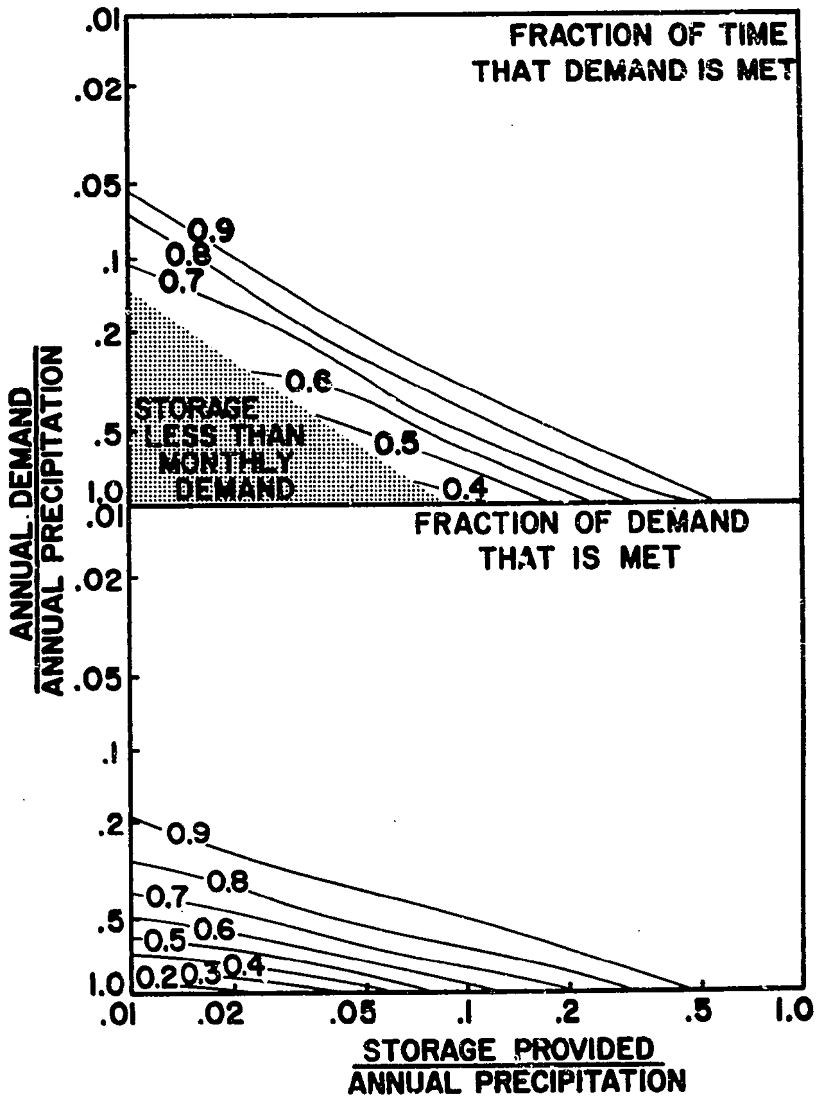

FIGURE 44 *Reliability of rainwater systems vs. demand and storage considering variability of rainfall in each month*

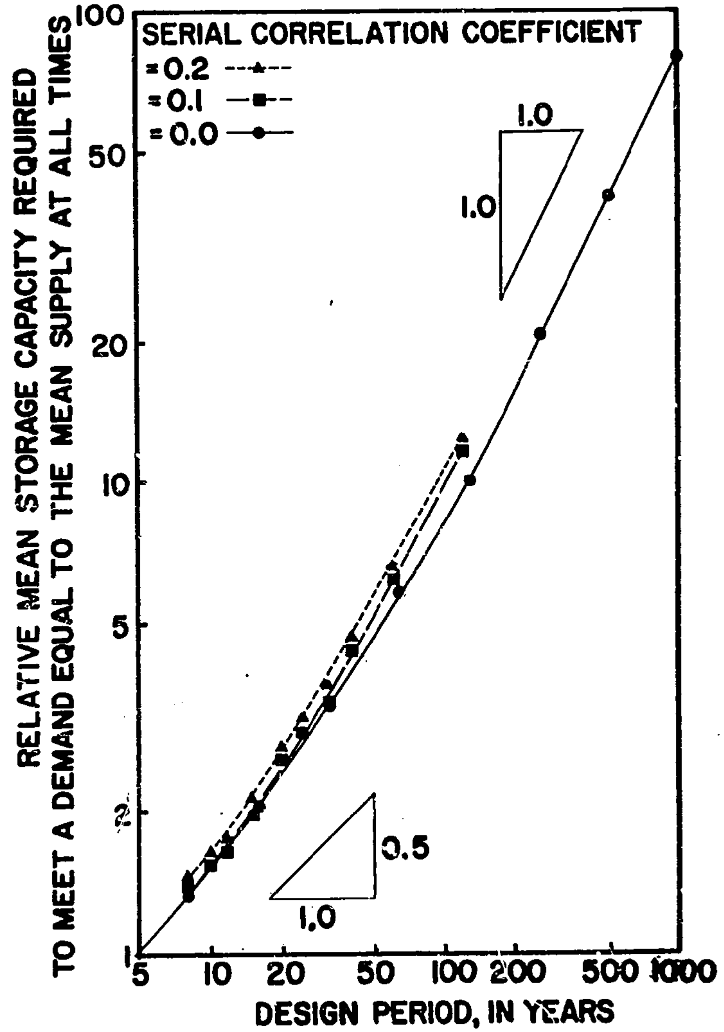

FIGURE 45 *Mean storage volume to meet 100% of demand vs. length of record for uncorrelated and serially correlated synthetic rainfall records*

CHAPTER FOUR

RAINWATER CHARACTERIZATION AND QUALITY ENHANCEMENT

Throughout the fall-winter-spring wet season of 1977-78, rainwater from a 1900 square foot roof area located approximately one-fourth mile from the eastern shore of San Francisco Bay, in Richmond, was collected in a tipping bucket gauge for measurement. The roof slopes from its lower southern edge 14 feet from the ground at a slope of 23 percent to the high edge. The roof material is asbestos cement, a material that would not be recommended for collection of potable water.

CONTAMINATION OF RAINWATER Contamination of water collected from the roof derives from the following sources:

Wet washout of atmospheric pollutants during rainfall

Dry fallout of atmospheric pollutants during dry period

Flushing of bird droppings, eroded or weathered particles of roofing material, and soil deposited during construction or maintenance of the roof.

Although studies of the quality of rainwater have examined up to 30 elements, this study was concerned with contaminants significant to the sanitary quality of drinking water. In the urban Richmond setting, much of the contamination of rainwater collected from a roof is from the air. From Table 15 it is evident that the particulates in California air most likely to be significant from the viewpoint of the sanitary quality of rainwater are iron and lead. Note that of the 13 locations in Table 15 minimum values of both iron and lead were recorded at Salinas, while maximum values were recorded at Indio and Riverside, respectively.

The concentration of heavy metals in air is directly related to the proximity and intensity of industrial activity, as may be seen from the data presented for European locations in Table 15. The concentrations of iron, lead, and manganese in air at the European industrial location in Table 15 are comparable to the respective mean concentrations for the generally industrial California locations in Table 14. Lacking air quality data for rural California, it is possible that data for rural and mountain settings in Europe may reasonably well represent corresponding locations in California. Note that concentrations of iron and lead shown in Table 15 for rural air are similar to those in Table 15 for Salinas, California.

During rain, particulates are scavanged from air by raindrops, predominantly within the clouds but also below the cloud base.[3] Scavanging accumulates contaminants in the rainwater. The concentration of a constituent in rain divided by the weight concentration of the same constituent in air defines the washout factor. For a remote area in Britain, the washout factor for 30 elements was found to be generally between 500 and 2000 in spite of several orders of magnitude of range in the concentration of these elements in the air.[4]

In another study, modeling results supported by field data indicated rather lower values for the washout factor, which was found to vary inversely with rainfall intensity.[3] For iron and lead, the washout factor ranged from approximately 300 for light rain of intensity 0.01 in/hr, to 70 for heavy rain falling at 1 in/hr. Using these values for the washout factor together with the mean concentrations of iron and lead in California air from Table 15, the concentration of iron in rainfall at the 13 California locations considered would normally range from $1121 \times 300 \times 10^{-6} = 0.34$ mg/ℓ to $1121 \times 10 \times 10^{-6} = 0.08$ mg/ℓ depending on rainfall intensity, while lead may vary from $787 \times 300 \times 10^{-6} = 0.24$ mg/ℓ to $787 \times 70 \times 10^{-6} = 0.06$ mg/ℓ.

Since the iron is in particulate form albeit very finely divided, it is probably of little sanitary significance in this concentration range, but the concentration of lead suggested for rainwater in urban/industrial locations in California exceeds the maximum level of 0.05 mg/ℓ recommended for drinking water, even before the rain reaches the ground.[5]

TABLE 14

AVERAGE CONCENTRATION OF SELECTED ELEMENTS IN AIR AT 13 CALIFORNIA SITES[a] [2]

Element	Concentration[b], in Nanograms per Kilogram of air	
	Mean	Range
Silicon	2623	883-6560[d]
Sulfur forms	1727	444[c]-3348
Iron	1121	367[c]-2825[d]
Lead	787	149[c]-1416
Calcium	732	238[c]-2185[d]
Aluminum	646	96-2030[d]
Sodium	605	141-1426
Potassium	514	183[c]-1296[d]
Chloride	487	15-1680
Bromide	153	29[c]-240
Magnesium	113	64-164
Titanium	102	20[c]-260[d]
Zinc	70	5[c]-158
Manganese	28	6-58[d]
Vanadium	18	4-59
Copper	8	2[c]-22

[a] The sites are: Sacramento, Richmond, Livermore, Oakland, San Jose, Salinas, Bakersfield, Los Alamitos, Los Angeles, Azusa, Riverside, Indio, and El Cajon.

[b] Data are averages for the period July 1 — September 30, 1973. The column headed "Mean" is the mean of 13 locations. Values were adjusted from volume concentration based on a density for air of 1.2 kg/m^3 assuming 20°C and 760 mm Hg.

[c] Minimum value recorded at Salinas.

[d] Maximum value recorded at Indio.

TABLE 15

RELATIONSHIP OF HEAVY METAL CONCENTRATION IN AIR TO PROXIMITY OF INDUSTRIAL ACTIVITY[3]

Concentrations[a], in Nanograms per Kilogram of Air				
Setting[b]	Industrial	Rural	Mountain	Oceanic
Total particulates	7,500	3,400	2,100	970
Iron	980	370	48	14
Lead	560	130	37	4
Manganese	40	18	15	0.6
Cadmium	5	2	1	0.2

[a] Data are means for 1975, corrected from volume concentration to mass concentration based on density for air of 1.24 kg/m^3 at 10°C and 760 mm. Pressures and temperatures at individual sites were adjusted for altitude according to the adiabatic lapse rate for dry air.

[b] Locations are, respectively: Westend Frankfurt am Main, Kleiner Feldberg (823 m), Corviglia (2500 m), and in the Atlantic Ocean, 20°N, 15°W.

The second source of contamination of rainwater collected from a roof is washing off of particulates during dry periods. In a remote area in Britain with an annual rainfall of 56 inches the dry deposition ranged from 1 to 19 percent of the total deposition for 22 out of 23 elements studied.[4] For iron, dry deposition accounted for 17 percent of the total, while for lead less than 10 percent dry deposition was recorded. For urban areas in arid zones the proportion of dry deposition is likely to be greater.

Total particulate deposition rates measured at rooftop level in New York City can be used as an estimate of possibly the maximum to be expected in an urban area.[6] When divided by the annual precipitation of 56 inches, these total annual rooftop deposition rates can be expressed in terms of the mean concentration of metals in runoff from the roof. In decreasing order these concentrations are iron 2.5 mg/ℓ, zinc 0.65 mg/ℓ, lead 0.33 mg/ℓ, manganese 0.07 mg/ℓ, copper 0.06 mg/ℓ, nickel 0.05 mg/ℓ, chromium 0.03 mg/ℓ, vanadium 0.006 mg/ℓ, and cadmium 0.005 mg/ℓ. Note that this concentration of lead is more than six times that permitted by the National Standards.[5]

The third source of contamination of rainwater is bird droppings.

CHEMICAL ANALYSIS OF RICHMOND RAINWATER Chemical analyses of rainwater samples collected during the period of operation of the prototype rainwater collection system at Richmond are presented in Table 16.

The first line of Table 16 (Sample 1) presents analyses for the first runoff producing rainfall of the wet season, after several rainless months. With a suspended solids concentration and COD approaching 200 mg/ℓ, and a total nitrogen concentration of 10 mg/ℓ, this water resembles a weak sewage. Sample 1 was collected after 0.01 inch of runoff from the roof, while the second and third samples were collected after 0.09 and 0.17 inch of runoff, respectively. Each parameter decreases steadily with time, a tendency that persists through the following day, with the exception of lead. The increase in lead concentration at the beginning of the second day may be due to washout from the air of automotive exhaust products generated by the morning commute traffic.

In explanation of the dual columns for iron and lead in Table 16, the concentration of these elements was occasionally below the detection limit of the atomic adsorption spectrophotometer used for analyses. Values in the column headed "From 20-fold concentration" are one-twentieth the concentration determined after evaporating the sample to one-twentieth of its original volume following filtration and acidification.

Excluding the first three samples that undoubtedly represent washoff of dry deposition on the roof, the mean concentrations of iron and lead in Table 16 are 0.23 mg/ℓ and 0.08 mg, respectively. These values are within the ranges anticipated for the washout concentrations of 0.08 - 0.34 mg/ℓ for iron, and 0.06 - 0.24 mg/ℓ for lead, on the basis of a washout factor varying from 70 for heavy rain to 300 for light rain. Applying the same washout factor to the iron and lead concentrations in rural and mountain air cited in Table 16, we can estimate the iron and lead concentrations in rural and mountain rainfall. On this basis, the concentrations of iron and lead in rural rainfall might be expected to be in the range 0.03 - 0.11 mg Fe/ℓ and 0.01 - 0.04 mg Pb/ℓ, while values for mountain rain would be 0.003 - 0.015 mg Fe/ℓ and 0.003 - 0.011 mg Pb/ℓ.

From these calculations we expect that for rural or mountain areas well removed from industrial activity and high traffic densities, the mean concentration of lead in rainwater would not exceed the limit of 0.05 mg Pb/ℓ for drinking water. We recommend that rainwater be analyzed for lead prior to consumption in doubtful cases.

MICROBIOLOGICAL ASSAY OF RICHMOND RAINWATER Bacterial contamination of rainwater collected from roofs is most probably from bird droppings on the roof. Table 17 presents various microbiological assays on two rainwater samples collected from the roof.

For Sample 1A, the ratio of the 20°C plate count to the 35°C plate count was 360/160 = 2.25. As a general rule, a ratio of 10 or more is indicative of an unpolluted water, while a ratio of less than 10 indicates a polluted water. The ratio of 2.25 obtained for Sample 1A indicates a polluted water. A large number of fungal growths were observed on the 20°C plate.

TABLE 16

CHEMICAL ANALYSIS OF RAINWATER COLLECTED FROM ROOF AREA

Sample No.	Collection Date	Conductivity (μmho cm^{-1})	pH (units)	Turbidity (Nephlemetric turbidity units)	Suspended Solids (mg/ℓ)	Chloride (mg Cl^-/ℓ)	Chemical Oxygen Demand (mg/ℓ)	Nitrogen (mg N/ℓ)			Iron[c] (mg Fe/ℓ)		Lead[c] (mg Pb/ℓ)	
								Total Kjeldahl	Ammonia	Organic	From Sample	From 20-Fold Concentration	From Sample	From 20-Fold Concentration
1	9-16-77 10:30 am	392	7.4	52	173	88.3	178	10.3	3.2	7.1	6.9	--	0.4	0.35
2	9-16-77 11:30 am	181	7.7	13	58	26.9	50	3.1	0.7	2.4	3.2	1.8	0.2	0.15
3	9-16-77 12:30 pm	133	7.65	6.2	18	22	25	3.9	0.00	3.9	1.3	0.94	0.0	0.10
4	9-19-77 8:00 am	20.7	7.6	1.7	1	7.3	0.0	1.7	0.00	1.7	0.3[a]	0.30	0.1	0.22
5	9-26-77 12:30 pm	52.3	6.7	3.2	4.2	--	--	1.8	1.05	0.7	--	0.24	--	0.07
6	9-27-77	89.7	6.6	3.2	--	--	--	1.7	0.99	0.7	0.4[a]	0.24	0.0	0.13
7	9-28-77 1:30 pm	100	6.4	5.7	19.2	--	--	0.73	0.70	0.03	1.1	0.62	0.1	0.06
8	10-27-77	53.5	6.5	1.2	1.8	--	1.9	0.39	0.31	0.08	--	0.18	--	0.14
9	10-28-77	44.1	6.7	1.9	--	--	4.3	0.00[b]	0.28	∿ 0	0.4[a]	0.12	0.1	0.02
10	11-4-77	38.5	6.7	1.5	--	--	8.2	0.04[b]	0.10	∿ 0	0.3[a]	0.16	0.1	0.02
11	1-13-78 3:00 pm	65.0	6.2	1.2	0.6	--	7.3	0.01	0.00	0.01	--	0.08	--	0.03
12	2-12-78	--	--	--	0.4	--	--	0.00	0.00	0.00	--	0.09	--	0.04

[a] Value below recommended limit for accurate determination.

[b] Refluxer leakage caused low value.

[c] Determined or filtered, acidified sample.

TABLE 17

MICROBIOLOGICAL QUALITY OF RAINWATER COLLECTED FROM ROOF AREA AND EFFECT OF CHLORINATION ON MICROBIOLOGICAL QUALITY

Sample No.	Collection Date	Presumptive Coliforms (MPN/100 mℓ)	Fecal Coliforms (MPN/100 mℓ)	Fecal Streptococci (MPN/100 mℓ)	Standard Plate Count (number/100 mℓ)		Presumptive Coliforms After 1 hour of Exposure to Chlorine (MPN/100 mℓ)	Nominal Chlorine Dose (mg Cl/ℓ)	Chlorine Forms in Dosed Water mg Cl/ℓ		
					35°C	20°C			Free Chlorine	Monochloramine	Dichloramine and Nitrogen Trichloride
1A	11-20-77	43	<3	230	160	360	--	--	--	--	--
2A	13-1-78	20	--	--	--	--	21	0	0.00	0.00	0.00
2A	13-1-78	20	--	--	--	--	<2	1	0.26	0.08	0.06
2A	13-1-78	20	--	--	--	--	<2	2	1.42	0.13	0.17
2A	13-1-78	20	--	--	--	--	<2	5	5.84	0.10	0.20
2A	13-1-78	20	--	--	--	--	<2	10	11.83	0.00	0.48
2A	13-1-78	20	--	--	--	--	<2	20	28.53	0.40	0.60

Again for Sample 1A, the ratio of fecal coliforms to fecal streptococci was <3/240 or <0.013. Generally, a ratio of greater than 4 is indicative of human waste, while a value less than 1 indicates animal waste. The ratio of <0.013 suggests animal waste, probably from seagulls on the roof.

Sample 2A was chlorinated. For every level of chlorination from 1 mg Cl/ℓ no coliforms were detected after one hour of contact time. Over the same time interval, no significant change in the coliform density of an unchlorinated control was observed.

ANALYTICAL METHODS

Conductivity — A Beckman conductivity bridge, model RC-19, was used.

pH — A Radiometer pH meter, Model 22s, was used.

Turbidity — A Hach turbidimeter, Model 2100A, was used.

Suspended Solids — This was determined as total nonfiltrable residue dried at 103-105°C, using Whatman glass microfiber paper, GF/C, as described in *Standard Methods*.[7]

Chloride — An amperometric titrator was used.

Chemical Oxygen Demand — The procedure described in *Standard Methods*[7] was used.

Ammonia — The titration procedure described in *Standard Methods*[7] was used.

Kjeldahl Nitrogen — The procedure described in *Standard Methods*[7] for total Kjeldahl nitrogen was used.

Organic Nitrogen — This was computed by subtraction of ammonia nitrogen from total Kjeldahl nitrogen.

Iron and Lead — The atomic adsorption procedures described in *Standard Mathods*[7] was used, on samples filtered through Whatman GF/C filter paper and subsequently acidified. A Perkin Elmer Model 460 atomic adsorption spectrophotometer was used. To enhance the sensitivity of the analyses most of the samples were concentrated 20 times by evaporation before analysis, and results reported as 1/20 of the resulting values.

Chlorine Residual — The FAS-DPD method described in *Standard Methods*[7] was used.

Coliforms, Fecal Coliforms, and Fecal Streptococci — The multiple tube procedure described in *Standard Methods*[7] was used.

Plate Count — The standard plate count procedure described in *Standard Methods*[7] was used.

TREATMENT OF RAINWATER FOR QUALITY ENHANCEMENT The simplest method of treatment to remove contaminants from rainwater is settlement. Figure 46 presents the results of a 45-hour settlement test, during which time a reduction in turbidity of almost 80% was obtained. After the first 10 minutes of settling residual turbidity was inversely proportional to the time of settlement, as indicated by the fit of data points to the straight line. Also, the residual turbidity at 70% of the column depth remained close to 88% of the turbidity at 30% depth.

Since the residual turbidity of 13 NTU exceeds the standard for drinking water of 1 NTU,[5] further treatment of rainwater prior to consumption is indicated.

To investigate the further removal of turbidity by alum coagulation, standard jar tests were performed.[8] Starting with rainwater with an initial turbidity of 18 NTU, initial pH of 6.5, and initial alkalinity of 8 mg $CaCO_3$/ℓ, various doses of aluminum sulfate and sodium hydroxide solutions were added, and the jar test conducted involving 1 minute of flash mix followed by 20 minutes of flocculation at 60 rpm, then 60 minutes of settlement. Results, presented in Figure 47, demonstrate that in spite of the low alkalinity of rainwater, sodium hydroxide did not enhance the removal of turbidity by coagulation. For this water the optimum alum dose was approximately 10 mg Al/ℓ, for a minimum residual turbidity of 0.2 NTU.

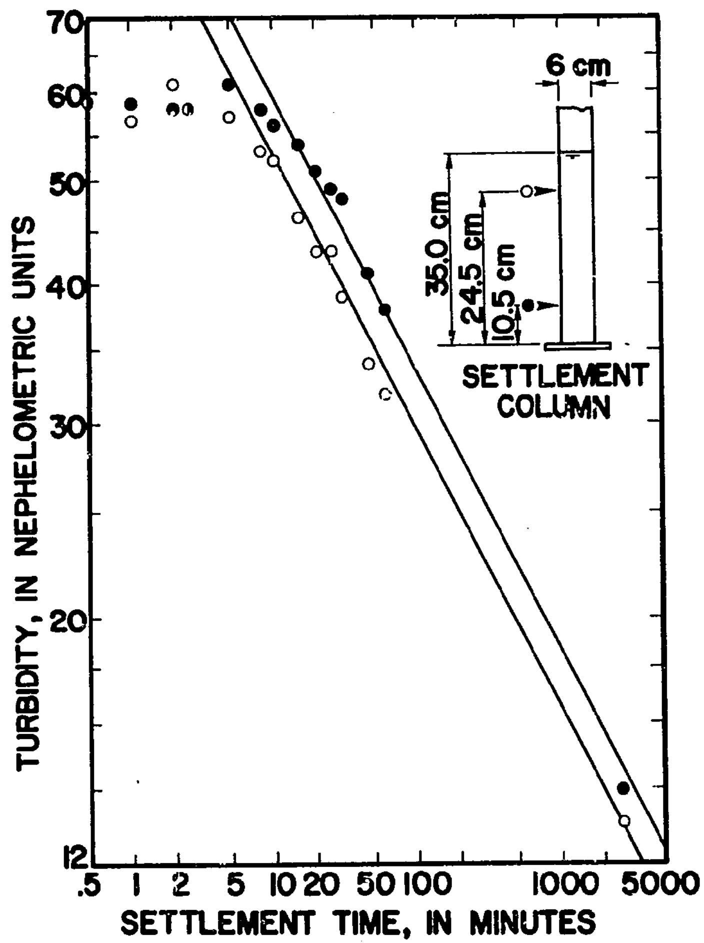

FIGURE 46 *Reduction in turbidity of rainwater during settlement*

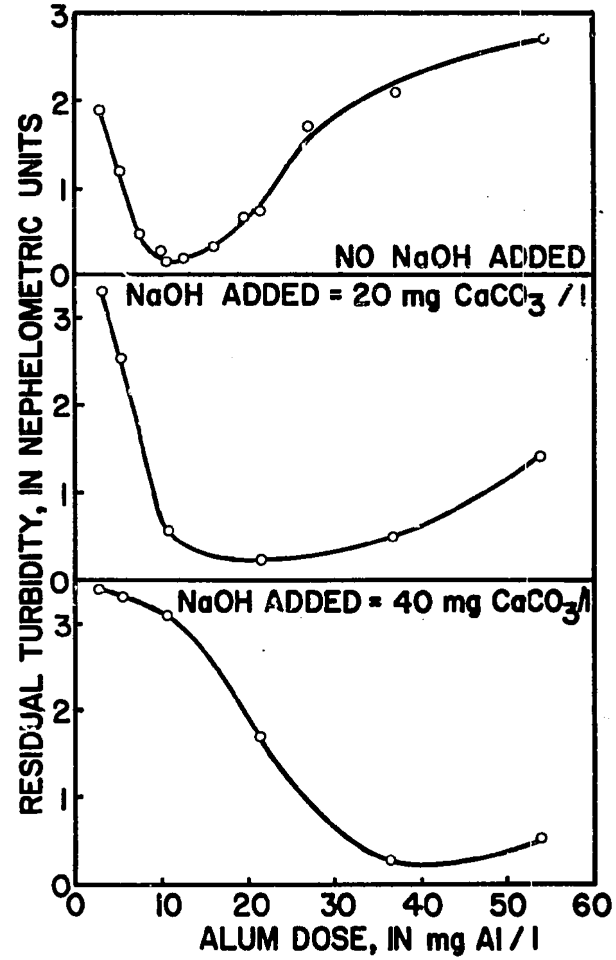

FIGURE 47 *Residual turbidity of rainwater after alum coagulation*

Table 18 demonstrates the efficacy of chlorination for disinfection of rainwater, although the question of the persistence of chlorine in stored water remains. Chlorine is lost from stored water to the air, and due to oxidation of ammonia and organic matter in the water. The persistence of chlorine in stored rainwater was studied, using water of pH $\sim$ 6.8, a chemical oxygen demand of $\sim$40 mg/ℓ, an ammonia concentration of $\sim$0.9 mg N/ℓ, and a total Kjeldahl nitrogen concentration of $\sim$ 2.3 mg N/ℓ.

Table 18 shows the various forms of chlorine residual in both rainwater and distilled water for initial chlorine doses from 1 to 100 mg Cl/ℓ, and contact times of 0.25 hour to 168 hour (1 week). Total residual is the sum of free residual chlorine plus mono- and di-chloramine, and nitrogen trichloride, while combined residual is the sum of mono- and di-chloramine and nitrogen trichloride. Free chlorine is therefore the difference between the total and combined residual. Mono-chloramine is the difference between the combined residual and the sum of di-chloramine.

Figure 48 shows the variation of chlorine residual at various doses with time for both rainwater and distilled water. Depletion of chlorine with time occurs from both rainwater and distilled water, though more rapidly from rainwater. Since chlorine is lost from distilled water at a rate roughly in proportion to its concentration, dissolution of chlorine to the air would appear to be a factor contributing to the decay of chlorine. The presence of combined residuals in distilled water is not understood; however, since these apparent combined residuals vary little with time, they would not contribute to the rate of decay of chlorine.

TABLE 18

LOSS OF CHLORINE DURING STORAGE FROM RAINWATER AND DISTILLED WATER

Chlorine Dose (mg/ℓ)	Chlorine Residual	Rainwater Chlorine Concentration (mg/ℓ) After Stated Time							Distilled Water Chlorine Concentration (mg/ℓ) After Stated Time						
		0.25 hours	1 hour	2 hours	24 hours	48 hours	120 hours	168 hours	0.25 hours	1 hour	2 hours	24 hours	48 hours	120 hours	168 hours
1	Total[a]	0.95	0.85	0.90	0.25	0.15	0.10	0.10	1.50	1.55	1.35	1.05	1.00	1.23	1.03
	Comb.[b]	0.85	0.85	0.90	0.25	0.15	0.10	0.10	0.55	0.70	0.40	0.50	0.50	0.35	0.43
	II + III[c]	0.15	0.15	0.25	0.15	0.10	0.07	0.10	0.20	0.30	0.20	0.15	0.20	0.15	0.13
2	Total	1.86	1.86	1.71	1.06	0.90	0.35	0.32	2.74	2.62	2.82	2.57	2.31	2.31	1.99
	Comb.	1.76	1.85	1.51	1.06	0.90	0.35	0.32	0.60	0.70	0.55	0.50	0.90	0.60	0.75
	II + III	0.35	0.40	0.45	0.30	0.15	0.10	0.12	0.25	0.35	0.35	0.30	0.35	0.40	0.30
5	Total	3.2	3.2	3.2	2.1	1.3	1.0[d]	0.7	3.7	3.5	3.4	3.3	2.6	2.9[d]	2.9
	Comb.	2.3	2.9	2.8	1.9	1.2	1.0[d]	0.7	0.9	1.1	1.0	0.9	1.0	0.6[d]	0.8
	II + III	0.5	0.6	0.6	0.4	0.2	0.2[d]	0.1	0.3	0.3	0.2	0.3	0.3	0.3[d]	0.3
10	Total	4.8	4.5	4.3	2.3	0.5	0.4[d]	0.3	6.2	5.9	6.1	5.8	6.1	6.0[d]	6.1
	Comb.	4.3	4.2	4.1	2.2	0.5	0.4[d]	0.3	0.7	0.4	0.3	0.4	0.4	0.4[d]	0.5
	II + III	3.2	3.3	3.3	1.8	0.4	0.2[d]	0.1	0.7	0.4	0.3	0.3	0.4	0.3[d]	0.3
25	Total	10.3	12.1	17.5	5.3	2.6	0.9	0.4	14.5	15.7	16.6	12.2	9.6	14.6	13.9
	Comb.	2.6	1.8	1.7	1.6	1.4	0.9	0.4	4.4	0.8	0.8	0.8	1.1	0.8	0.9
	II + III	1.3	1.2	0.7	1.0	0.9	0.7	0.2	0.7	0.8	0.7	0.7	0.6	0.8	0.8
50	Total	34.1	17.1	28.5	23.1	21.7	16.3	13.1	20.1	24.2	27.1	25.0	18.7	27.7	24.6
	Comb.	2.8	2.4	2.6	2.4	2.8	1.4	1.4	0.8	1.3	1.5	1.6	7.4	1.0	2.4
	II + III	2.0	1.8	1.6	1.4	2.0	0.9	0.9	0.7	1.0	1.0	1.4	2.0	0.8	2.0
100	Total	46.6	56.4	62.4	54.7	45.3	52.3	43.1	43.5	30.2	64.9	49.9	59.2	51.7	54.1
	Comb.	22.1	2.8	2.6	2.5	2.8	2.0	2.8	13.7	1.2	2.0	1.8	1.1	2.2	3.4
	II + III	2.2	1.6	1.6	1.7	2.0	2.0	2.4	2.9	1.2	1.6	1.0	0.8	1.4	3.0

[a]Free Cl_2 + NH_2Cl + $NHCl_2$ + NCl_3. [b]NH_2Cl + $NHCl_2$ + NCl_3. [c]$NHCl_2$ + NCl_3. [d]Values read after 96 hours.

For rainwater dosed with chlorine up to 25 mg Cl/ℓ the free residual persists even for a dose as low as 1 mg Cl/ℓ, as is apparent from Figure 49. Considering that the water used in these experiments was as contaminated as might be expected under the worst conditions, a weekly chlorine dose of 2 mg Cl/ℓ appears appropriate in rural areas at the end of a dry spell, reduced to 1 mg Cl/ℓ per week during persistent rainy periods. Colorimetric testing for a residual would be preferable, but perhaps impractical for owners of individual water supply systems.

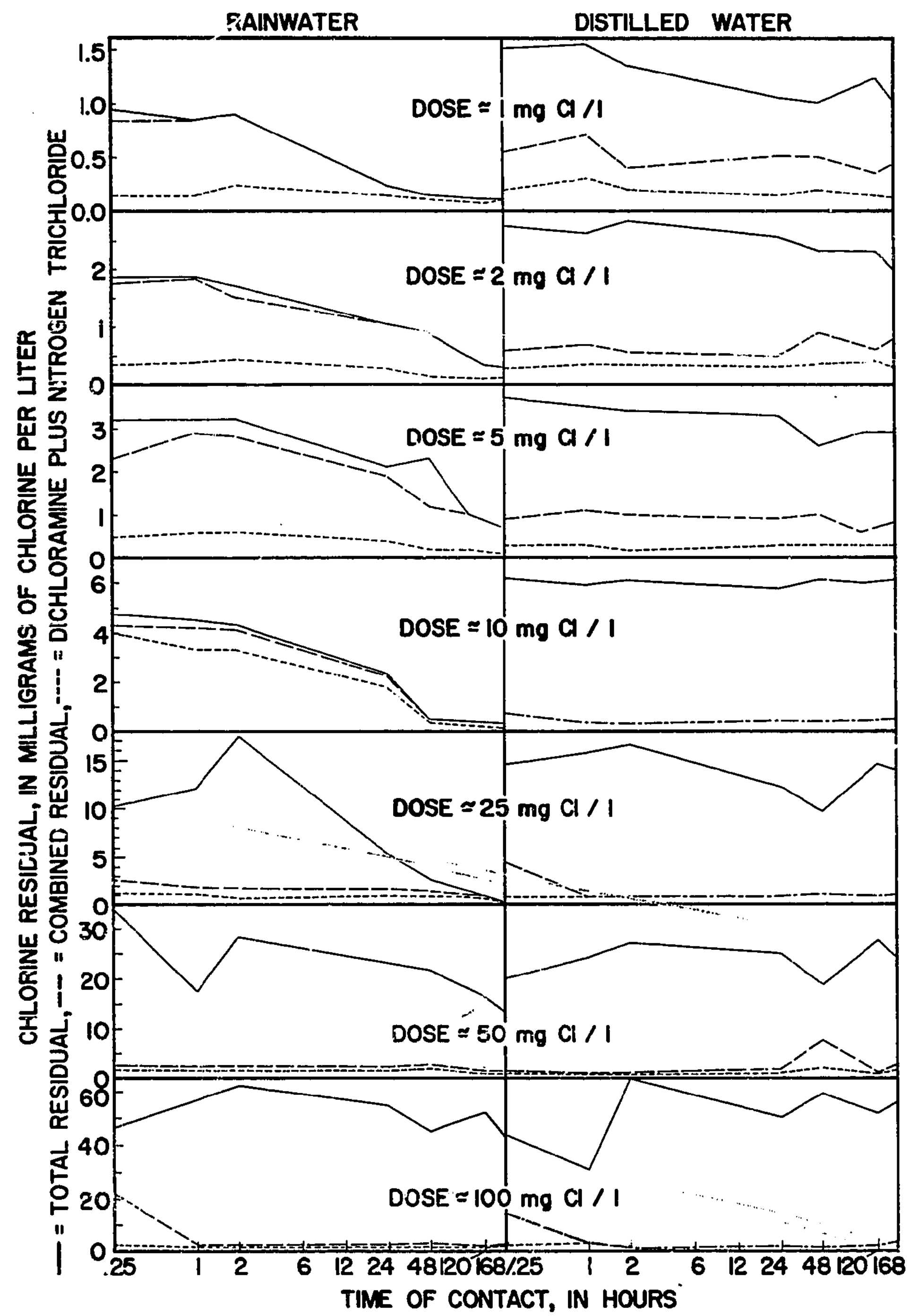

FIGURE 48 Time variation of chlorine residual in rainwater and distilled water

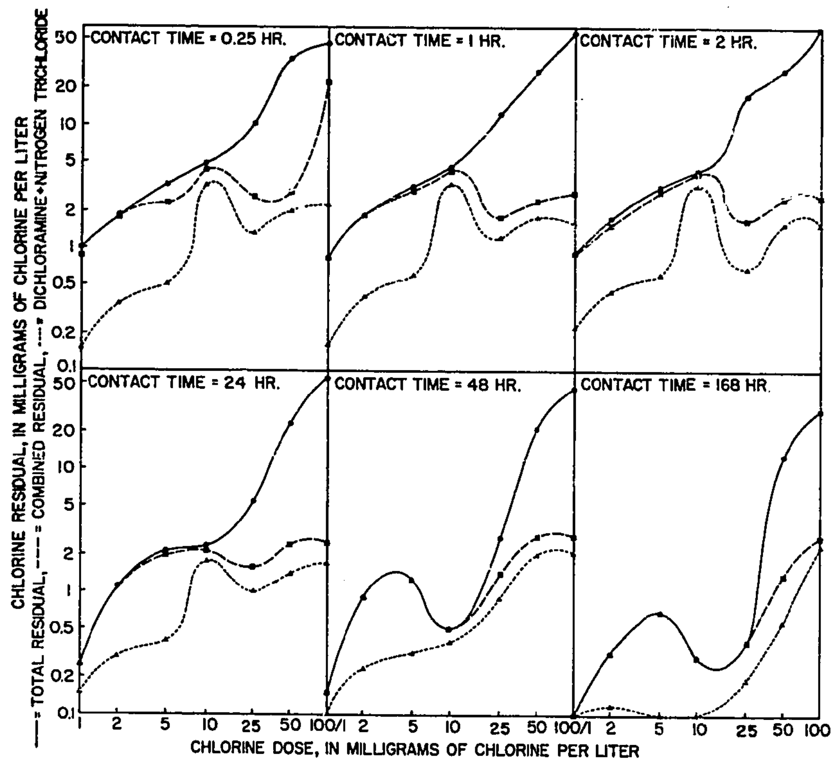

FIGURE 49 *Chlorine residual versus chlorine dose at various times after application of chlorine*

PRACTICAL MEASURES FOR ATTAINING A POTABLE RAINWATER SUPPLY Within perhaps thirty miles of industrial areas in California there is a risk that the concentration of lead in rainwater will exceed that recommended for potable water.[5] Analytical testing of rainwater for lead is recommended in suspect areas, prior to use of rainwater for a drinking water supply.

There are many situations where rainwater collection systems may be feasible provided measures are taken to protect and enhance the quality of the supply. For several years a rainwater collection system provided the sole supply at Point Reyes Lighthouse 32 miles northwest of San Francisco, for the lighthouse staff and for the foghorn steam boilers. Nowadays the paved collection areas and storage tanks are used as a reserve for firefighting, and potable water is trucked in for the resident Coast Guard and National Parks Service personnel. Some Air Force bases in Florida also collect rainwater from runways for firefighting. Possibly the best-known collection system for drinking water is on Gibralter.

On a domestic scale, quality protection and enhancement measures must be simple, reliable, and constructed to avoid any significant possibility of accidentally crucially contaminating the supply. To achieve this, the first step is to arrange for the first flush of rain containing dust and bird droppings to be diverted away from the storage tank.

Figure 50 illustrates a collection trap that can be used to intercept the first flush of rain before it enters the rainwater storage tank. This trap consists of a large jar or similar receptable connected by a vertical downspout to the guttering, or to a level section of downspout leading to the rainwater tank. In order for the trap to intercept 0.01 inch of rain (shown in this study to be most highly polluted) the capacity of the jar should be about 6 gallons per 1000 square feet of roof area. When the jar fills, a tennis ball (or similar), slightly smaller than the inlet pipe, floats up to seal the inlet pipe of the trap, and allows water to pass to the collection tank. To reset the trap, a couple of squeezes on the dime-store bellows pump will start the water siphoning out of the trap, until the water level reaches the end of the tube inside the jar. The volume of first flush to be intercepted is that volume above the level of the end of the tubing in the jar. Occasionally the jar should be removed and rinsed out.

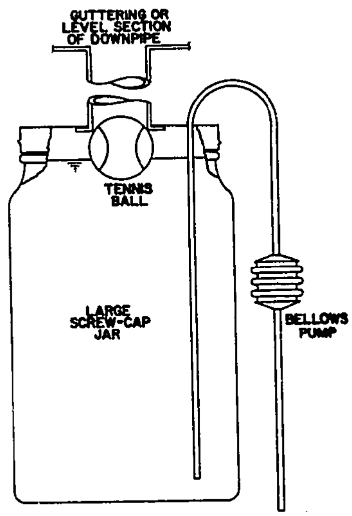

FIGURE 50

First flush collection trap

To disinfect the water the simplest procedure is to add Clorox or similar chlorine bleach weekly, at the rate of one ounce per 200 gallons of water in storage after dry periods, or one ounce for each 400 gallons of water stored during wet spells. A dip-stick or transparent tubing indicating the level of water in the tank can be calibrated with the number of ounces of chlorine bleach to be added each week. If a chlorinous taste develops in the water (more probably due to the presence of chloramines than due to chlorine itself), it may be reasonably safe to dose weekly with one ounce for each 400 gallons of water. If, due to absence of the occupants, water is not chlorinated for a week or more, one ounce of chlorine bleach for each 200 gallons of water should be added to the storage tank on return.

Based on the SERL analysis for Clorox of 5% chlorine (50,000 mg Cl/ℓ) a dose of one ounce of Clorox per 200 gallons of water is equal to 2 mg Cl/ℓ, while one ounce of Clorox per 400 gallons of water is equal to 1 mg Cl/ℓ. In the tests described above on rather grossly contaminated rainwater, for one week a chlorine dose of 1 mg Cl/ℓ was shown to maintain a measurable combined chlorine residual.

If the rainwater contains objectionable turbidity, alum coagulation can be used to clarify the water. Generally, the alum dose for minimum residual turbidity should be determined by jar testing the individual water, though due to the rather uniform character of rainwater the optimum alum dose established in this research of 10 mg Al/ℓ may well be valid.

Removal of turbidity by alum coagulation involves three steps: rapid mixing of the alum throughout the water to be treated; a period of gentle agitation to allow the coagulant to enmesh the turbidity particles in the water; and a quiescent period as the enmeshed particles of turbidity and coagulant settle from the water, leaving clear water above.[9] For treatment of rainwater for domestic use it is possible to arrange for the rapid mix, gentle agitation, and quiescent settlement stages to be performed in a rainwater storage tank, after modification of the plumbing as shown in Figure 51.

Typically, water is pumped from a rainwater tank into the household. To modify this equipment for coagulation of the water, it is necessary to add appurtenances as shown in Figure 51:

1) A pipe branches from the pump outlet, delivering into the tank a little below top water level, fitted with two valves, A and C.

2) A pipe branches from the pump inlet fitted with a valve, B, leading by a length of ¼ inch flexible plastic tube fitted with a pinch clamp, valve D, to a bottle containing the coagulant. Valves A and B are interlocked so that they must be both open, or both closed, at any time; this can be arranged using globe valves.

3) Baffles near the floor of the tank minimize resuspension of previously settled sediment during the period of mixing and gentle agitation. (It would be preferable to remove this settled material from the tank with a swimming pool-type vacuum cleaner before and after each treatment of the water with coagulant, thereby obviating the need for baffles.)

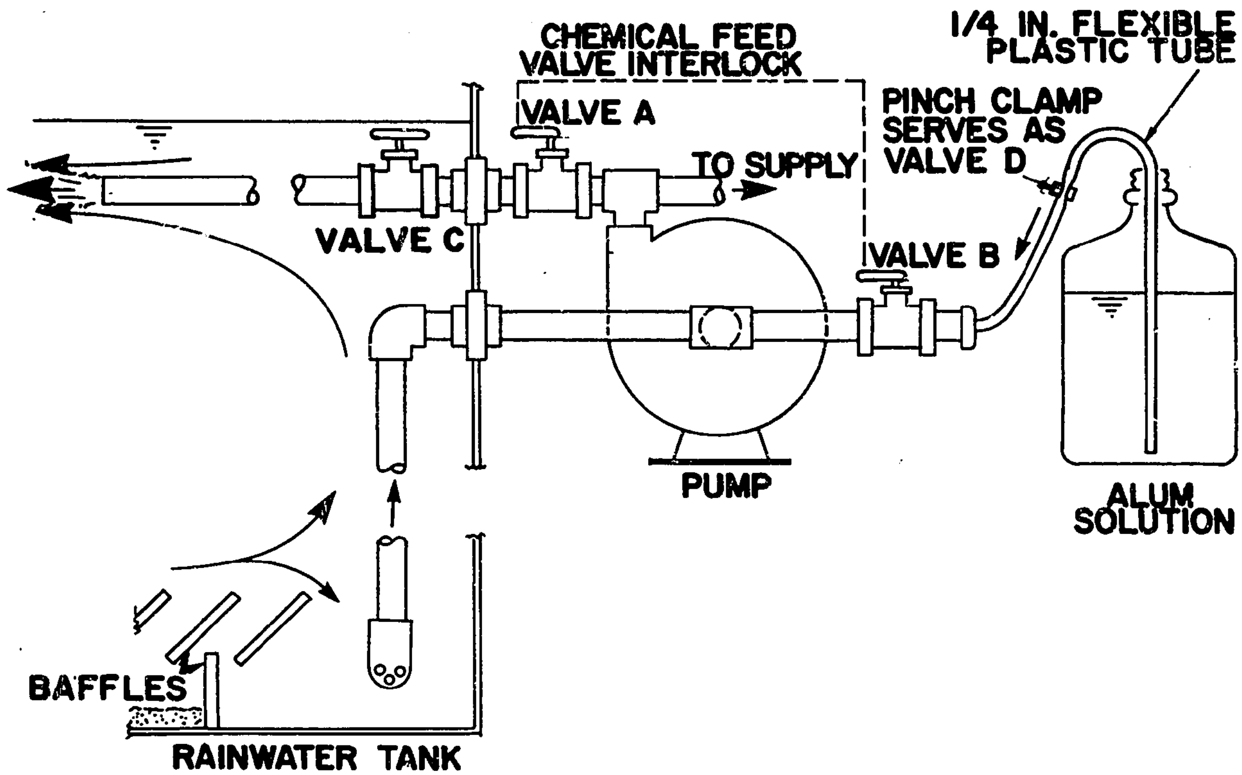

FIGURE 51 Modification of rainwater tank for coagulation of water

From Figure 51 it can be seen that when valves A and B are closed the pump delivers water from the tank to the household. When valves A and B are opened, water is circulated back into the tank thereby agitating the contents of the tank. Also, with valves A and B open the coagulant in the bottle is drawn into the pump and is mixed with water drawn from the tank.

Rapid and thorough dispersion of coagulant throughout the water to be treated is quite critical to the success of alum coagulation, as is the intensity of agitation. For thorough dispersion of coagulant throughout the water the coagulant should be introduced as slowly as possible into water circulating from the tank through the pump and back to the tank. A suggested minimum time for feeding coagulant into the pump is the time for a volume of water equal to the capacity of the tank to pass through the pump. Likewise, the degree of agitation of tank contents by the pumped water depends on the pumping rate.

The horsepower required for agitation is:

$$P = \frac{G^2 \mu V}{4114} \tag{17}$$

in which P = horsepower; G = shear velocity = 45 sec^{-1}, a value within the recommended range of 30-60 sec^{-1}; μ = viscosity of water = 2.735 X 10^{-5} lb-sec/ft^2 at 10°C; and V = the storage capacity, in gallons.[9] Substituting values for G and μ, P = 0.0135 horsepower per thousand gallons. Because hydraulic power is transmitted rather inefficiently from the pump to the body of water in the tank, it is recommended that a minimum of 0.1 HP per 1000 gallons be provided. By throttling down valve C, the actual power delivered by the pumped water can be adjusted to 0.0135 HP per 1000 gallons.

To develop a procedure for adjustment of valve C, the horsepower delivered by the jet of water into the tank is:

$$P = \frac{D^2 \gamma \nu^3}{201680g} \tag{18}$$

in which D = diameter of pipe delivering into the tank, in inches; γ = unit weight of water = 62.4 lb/ft^3; ν = velocity of jet into tank, in feet per second; and g = acceleration due to gravity = 32.2 ft/sec^2. To determine the unknown value of ν the trajectory of the jet of water issuing horizontally from the pipe into the tank is measured, which conforms to:

$$\nu = \sqrt{\frac{g}{2}\frac{X^2}{Y}} \tag{19}$$

in which X and Y = respectively the horizontal and vertical distances from where the jet leaves the pipe to where it impinges on the wall or floor of the tank, in feet. Combining Equations 17-19:

$$Y = 12.86\ X^2\ D^{4/3} V^{-2/3} \tag{20}$$

For a pump delivering at this rate, the time required for a volume of water equal to the capacity of the tank to pass through the pump is:

$$T = 0.1018\ V\ Y^{0.5}\ D^{-2} X^{-1} = 36.5\ V^{2/3}\ D^{-4/3} \tag{21}$$

in which T = time for circulation of one tank volume = coagulant feed time, in minutes. Figure 52 was prepared from Equations 20 and 21.

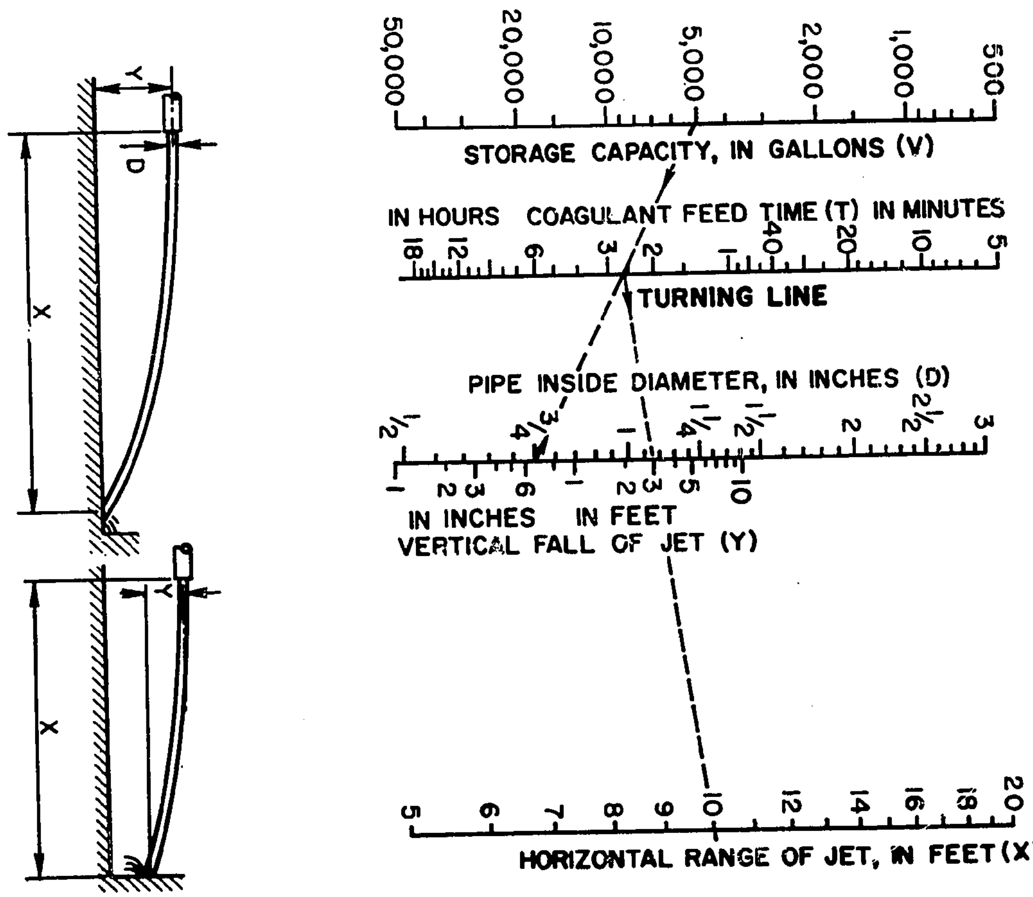

FIGURE 52 *Nomograph for adjustment of jet velocity for optimal agitation and adjustment of time of feeding coagulant to water for adequate mixing. Diagrams show method of measurement of jet trajectory.*

The example case in Figure 52 is for a 5,000 gallon tank fed by a 3/4 inch pipe that discharges horizontally at a horizontal distance of 10 feet from the opposite wall of the tank. Valve C should be adjusted until the jet strikes the wall 3 feet below the level of the pipe. Alternatively, if the tank is wider than 10 feet and the jet discharges 3 feet above the floor, valve C should be throttled until the jet impinges on the floor 10 feet horizontally from the end of the pipe. Also from Figure 52, the coagulant feed time of 2.6 hours is obtained. The pumping rate is 5,000 gallons per 2.6 hours or 32 gallons per minute.

Having adjusted valve C to obtain the required intensity of agitation of the tank contents, it remains to adjust valve D to dispense the alum solution in the specified time. For this purpose the alum solution bottle is filled with water and the pump run with valves A and B open for a period equal to half the required chemical feed time. If at the end of this period the alum solution bottle is less than half full, valve D should be closed a little by pinching the tube and the test repeated until approximately half of the contents are removed in one half of the required chemical feed time. If less than one half is removed, valve D should be opened a little. For these tests, and for subsequent operation, the alum solution bottle should be kept at the same level; a little below the water level in the tank is best.

When valves C and D are adjusted they are not touched again. Operation of the system involves manipulation of valves A and B only, which are interlocked to open and close together, to avoid the possibility of pumping alum solution directly into the household. Each time water in the tank is coagulated the pump should be run with valves A and B open for 30 minutes longer than the coagulation time, then A and B should be closed.

The alum solution is prepared by placing in the alum bottle one pound of alum ($Al_2(SO_4)_3.18H_2O$) for each thousand gallons of water in the tank, filling the coagulant bottle with water, and shaking until dissolved. When dispersed throughout the contents of the tank this is equal to a dose of 9.7 mg Al/ℓ which was determined to be optimal in the jar tests on SERL rainwater.

Planning for an Individual Water System[10] provides a general guide to many aspects of planning for rainwater collection systems.

SUMMARY AND CONCLUSIONS

Rainwater collected from a house roof into a large storage tank can provide a sufficient supply for minimal household use. Because of the cost of the large storage tank, rainwater collection systems are unlikely to be competitive where piped water is available, or where a suitable surface water or groundwater source is at hand. A much smaller storage tank will suffice if the rainwater collection system is operated conjunctively with an alternative supply such as a tanker truck, using the alternative supply during the dry season.

The performance of rainwater collection systems is investigated from 40 years of rainfall records at 13 California locations representing the major climatic regions of the state. Over all these locations a consistent relationship emerges between the year-round daily supply of water and the collection area, storage volume, and annual rainfall at the location of interest. This relationship can be used in the design of a rainwater supply system, either as the sole source or in conjunction with an alternative source.

To interpret the emperical design relationships established, statistics of rainfall at the 13 California locations are evaluated. Quite consistently, 88 percent of the annual rain falls during the November-March wet season. The scant summer rainfall is highly variable from year to year ($CV \lesssim 3$) and highly skewed ($\gamma_3 \lesssim 4$), compared to winter rainfall ($CV \approx 1$, $\gamma_3 \approx 1$). Wet season rainfall is log-normally distributed, but summer rainfall defies any common distribution. Slight serial correlation is observed for wet season rain ($r = 0.2$) but not for summer rain ($r = 0$).

From these statistics up to 1,000 years of monthly rainfalls are generated synthetically, and calculations made of the storage volume needed to sustain specified levels of demand at different levels of reliability. For collection system design periods up to about 40 years the storage capacity needed in a perfectly reliable system varies as the 0.6 power of the design period. If occasional failure to supply the total specified demand can be tolerated, the design period is of little significance. Storage capacities computed from synthetic records with zero variance and zero serial correlation (but with the observed annual distribution of monthly rainfall) are only slightly less than those computed from the actual values of variance and serial correlation. Thus, as an alternative to the suggested design procedure, the storage capacity can readily be estimated from monthly mean rainfall data, adding about 50 percent to the storage so computed to hedge against dry years.

Chemical and microbiological analyses of rainwater collected from a roof in the San Francisco Bay area are presented. The first flush of rainwater from a roof is grossly contaminated, being similar to sewage in composition. Even after 24 hours of rain, the concentration of lead remains comparable to or above the limit recommended for drinking water, apparently due to washout from the air. For this reason, consumption of rainwater collected in urban areas is not recommended. Microbiological contamination of rainwater appears to derive from flushing of bird droppings on the roof.

Treatment of rainwater for quality enhancement is demonstrated. Chlorination at 1 mg Cl/ℓ for one hour is effective for disinfecting the water. Settlement in the storage tank was shown to remove about 80 percent of initial turbidity in one day, though the residual turbidity remained in excess of drinking water standards. Alum coagulation reduced the residual turbidity below the specified level of 1 NTU. Practical methods of implementing quality enhancement measures on a household scale are presented, with construction diagrams.

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