From Bras, Hydrology, An Introduction to Hydrologic Science, 1990

4.7.3 Mean Areal Precipitation

There are two common spatial averages used in hydrology, the mean areal precipitation of a storm event and the time-averaged mean areal precipitation over a given period of time. Mathematically, they are defined as

Areal mean of an event:

$$P_1 = \frac{1}{A}\int_A f(x)\,dx \tag{4.30}$$

Long-term areal average:

$$P_2 = \frac{1}{T}\frac{1}{A}\sum_{i=1}^{T}\int_A f(x, t_i)\,dx\,, \qquad T \to \infty \tag{4.31}$$

where $f(x)$ is the function describing a storm total accumulation at all points x_i; and $f(x, t_i)$ is a function describing total precipitation at x and period t_i.

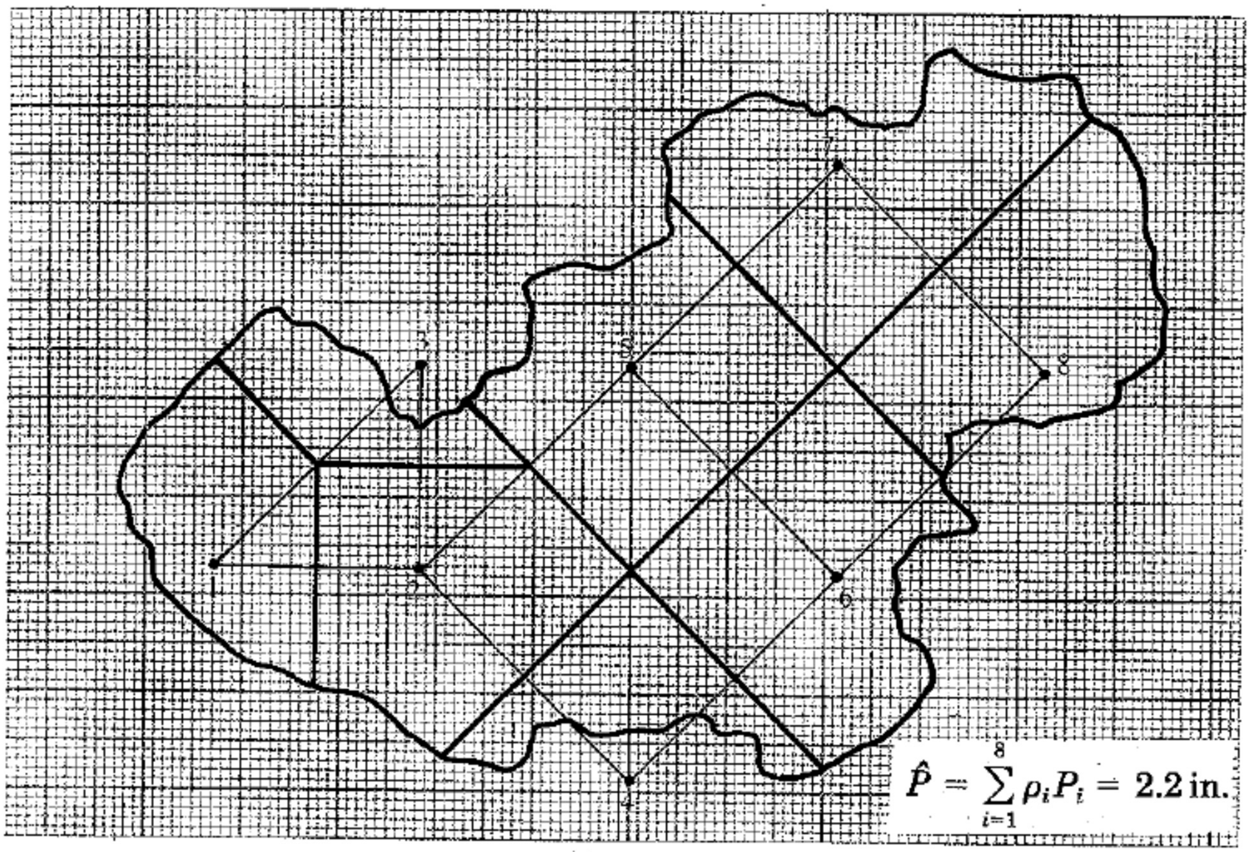
Since rainfall observations are generally point values, imperfect for that matter, we do not know the function $f(x)$. Generally, the spatial integration is then approximated by some sort of discrete weighted average. The weights would be one over the number of stations if observations were uniformly distributed and the rainfall process is completely homogeneous in space. This is certainly not the case.

Knowing a spatially varying mean behavior and/or the spatial correlation of the rainfall process, optimal weights could be determined (Lenton and Rodriguez-Iturbe [1977]; Bras and Rodriguez-Iturbe [1976]; Delhomme and Delfiner [1973]). The weights would be optimal in the sense that the mean square error of approximating Eqs. (4.30) and (4.31) is minimized. The mean square error is defined as $E[(P - \hat{P})^2]$, where P is the desired statistic, $\hat{P}$ is its estimate, and E is the expectation (computation of the mean) operator.

Commonly, two different methods to obtain areal averages of storm events are used. The first method is the Thiessen weighting scheme. Figure 4.30 illustrates the method. An area with eight rainfall stations is shown. Rainfall values at each location are also given. The weighting mechanism is of the form

$$\hat{P} = \sum_{i=1}^{N} \rho_i P_i\,, \tag{4.32}$$

where ρ_i is the weight applied to observation P_i. In the Thiessen method, the weight is a measure of rain-gage contributing area. In the procedure, all rain gages are connected, shown in thin lines in the figure. Connecting lines are bisected and extended until they intersect other bisectors. The result is a

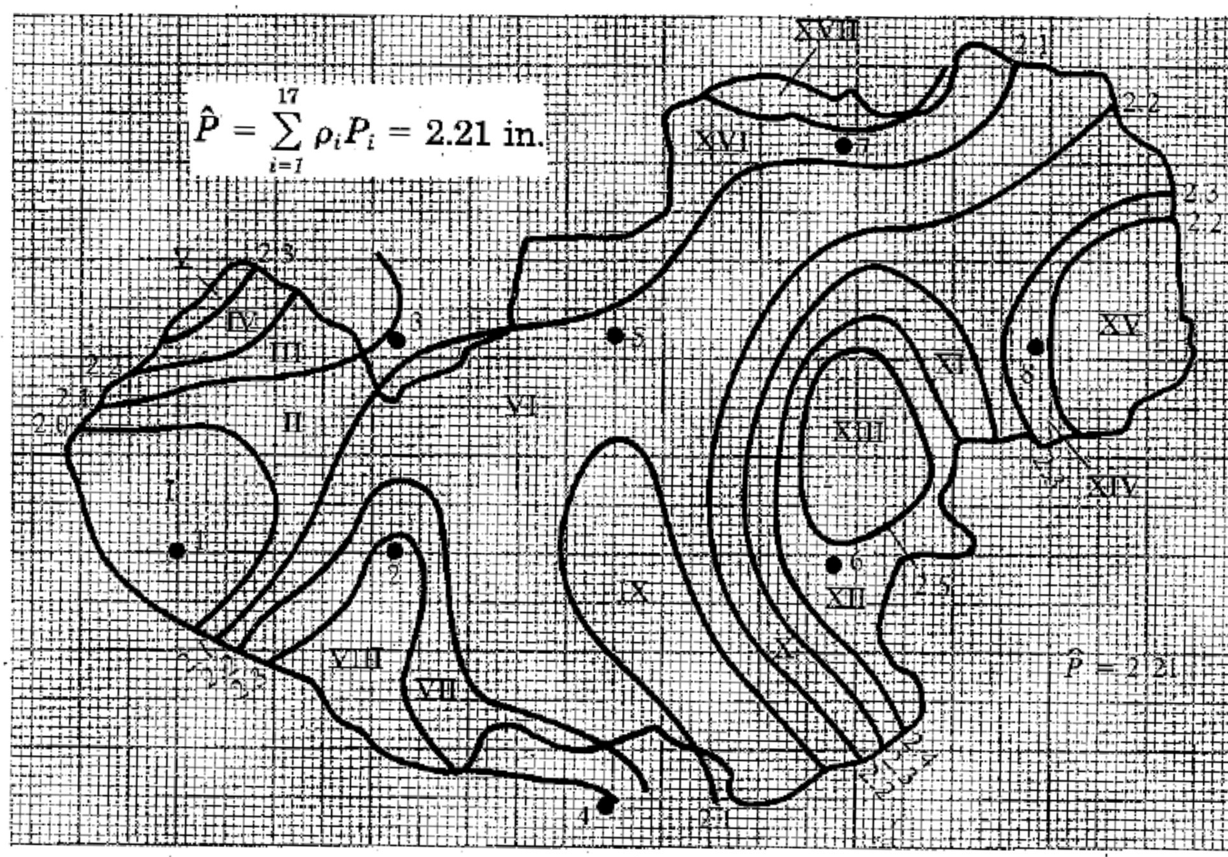


STATION	PRECIPITATION, P_i (INCHES)	THIESSEN WEIGHT, ρ_i
1	1.9	0.105
2	2.3	0.1611
3	2.1	0.0540
4	2.3	0.0705
5	2.2	0.1607
6	2.4	0.1567
7	2.1	0.1560
8	2.2	0.1360

FIGURE 4.30 Illustration of Thiessen coefficients.

polygonal pattern, shown in thick lines in the figure. Each station is surrounded by a closed polygon of given area. The weights ρ_i are given by A_i/A, where A_i is the area of the polygon around station i and A is the total area. The area of each polygon can be estimated by planimeter or any other valid approximation. Here, the area was measured by counting the small squares of the superimposed fine grid. The reader is challenged to repeat the exercise. There is a good chance of proving me wrong! The obtained mean areal precipitation was 2.2 in.

The second common method is the isohyetal method. An isohyetal map is one showing lines of equal precipitation (isohyets). In this method, the weights ρ_i are again A_i/A, where A_i is the area between isohyets. The weighted precipitation values are the average between contiguous curves of equal precipitation. This is illustrated in Figure 4.31. Shown in the figure are isohyets every 0.1 in. for the same storm of Figure 4.30. The areas enclosed by equal precipitation curves are numbered I to XIV. Again, the areas were measured by counting enclosed squares of the superimposed grid. To



AREA	P_i	ρ_i	AREA	P_i	ρ_i
I	2.05	0.0663	X	2.25	0.0965
II	2.05	0.0426	XI	2.35	0.0468
III	2.15	0.0166	XII	2.45	0.0512
IV	2.25	0.0098	XIII	2.55	0.0417
V	2.35	0.0027	XIV	2.25	0.0237
VI	2.15	0.2952	XV	2.25	0.0563
VII	2.25	0.0444	XVI	2.15	0.0778
VIII	2.35	0.0370	XVII	2.05	0.0138
IX	2.15	0.0776			

FIGURE 4.31 Illustration of the isohyetal method for computing mean areal precipitation.

each area we assigned the mean precipitation of the two boundary isohyets. Where necessary, the basin boundary was given a value 0.1 in. less than the encompassing interior isohyet. The obtained mean areal precipitation was 2.21 in., very close to that resulting from the Thiessen polygon method. Given the uniformity of the storm we are dealing with, this is not surprising.

The isohyetal method is preferable and more accurate. Its main limitation is that it requires enough observations to permit the drawing of contours of equal precipitation. On the other hand, a hydrologist knowledgeable of the typical precipitation patterns in a given area can obtain a better estimate of mean areal precipitation.

Depth–Area–Duration Curves

In Section 4.5 we saw that the area-averaged rainfall depth decreased with increasing area. We also mentioned that as depth and duration increase, the areal average increases and the accumulation generally becomes more uniform in space. It is sometimes useful to quantify these relationships for a given storm or set of storms. The result is the depth–area–duration curve. To obtain this curve for a given storm, we must have the storm history, say at intervals Δt, for a large number of stations within the area. A normal procedure would then be

1. Select intervals of area ΔA such that the total area is given by $A = m\,\Delta A$. Define $A_n = n\,\Delta A$; $n \le m$.
2. Define the precipitation over the area at all time intervals Δt.
3. For all time intervals Δt, find the maximum mean areal precipitation over a subarea of size A_n, arbitrarily located within the region. In order to maximize the mean areal precipitation over A_n, it is recommended that isohyetal maps of precipitation at time interval Δt be prepared. Repeat this step for all subareas A_n, $n = 1, \ldots, m$.
4. Repeat Step 3 for accumulations over time intervals $2\,\Delta t$, $3\,\Delta t$, and so on, until a period equal to the storm duration is covered.
5. Plot the maximum areal average depth for each period $\ell\,\Delta t$, $\ell = 1, \ldots, L$ (where L is storm duration divided by Δt) against its corresponding A_n.

A typical depth–area–duration curve is shown in Figure 4.32. If the storm has multiple centers, it can be analyzed by centers and the results combined at the plotting stage.

4.7.4 Frequency Analysis

Precipitation, streamflow, evaporation, and all other hydrologic and geophysical processes can be characterized as random occurrences. It is impossible to predict what the future realizations of the processes will be. The analysis of precipitation data should then follow well-established statistical procedures. For example, intensity–frequency–duration (IFD) curves are a

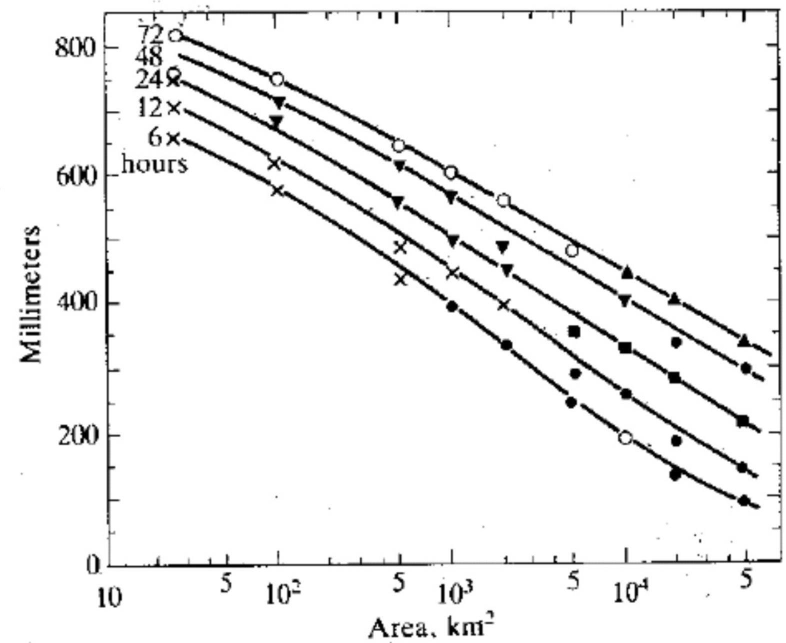


FIGURE 4.32 Diagrammatic presentation of maximum depth–area–duration curves for a catchment. Symbols indicate separate storms. Note the enveloping of data points. Source: A. J. Raudkivi, *Hydrology: An Advanced Introduction to Hydrological Processes and Modelling*. Copyright 1979 by Pergamon Press. Reprinted with permission by the author.

classical rainfall analysis tool that relates the probability of occurrence of storms of given duration and intensity. Probability of occurrence is usually measured in terms of recurrence interval (return period). The recurrence interval of a storm T is the mean time that will go by before an event equaling or exceeding the storm magnitude occurs. Mathematically, it is equal to the inverse of the probability of equaling or exceeding the event in a unit time period. For example, a 50-year-recurrence storm is one that has a probability of being equaled or exceeded in any one year of 1/50. On the average it will take 50 years before that occurs. IFD curves and other probabilistic and statistical measures will be studied in Chapter 11. They are discussed separately in order to make a more complete presentation and to emphasize their applicability to all types of data.

4.7.5 Network Design

As remarked by Lenton and Rodriguez-Iturbe [1974], it is necessary that "all aspects of data management be integrated—the initial collection of data cannot and should not be treated separately from the later stages of data analysis and synthesis." The data management and collection procedure must be defined in terms of the final objectives, goals, and uses of collected information.

Hydrologic-data-collection networks have been divided into various levels (Rodda [1969]). Levels I and II can be related to problems of regional estimation—i.e., there is no clearly defined final goal or use for the collected data. The problem of rainfall monitoring for estimating the total precipitation areal average for a storm event and the problem of finding the long-term (time) mean areal precipitation fall in these two levels. Level III networks are those designed to collect data for a specific, clearly defined, objective, which would imply known net benefits or utility of the data. The problem of rainfall monitoring for use together with a flood forecasting system theoretically fits this framework.

Historically, network design has been strongly influenced by issues of convenience and cost, ignoring the issues of required accuracy. Network design should involve stating the number and location of stations necessary for achieving the accuracy demanded by a given data use and under stated budgetary constraints.

Traditionally, the above objectives were accomplished using heuristic criteria. For example, McKay (Gray [1973]) mentions that for standard precipitation gages a 15-mile separation is adequate for Canadian conditions. Following are a few traditional design criteria and results.

The "index approach" requires the logical condition that sensors have the highest possible correlation with the effects that are being measured. One gage should be located in each "homogeneous" area. Each station should be highly correlated with surrounding effects but uncorrelated among themselves.

Several experiments have been performed on very densely gaged regions. McGuinness [1963] suggests the following formula for Coshocton, Ohio:

$$E = 0.03P^{0.54}G^{0.24}, \tag{4.33}$$

where E is the absolute difference in inches between observed and true average rainfall; P is the rainfall in inches for the "true" dense network; and G is the network density in square miles per gage for a reduced network. The above formula was developed from data of watersheds less than 25 mi^2 but was found to be consistent for larger areas. Being of local origin, extrapolation to other areas is speculative.

Hershfield [1965] suggested that the average spacing between gages should be that required for obtaining a correlation of 0.9 between station values. He related this spacing and correlation to the two-year recurrence, 24-hour duration rainfall and the two-year recurrence, one-hour duration rainfall. Figure 4.33 gives Hershfield's results. Holtan et al. [1962] recommend various rain-gage densities for agricultural areas. These are given in Table 4.5.

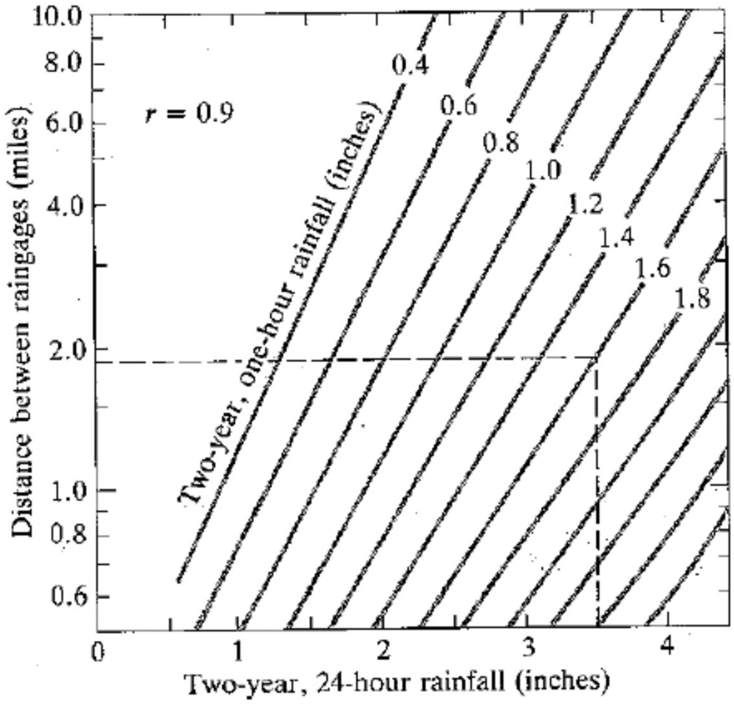


FIGURE 4.33 Diagram for estimating the distance between gages as a function of the two-year, 24-hour and two-year, one-hour rainfall. Source: After Hershfield [1965]. "On the Spacing of Rain Gages", in *Symposium on Design of Hydrological Networks*, vol. 1, pp. 72–81. IAHS Publ. no. 67.

A well-known study in the Muskingum River Basin by the U.S. Weather Bureau [1947] resulted in Figure 4.34, giving the standard error of estimating mean areal precipitation as a function of gage density and total area.

The following minimum densities of precipitation networks have been recommended for general hydrometeorologic purposes (Gray [1970]).

1. Flat regions of temperate, mediterranean, and tropical zones, 600 to 900 km^2 per station.

TABLE 4.5 Number of Rainfall Stations Required

SIZE OF DRAINAGE AREA (ACRES)	GAGING RATIO (mi^2/gage)	MINIMUM NUMBER OF STATIONS
0–30	0.05	1
30–100	0.08	2
100–200	0.10	3
200–500	0.16	1 per 100 acres
500–2500	0.40	1 per 250 acres
2500–5000	1.00	1 per square mile
over 5000	3.00	1 per each 3 mi^2

Source: Holtan et al. [1962].

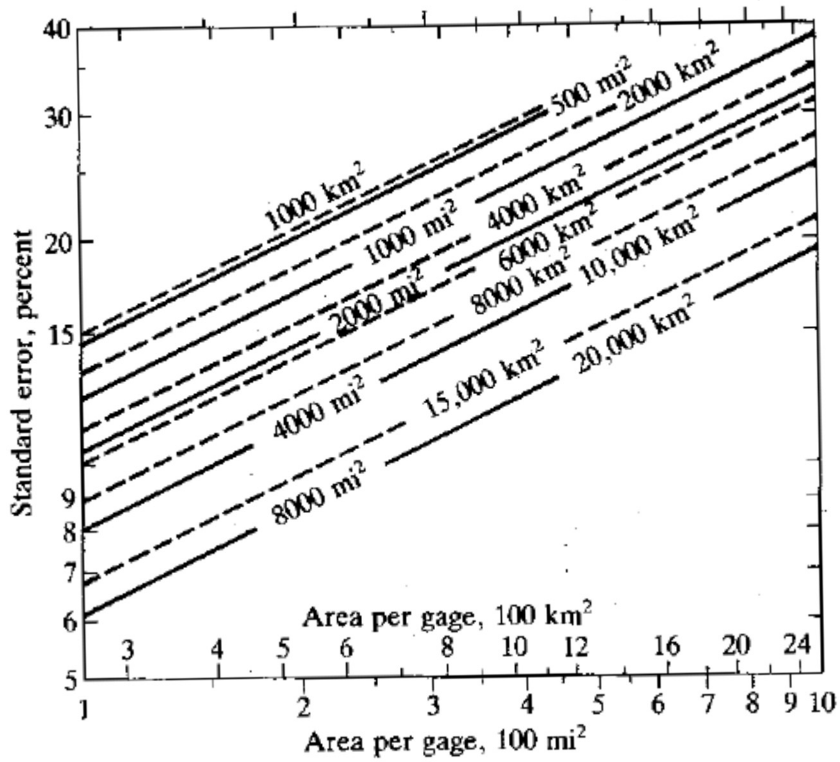


FIGURE 4.34 Standard error of storm precipitation averages as a function of network density and area for the Muskingum Basin. Source: U.S. National Weather Service [1972].

2. For mountainous regions of temperate, mediterranean, and tropical zones, 100 to 250 km^2 per station.
3. For small mountainous islands with irregular precipitation, 25 km^2 per station.
4. For arid and polar zones, 1500 to 10,000 km^2 per station.

*Generalized Network Design

Generalized and theoretical approaches to rainfall network design exist. Although different in techniques and assumptions, all procedures require some knowledge of the rainfall-process spatial correlation. The spatial correlation measures the level linear dependence of precipitation at two points separated a distance v from each other. A correlation of 1 (or -1) will imply perfect linearity. For precipitation, correlation is generally between 0 and 1 and gets smaller as the points are farther apart. A point is perfectly correlated with itself, since v is zero in that case.

Rodriguez-Iturbe and Mejia [1974] developed design curves for the mean square error of estimating the areal average of precipitation (Eq. 4.30) using a random sampling technique. Figure 4.35 gives one such curve, corresponding to random sampling and exponential-type correlation function in space, implying that the correlation falls exponentially with distance between stations. For isotropic, homogeneous random fields, the correlation is just a function of the distance between points v. The results of Figure 4.35 correspond to

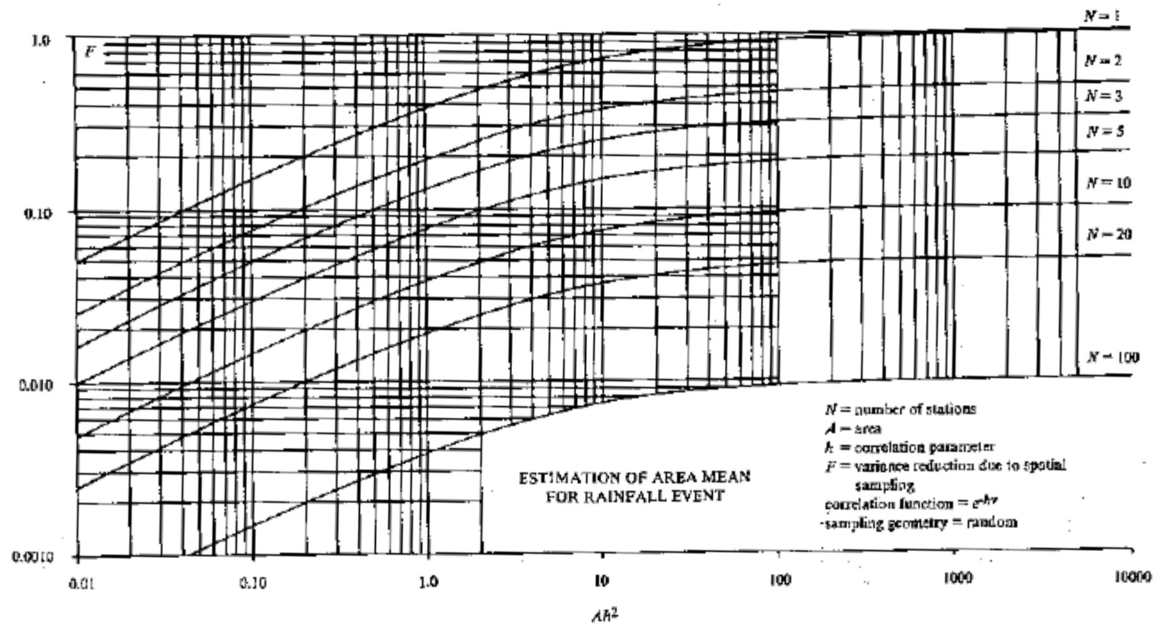


FIGURE 4.35 Variance reduction factor due to spatial sampling with random design used in the estimation of areal mean of rainfall event with $r(v) = e^{-hv}$. Source: I. Rodriguez-Iturbe and J. M. Mejia, "The Design of Rainfall Networks in Time and Space," *Water Resources Res.,* 10(4):725, 1974. Copyright by the American Geophysical Union.

a correlation of the form e^{-hv}, so $v = 0$ implies that rainfall at a point is perfectly correlated with itself. The correlation decreases as the distance between points v increases. The parameter h (km^{-1}) controls the decay in correlation with distance. Random sampling implies that the observations can be anywhere in space. The ratio of mean square error (MSE) to point variance (it is assumed that the process has the same variance everywhere) is given in terms of the number of stations N randomly located in space, and a nondimensional area Ah^2, where h is the parameter of the correlation function:

$$\text{MSE} = F(N; Ah^2)\sigma^2. \tag{4.34}$$

Figure 4.36 gives a similar curve for stratified sampling. Stratified sampling refers to random data collection within prespecified strata or regions. Note that the sampling error is smaller under these conditions. Rodriguez-Iturbe and Mejia [1974] assume perfect observations.

In the same work, Rodriguez-Iturbe and Mejia developed curves for evaluating networks designed to obtain the long-term areal average as defined previously (Eq. 4.31). They assume a separable, in time and space, covariance structure of the form $\text{cov}(v, \tau) = \sigma^2 r(v)\rho^\tau$, where σ^2 is the point variance of rainfall, $r(v)$ is the correlation due to distance v between points, ρ is the lag-one serial (time) correlation of data, and τ is the time between data points. The results are that the MSE of estimating the long-term areal average is given by

$$\text{MSE} = F_1(T)F_2(N; Ah^2)\sigma^2, \tag{4.35}$$

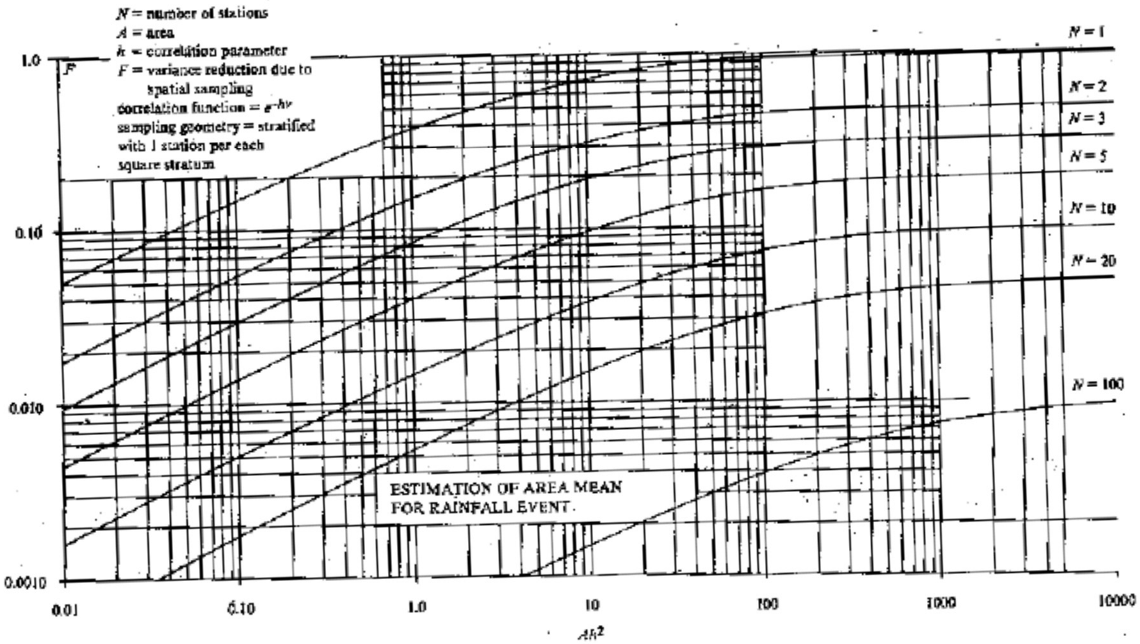


FIGURE 4.36 Variance reduction factor due to spatial sampling with stratified design used in the estimation of areal mean of rainfall event with $r(v) = e^{-hv}$. Source: I. Rodriguez-Iturbe and J. M. Mejia, "The Design of Rainfall Networks in Time and Space," *Water Resources Res.,* 10(4):726, 1974. Copyright by the American Geophysical Union.

where F_1 is a factor function of the number of time periods of observation T and the lag-one autocorrelation of the process. The dependence is shown in Figure 4.37. Figures 4.38 and 4.39 give $F_2(N; Ah^2)$, which is the space-dependent factor, for random and stratified sampling and exponential-type spatial correlation. The variables are the same as for Figures 4.35 and 4.36.

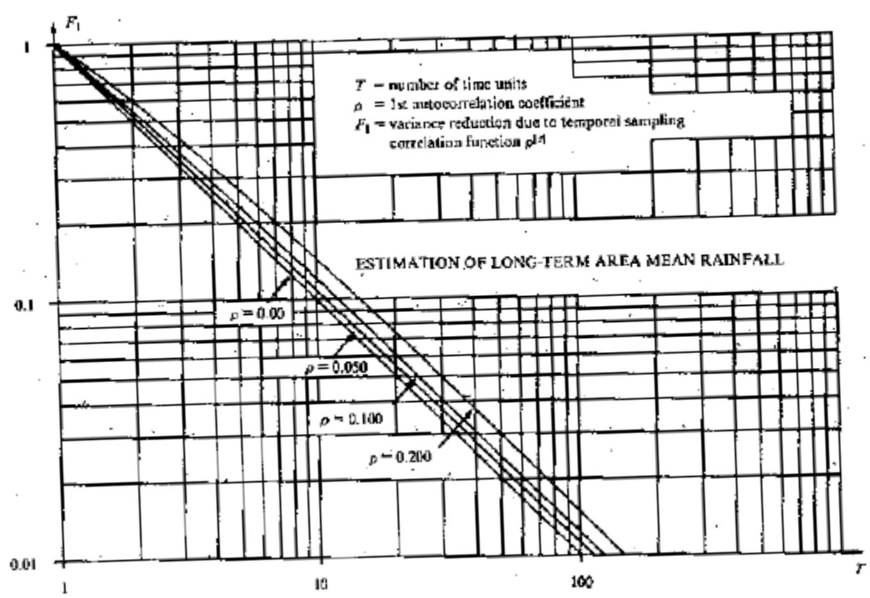


FIGURE 4.37 Variance reduction factor due to temporal sampling used in the estimation of long-term mean areal rainfall. Source: I. Rodriguez-Iturbe and J. M. Mejia, "The Design of Rainfall Networks in Time and Space," *Water Resources Res.,* 10(4):718, 1974. Copyright by the American Geophysical Union.

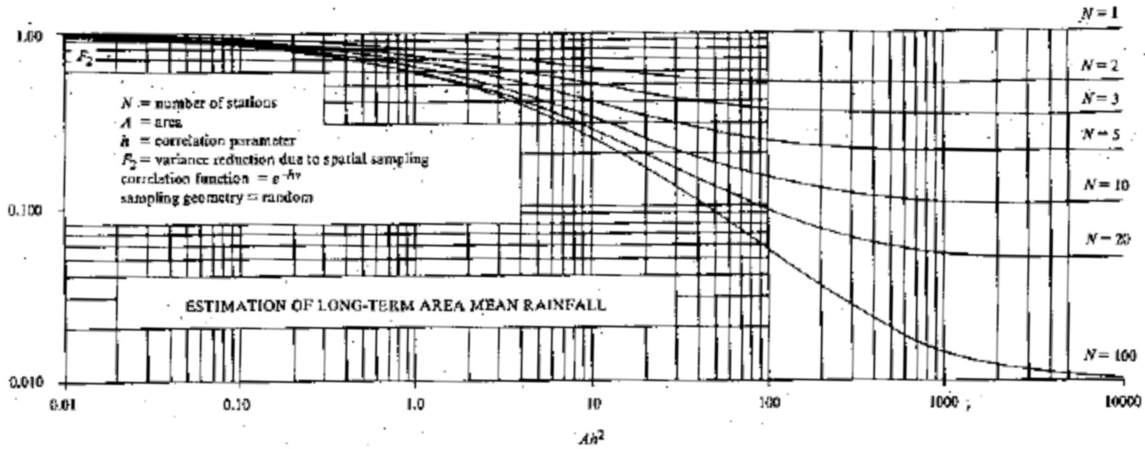


FIGURE 4.38 Variance reduction factor due to spatial sampling with random design used in the estimation of long-term mean areal rainfall with $r(v) = e^{-hv}$. Source: I. Rodriguez-Iturbe and J. M. Mejia, "The Design of Rainfall Networks in Time and Space," *Water Resources Res.*, 10(4):719, 1974. Copyright by the American Geophysical Union.

Bras and Rodriguez-Iturbe [1976] developed a method to handle the systematic sampling condition and instrument error. Systematic sampling implies that stations are given known positions in space. The procedure uses estimation theory and solves for the optimal network to obtain mean areal precipitation of an event by minimizing an objective function of mean square error (accuracy measure) and cost.

Bras and Colon [1978] address the network design for the long-term areal average under the previously mentioned systematic sampling techniques

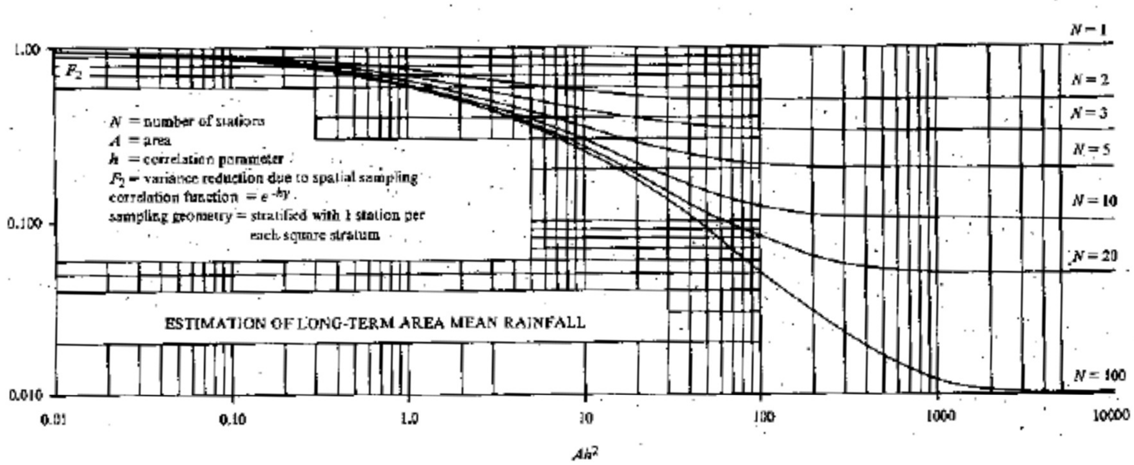


FIGURE 4.39 Variance reduction factor due to spatial sampling with stratified design used in the estimation of long-term mean areal rainfall with $r(v) = e^{-hv}$. Source: I. Rodriguez-Iturbe and J. M. Mejia, "The Design of Rainfall Networks in Time and Space," *Water Resources Res.*, 10(4):721, 1974. Copyright by the American Geophysical Union.

(i.e., not only number but station locations are specified). Estimation theory was used to find the mean square error of estimation expression and include instrument errors in the analysis. The interested reader is referred to Bras and Rodriguez-Iturbe [1985] for a complete view of the above procedures.

EXAMPLE 4.4

Monitoring Network Design

Rodriguez-Iturbe and Mejia [1974] illustrated the network-design exercise with an example from the Central Venezuela region. The region is shown in Figure 4.40, together with the location of its 26 rain gages, over its 30,000-km^2 area. Also shown are the mean annual precipitation isohyets. Table 4.6 gives the stations' annual means and their standard deviation computed as

$$\text{standard deviation} = s = \left[\frac{1}{N-1}\sum_{i=1}^{N}(X_i - \overline{X})^2\right]^{1/2},$$

where N is the number of years of data, X_i is the data point for year i, and $\overline{X}$ is the mean for the particular station,

$$\overline{X} = \frac{1}{N}\sum_{i=1}^{N} X_i \,.$$

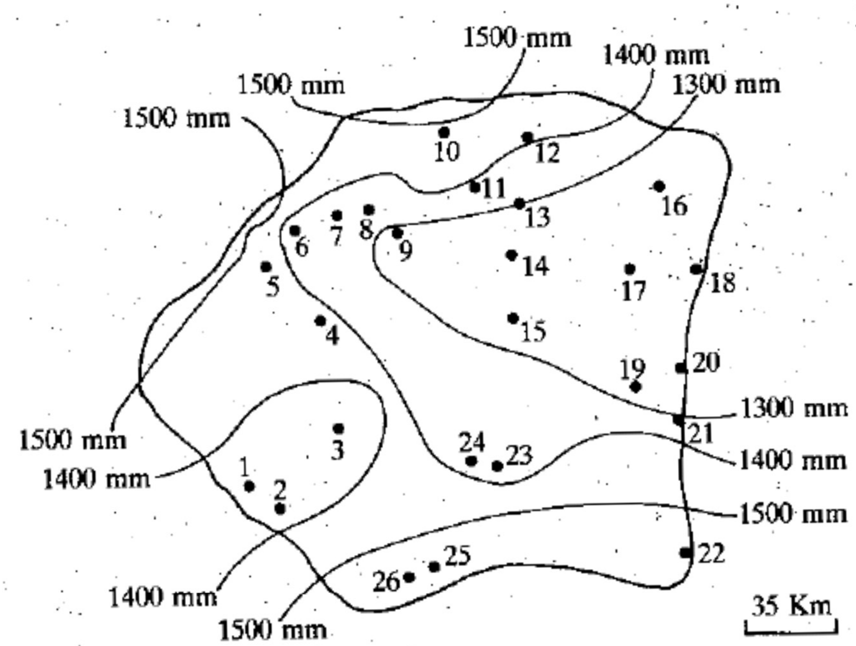


FIGURE 4.40 Central Venezuela region (Portuguese state) used in the example of monitoring network design. Source: I. Rodriguez-Iturbe and J. M. Mejia, "The Design of Rainfall Networks in Time and Space," *Water Resources Res.*, 10(4):715, 1974. Copyright by the American Geophysical Union.

TABLE 4.6 Description of Rainfall Data Used in the Central Venezuela Example

STATION	YEARS OF RECORD	MEAN (mm)	STANDARD DEVIATION (mm)
1	1958–1971	1445	193
2	1955–1971	1412	131
3	1955–1965	1269	234
4	1951–1971	1404	127
5	1956–1971	1500	156
6	1955–1971	1342	189
7	1953–1971	1328	234
8	1948–1971	1294	248
9	1954–1971	1144	195
10	1943–1971	1440	194
11	1956–1971	1341	223
12	1950–1971	1427	261
13	1944–1971	1318	200
14	1958–1971	1296	210
15	1953–1971	1308	225
16	1961–1971	1240	228
17	1961–1971	1255	215
18	1954–1971	1155	206
19	1952–1964	1325	221
20	1958–1971	1252	276
21	1952–1971	1269	246
22	1952–1971	1514	318
23	1961–1971	1462	283
24	1948–1965	1370	194
25	1952–1965	1429	191
26	1946–1965	1452	199

Source: I. Rodriguez-Iturbe and J.M. Mejia, "The Design of Rainfall Networks in Time and Space," *Water Resources Res.* 10(4):721, 1974. Copyright by the American Geophysical Union.

The objective is to study the trade-off between number of stations and years of data when it is desired to design a sampling network that will achieve a given level of accuracy in computing the long-term mean areal precipitation (Eq. 4.31). To achieve this, we will make use of Eq. (4.35), which expresses the mean square error of estimation as a function of the point variance, a factor involving the number of years in the record $F_1(T)$; and a factor involving the number of stations in the region $F_2(N; Ah^2)$.

The procedure requires us to compute the point variance over the region, the lag-one (one-year lag) autocorrelation coefficient, and the spatial correlation. Computing the variance of all records of all stations put together, we get $\sigma^2 = 5.44 \times 10^4\,\text{mm}^2$. A study of the correlation between records one year apart indicates that there is no linear statistical relationship between the rainfall accumulation of two adjacent years, i.e., $\rho = 0$. We will assume that the spatial correlation falls exponentially with distance between points v:

$$r(v) = e^{-hv}.$$

The question is what value to give the decay parameter h. In their work, Rodriguez-Iturbe and Mejia [1974] argue that the spatial correlation should be calibrated to a typical distance in the area in question. Their suggestion is to calibrate the correlation between two points chosen randomly in the area. The distance between two random points in an area obeys a precomputable probabilistic distribution. Details are beyond the scope of this work but it suffices to state the following. If λ is the ratio of the sides of a rectangle, then the mean distance between two points of a rectangle of unit area is

Unit Area Rectangle

λ	$\bar{v}$
1	0.5214
2	0.5691
4	0.7137
16	1.3426

Most basins are reasonably approximated by rectangles. The Central Venezuela region is well represented by a rectangle of side ratio $\lambda = 2$. This rectangle would have a diagonal (maximum distance) of 265 km. To obtain the mean distance between two points for the Venezuelan region, we need only scale the unit area rectangle results by the ratio of diagonals. The unit area rectangle with $\lambda = 2$ has diagonal of 1.58; therefore the Central Venezuela region has a mean distance between points of

$$\bar{v} = (265/1.58) \times 0.5691 \approx 100\,\text{km}.$$

Rodriguez-Iturbe and Mejia [1974] computed the sample spatial correlation between points 100 km apart as 0.21. Therefore the correlation function must satisfy

$$r(100) = e^{-h100} = 0.21,$$

which yields $h = 0.0156\ \text{km}^{-1}$ and $Ah^2 = 7.3$.

TABLE 4.7 Variance Reduction Factor Due to Spatial Sampling $F_2(N; Ah^2)$ with $Ah^2 = 7.3$ in the Central Venezuela Example. Exponential Correlation, Random Sampling.

N	$F_2(N; Ah^2)$	N	$F_2(N; Ah^2)$
1	1.00	10	0.37
2	0.65	20	0.33
3	0.54	100	0.31
5	0.43		

Source: I. Rodriguez-Iturbe and J.M. Mejia, "The Design of Rainfall Networks in Time and Space," *Water Resources Res.*, 10(4): 721, 1974. Copyright by the American Geophysical Union.

The variance reduction factors due to spatial sampling, $F_2(N; Ah^2)$ are given in Table 4.7 and come from Figure 4.38 (assuming random sampling). The temporal reduction factor is obtained from Figure 4.37 ($\rho = 0.0$) and is given in Table 4.8.

Combining Tables 4.7 and 4.8, we can estimate the efficiency of different network schemes for the area considered. In the case of one station in operation during 20 years, we can expect a total variance reduction factor of

$$F_1(T) \times F_2(N; 7.3) = 1 \times 0.050 = 0.050 .$$

In other words, this network will produce an estimate of the long-term areal mean precipitation with a variance on the order of 5% of the variance of the

TABLE 4.8 Variance Reduction Factor Due to Temporal Sampling with $\rho = 0.0$

T	$F_1(T)$	T	$F_1(T)$
1	1.000	15	0.067
2	0.500	20	0.050
3	0.333	30	0.033
5	0.200	50	0.020
7	0.140	75	0.013
10	0.100	100	0.010

Source: I. Rodriguez-Iturbe and J. M. Mejia, "The Design of Rainfall Networks in Time and Space," *Water Resources Res.*, 10(4):722, 1974. Copyright by the American Geophysical Union.

point rainfall process. If we wish to accomplish that type of precision in a lapse of 10 years, we will need

$$F_2(N; 7.3) = 0.050/F_1(10) = 0.50.$$

This corresponds to $N = 4$ stations in the case of random sampling.

It is interesting to observe that the same precision of 0.050 cannot be obtained in a lapse of five years because it will be necessary for

$$F_2(N; 7.3) = 0.050/0.20 = 0.25,$$

which is a value smaller than the asymptotic value of $F_2(N; 7.3)$ when N goes to infinity. From Figure 4.38 it can be seen that with $Ah^2 = 7.30$ and $F_2(N; 7.3) = 0.25$, the corresponding value of N is still larger than 100. We thus have the important conclusion that trading time versus space in hydrologic data collection can be done when we do not reduce the time interval too much, but no "miracles" can be expected in short times even from the most dense of all possible networks.

Table 4.9 presents the combined factors $F_1(T) \times F_2(N; Ah^2)$ for the example under consideration. This product represents the total reduction in variance relative to variance of point rainfall when the long-term areal mean with N stations during T years is estimated. It can be seen that even for quite a small number of years (like 2, 5, or 10 years), five stations will accomplish

TABLE 4.9 Total Factor of Variance Reduction Due to Temporal and Spatial Sampling $F_1(T) \times F_2(N; Ah^2)$ in the Central Venezuela Region Constructed for the Exponential Correlation Function with a Randomly Designed Network

N	$T = 2$	$T = 5$	$T = 10$
1	0.500	0.200	0.100
2	0.325	0.130	0.065
3	0.270	0.108	0.054
5	0.215	0.086	0.043
10	0.185	0.074	0.037
20	0.165	0.066	0.033
100	0.155	0.062	0.031

Source: I. Rodriguez-Iturbe and J.M. Mejia, "The Design of Rainfall Networks in Time and Space," *Water Resources Res.*, 10(4):722, 1974. Copyright by the American Geophysical Union.

most of the possible reduction in variance, and there is little justification in going over this number. It can also be observed that $F_1(T)$ weights more than $F_2(N; Ah^2)$ in the reduction of the variance of the long-term areal mean; when $T = 5\,\text{yr}$, $F_1(T) = 0.200$, yet an equivalent value of $F_2(N; Ah^2) = 0.200$ cannot be obtained in this example. This shows again that trading time versus space, although it is possible and in some instances necessary, is an expensive proposition. ◆

4.8 SUMMARY

Hydrology has traditionally studied the fluxes of energy and water between the land masses and the atmosphere and oceans. Atmospheric precipitation is, after all, a key element of the hydrologic cycle, the major water input onto the land masses. For too long hydrologists have been content with just measuring precipitation and letting meteorologists be preoccupied with the mechanisms that lead to its formation. This must change. Hydrologists must become knowledgeable about atmospheric processes, particularly those influencing precipitation. This has become apparent as hydrologists realize that most existing precipitation models and meteorologic predictive tools are incompatible with the time and space scales required by representations of the hydrologic land processes of interest. It is also now clearer that the atmospheric and surface processes are interdependent with negative and positive feedbacks that must be understood before any one part becomes explainable. In essence, hydrologists and meteorologists must learn more of each others' efforts and begin to cross the artificial disciplinary barriers that exist.

Chapters 3 and 4, probably a very modest beginning, intended to introduce hydrologists to some of the meteorology that relates to precipitation. A significant amount of space is dedicated to cloud physics in this chapter. Together with the stability issues discussed in Chapter 3, this chapter provides a first-level discussion of all important convective mechanisms that control most precipitation.

This chapter also introduced traditional and modern ways of obtaining and analyzing precipitation data. The issue of monitoring network design was treated at some length, if anything to point out that it pays to think about and plan a monitoring experiment. Unfortunately, in traditional hydrology this most important step is more often than not skipped, commonly resulting in inefficient or even useless data-collection exercises.

Chapter 5 will talk about evaporation, the mechanisms that provide the atmospheric moisture that leads to precipitation. The reader is not to lose sight of the fact that precipitation and evaporation are much more than mass transfers. They are significant energy-transfer mechanisms. During precipitation latent heat is released. Without it there would be little precipitation, since that heat drives the convective mechanisms that lead to further condensation. During evaporation latent heat is absorbed. The fact that evaporated water at a site generally has little influence on precipitation at the same site implies that energy is then transported laterally as well as vertically, a requirement of the energy distributions discussed in Chapter 2.

REFERENCES

Amorocho, J., and J.R. Slack [1970]. "Simulation of Cyclonic Storm Field for Hydrologic Modeling." Presented at the 51st annual meeting of the American Geophysical Union, April 20–24, 1970, Washington, D.C.

Austin, P.M. (1987). "Relation between Radar Reflectivity and Surface Rainfall." *Monthly Weather Rev.* 115:1053–1070.

Barrett, E.C., and L.F. Curtis [1976]. *Introduction to Environmental Remote Sensing.* London: Chapman and Hall.

Battan, L. [1973]. *Radar Observation of the Atmosphere.* Chicago: University of Chicago Press.

Beard, K.V. [1976]. "Terminal Velocity and Shape of Cloud and Precipitation Drops Aloft." *J. Atmos. Sci.* 33:851–864.

Beard, K.V., and H.R. Pruppacher [1971]. "A Wind Tunnel Investigation of the Rate of Evaporation of Small Water Drops Falling at Terminal Velocity in Air." *J. Atmos. Sci.* 28:1455–1464.

Bedient, P.B., and W.C. Huber [1988]. *Hydrology and Floodplain Analysis.* Reading, Mass.: Addison-Wesley.

Braham, R.R. [1965]. "The Aerial Observation of Snow and Rain Clouds." Proceedings of an International Conference on Cloud Physics, May 24–June 1, 1965, Tokyo and Sapparo, Japan.

Bras, R.L., and R. Colon [1978]. "Time Averaged Areal Mean of Precipitation: Estimation and Network Design." *Water Resources Res.* 14(5):8878–8888.

Bras, R.L., and I. Rodriguez-Iturbe [1976]. "Network Design for the Estimation of Areal Mean of Rainfall Events." *Water Resources Res.* 12(6):1185–1195.

Idem. [1985]. *Random Functions and Hydrology.* Reading, Mass.: Addison-Wesley.

Budyko, M.I. [1955]. *Atlas of the Heat Balance.* Leningrad: Gidrometeoizdat.

Budyko, M.I., et al. [1962]. "The Heat Balance of the Surface of the Earth." *Soviet Geograph. Rev. Transl.* 3(5):3–16.

Byers, H.R. [1965]. *Elements of Cloud Physics.* Chicago: University of Chicago Press.

Carlson, P.E., and J.S. Marshall [1972]. "Measurement of Snowfall by Radar." *J. Appl. Meteorol.* 11:494–500.

Chua, S.H., and R.L. Bras [1982]. "Optimal Estimators of Mean Areal Precipitation in Regions of Orographic Influence." *J. Hydrol.* 57(112):23–48.

Corotis, R.B. [1974]. "A Stochastic Rainfall Model and Statistical Analysis of Hydrologic Factors." Evanston, Ill.: Northwestern University. (Ph.D. thesis.)

Coulman, C.E., and J. Warner [1976]. "Aircraft Observations in the Subcloud Layer over Land." Preprints International Cloud Physics Conference, July 26–30, 1976, Boulder, Colorado.

Dean, J.D., and W.M. Snyder [1977]. "Temporally and Areally Distributed Rainfall." *J. Irrig. Drain. Div.* 103(IR2):221–229.