Termination of Hydrologic Data Collection (A Case Study)

LEONARD J. LANE

Southwest Watershed Research Center, USDA-SEA, Tucson, Arizona 85705

DONALD R. DAVIS

Department of Hydrology and Water Resources, University of Arizona, Tucson, Arizona 85721

SORONADI NNAJI

Department of Environmental Sciences, University of Virginia, Charlottesville, Virginia 22903

Research objectives for the Southwest Watershed Research Center (SWRC), as determined by the U.S. Department of Agriculture-Science Education Administraion (USDA-SEA), require a broad data base. The operation of seven experimental watersheds near Albuquerque, New Mexico and Safford, Arizona, which only obtain data on precipitation and runoff, was examined to determine (1) if their operation should continue as is, (2) if their data collection abilities should be expanded, or (3) if their operation should be discontinued. The decision-making procedure is modeled in terms of the theory of 'bounded rationality' rather than classical optimization theory.

The choice of alternatives was subject to three constraints: that the resources for data collection activities at SWRC would not be increased, that it be administratively feasible, and that no research program be seriously impaired, A problem-data matrix that showed the data needs for several research objectives was constructed. Based on this matrix and an estimate of the value of the research to the agricultural community, the three alternatives for the operation of seven watersheds were evaluated.

Considering the constraint of no additional resources and of administrative feasibility, the alternative of closing the seven watersheds was the best. To check that the third constraint was not violated, regional studies were made to compare precipitation and runoff characteristics of the Safford and Albuquerque watersheds with other experimental watersheds. A Bayesian decision analysis on the worth of future data was made. The regional analysis and the Bayesian study showed that closure of the watersheds would be detrimental to the precipitation and runoff data base, but not to the extent of impairing research objectives. The Albuquerque and Safford watersheds were closed in June 1976.

INTRODUCTION

This paper reports the deliberations leading to the closing of seven experimental watersheds in Arizona and New Mexico. The question examined was whether to terminate, continue, or expand the data collection effort at these locations. The determination was made in terms of the overall research and data collection program of the U.S. Department of Agriculture, Science and Education Administration (USDA-SEA) as applied to the Southwest Watershed Research Center (SWRC). The decision-making procedure is modeled in terms of the theory of 'bounded rationality' rather than classical optimization theory.

For the Southwest Watershed Research Center, data collection is an important part of its research program to benefit the rangeland agricultural community of New Mexico and Arizona. This effort is part of a national program to conserve and manage agricultural water resources. Data are collected on many experimental watersheds throughout the region. The research program changes as research is accomplished and as new research priorities and programs are established. In these circumstances, data collection networks should be flexible. It should be possible to change data collection schemes as new problems appear and as old problems are settled. To attain this flexibility [*Onstad*, 1975], (1) there must be effective working communication and cooperation between the data collec-

tion and the analysis functions of the research program, (2) improved evaluation criteria must often be developed to measure the worth of data for specific research projects and to measure the worth of the projects, and (3) these criteria should be commensurate with research objectives as determined by public policy.

Experimental Watersheds

The Southwest Watershed Research Center operates a number of experimental watersheds in Arizona and New Mexico. The Walnut Gulch Experimental Watershed near Tombstone, Arizona is representative of watersheds in southeastern Arizona, and the Alamogordo Creek Experimental Watershed near Santa Rosa, New Mexico is representative of watersheds in eastern New Mexico. In addition there are a number of satellite locations, including four small watersheds near Safford, Arizona and three near Albuquerque, New Mexico. The 150 km^2 Walnut Gulch watershed is composed of over 30 subwatersheds where extensive hydrologic data are collected, and the 175 km^2 Alamogordo Creek also contains a number of subwatersheds where similar hydrologic data are collected [*Renard*, 1970]. Safford, Arizona is a satellite location to the more comprehensive research program on the Walnut Gulch Experimental Watershed located near Tombstone, Arizona. Similarly, the Albuquerque, New Mexico watersheds are satellite locations to the Alamogordo Creek Experimental Watershed located near Santa Rosa, New Mexico.

The Safford watersheds are located in eastern Arizona. Watershed areas range from 210 to 309 ha. These are semiarid rangeland watersheds in the southeastern Arizona Basin and Range Region. The four watersheds are separated by distances of from 19 km between the closest two watersheds to a distance of 51 km between the most distant pair.

The three Albuquerque watersheds are located in western New Mexico. Watershed areas range from 16 to 100 ha. These are semiarid rangeland watersheds in the Southwestern Desert Basin, Plains, and Mountain Region. The three watersheds are closely grouped so that for areal considerations they represent a point measurement when compared with the Safford watersheds. Additional information on both locations is given in 'Hydrologic Data for Experimental Agriculture Watersheds in the United States.' USDA Miscellaneous Publication 994, 1960-61, and subsequent years.

Available hydrologic data for these locations are summarized in Table 1 of this paper. Notice that the basic data resource here consists of rainfall and runoff. These data are obtained from continuous rainfall and runoff recorders at each of the seven watersheds. In terms of areal extent, these watersheds represent four points in Arizona and a single point in New Mexico. There are no sediment yield, evapotranspiration, or groundwater data for these locations.

Currently, USDA-SEA research policy is heavily oriented towards multidisciplinary research efforts involving many different scientific specialties, e.g., erosion and sediment transport, chemical transport, and hydrologic modeling studies are needed to meet the objective of improving procedures to evaluate the impact of land use and watershed management on runoff quality and quantity. Instrumentation to provide the broader range of data required for these multidisciplinary projects was installed in comprehensive experimental watersheds, such as Walnut Gulch and Almagordo, but not in the older watersheds located at a distance from the research centers. On older watersheds, such as the Safford and Albuquerque watersheds, only a narrow base of rainfall and runoff data are collected, while on the more recently developed watersheds, a wider range of data, including rainfall, runoff, evapotranspiration, groundwater, erosion and sediment transport, chemical transport, and water quality data, are collected. In the following discussions, research that uses the narrow data base only is called 'hydraulically oriented' research, while research that uses the broad data base is called 'multidisciplinary' research.

Problem Definition and Approach

Recent USDA-SEA research objectives [ARS, 1976] show increasing emphasis on research that requires a broad data base. At the same time, the older research objectives remain in force. Ideally, the data collection network would be expanded to meet the needs of the new research requirements. Solomon [1976] has concluded that the benefit cost ratio of data collection networks is quite high. However, the resources of SWRC are limited, so the question naturally arises: can the configuration of the SWRC data network be changed in a manner which would better enable the achievement of the research objectives?

In this context, determination of the configuration of the data network is a question of resource allocation with limited resources. If benefit, cost, and constraint functions are available, optimal allocation of resources can be determined by the use of Lagrangian analysis [Maass et al., 1962, chap. 4]. The detailed application of this technique to streamflow data network design has been demonstrated by Attanasi and Karlinger [1977], where the measure of benefit is the reliability of the streamflow estimates at ungaged sites.

The allocation of resources to the SWRC's data-gathering activities is a complex problem; in its most detailed form it involves the determination of the number, type, and location of the data collection activities at each of the experimental watersheds. To determine the optimal allocation would require the evaluation of each possible network configuration based on its effect on each of the SWRC's research programs and on the value of that program in meeting the public needs as seen by the USDA-SEA. In addition, explicit and implicit constraints on SWRC's activities would have to be met.

Determination of the effect of each data network configuration on each research project, especially in the early stages of the research, would be uncertain at best. Since the public need is diverse, there are many measures of the contribution of the research results to the public need. All in all, the detailed determination of the optimal allocation of the SWRC's data-gathering resources by classical optimization techniques would be a problem in stochastic multiobjective programming

TABLE 1. Available Data at Safford and Albuquerque Watersheds

Watershed	Drainage Area, ha	Types of Data
		Safford
45.001	210	Precipitation, runoff, topographic map, channel profile, and cross sections
45.002	276	Precipitation, runoff, topographic map, channel profile, and cross sections
45.004	309	Precipitation, runoff, topographic map, channel profile, and cross sections
45.005	293	Precipitation, runoff, topographic map, channel profile, and cross sections
		Albuquerque
47.001	100	Precipitation, runoff, hygrothermographs, topographic map, and channel data
47.002	16	Precipitation, runoff, hygrothermographs, topographic map, and channel data
47.003	71	Precipitation, runoff, hygrothermographs, topographic map, and channel data

Records began in 1939. Does not include intermittent observations on selected hydrologic variables.

TABLE 2. A Problem-Data Matrix for Selected Research at the Southwest Watershed Research Center

Type of Data	Type of Problem				
	Design of Small Hydraulic Structures, capacity	Water Balance Studies, annual yield	Erosion and Sediment Transport Studies, distributed flow	Chemical Transport Studies, distributed flow	Hydrologic Model, hydrologic simulation
	Precipitation				
Annual	C	A	B	B	A
Seasonal	C	B	B	A	A
Storm	A	B	A	A	A
	Runoff				
Annual	C	A	B	B	A
Seasonal	C	B	B	A	A
Storm	A	B	A	A	A
Quality	C	B	B	A	A
	Sediment Erosion				
Rates	C	C	A	A	C
Transport	C	C	A	A	C
Yield	B	C	A	A	C
	Evapotranspiration				
Annual	C	A	B	B	A
Seasonal	C	B	B	A	A
Short Term	C	B	B	A	A
	Groundwater				
Yield	C	A	C	A	A
Recharge	C	A	C	A	A
Quality	C	B	C	A	A

The code for matrix entries is A = essential, B = desirable, C = marginal.
Only precipitation and runoff data available for the Safford and Albuquerque watersheds.

of extremely large size. To make this allocation tractable, simplification was necessary.

It has been recognized [*Simon*, 1949, 1957] that for complex decision-making situations, classical optimization theory is normative rather than descriptive. In order to model what the decision-making process is, rather than what it should be, recognition of the perceptive and cognitive limitations of the decision maker must be made. *Simon's* [1957] 'bounded-rationality' theory of decision making takes these limitations into account: the decision maker constructs a simplified model of the problem, then 'satisfices' rather than optimizes, that is, the decision maker tries to attain a satisfactory return rather than a maximal return.

The decision problem concerning the allocation of SWRC's data collection resources was simplified as follows. Using the method described by *Ackoff and Sasieni* [1968], the research objectives were aggregated into two classes: hydraulically oriented research and multidisciplinary research. By the same method, the many complex alternatives for allocation of resources for research between the satellite and main experimental watersheds were aggregated into three classes: (1) continue the present data collection efforts, no change; (2) expand the data collection at Safford and Albuquerque at the expense of current programs; and (3) close the Safford and Albuquerque watersheds, and shift the resources to the other experimental watersheds. Following *Snodgrass* [1970], three constraints were determined: (1) to be economically sound, the chosen data network configuration must require no more resources than the present configuration; (2) the chosen data

network configuration and associated research must fit into the present administrative organization; and (3) the chosen data network configuration must not seriously impair the attainment of any research objective.

EVALUATION

In evaluating the three alternatives, the data requirements of each type of research project must be tabulated. Second, the value of future data to the project must be estimated, and finally, the potential research results must be weighed in the context of the overall USDA-SEA research objectives.

Problem-Data Matrix Analysis

The problem-data matrix analysis was designed to provide answers to the following questions: (1) What problems are representative of the questions being asked of the hydrologic research being conducted by the Southwest Watershed Research Center? (2) Which of these problems can be addressed by using the information being collected from the seven experimental watersheds at Safford and Albuquerque? (3) Are these problems and data commensurate? While data needs for a particular hydrologic study are often problem specific, and thus it is difficult to anticipate all data requirements, nevertheless, it is possible to specify which classes of data will be required.

As a first step, the problem-data matrix shown in Table 2 was formulated. The columns in the table represent problems for which data from the small watershed research program may be required. A main objective of each problem is given in

TABLE 3. Evaluation of Alternatives for the Safford and
Albuquerque Watersheds

Research Objective	Alternative		
	Close	Continue	Expand
hydraulic	small loss	no change	small loss
multidisciplinary	large gain	no change	small loss

parentheses at the top of each column. Each row of the table
corresponds to a particular type or class of hydrologic data.
Each entry in the table represents the need for the type of data
indicated (row) for the particular problem (column). For ex-
ample, in design of small hydraulic structures, individual
storm runoff is essential, as indicated by the entry A corre-
sponding to storm runoff. Annual precipitation was judged to
be of marginal need here and hence the entry C for annual
precipitation (the row 1, column 2 entry is a C).

Columns 4, 5, and 6 of Table 2 represent the multi-
disciplinary research problems, while columns 2 and 3 show
the data needs of the hydraulically oriented research. The
bulk of the data provided by the Safford and Albuquerque
watersheds are precipitation and runoff, while larger water-
sheds also provide data on sediment and erosion, evapotrans-
piration and groundwater, etc. Thus the larger watersheds can
provide data for all these research objectives while the Safford
and Albuquerque watersheds can only provide data for hy-
draulically oriented research.

Choice of Alternative

Examination of the problem-data matrix shows that the
closing of the Safford and Albuquerque watersheds will only
affect the hydraulically oriented research. The loss to this type
of research is deemed small, since data have been collected
since 1939 at these locations, and data will continue to be col-
lected at other locations. In a later section, this conclusion will
be examined in detail, as one of the constraints on the chosen
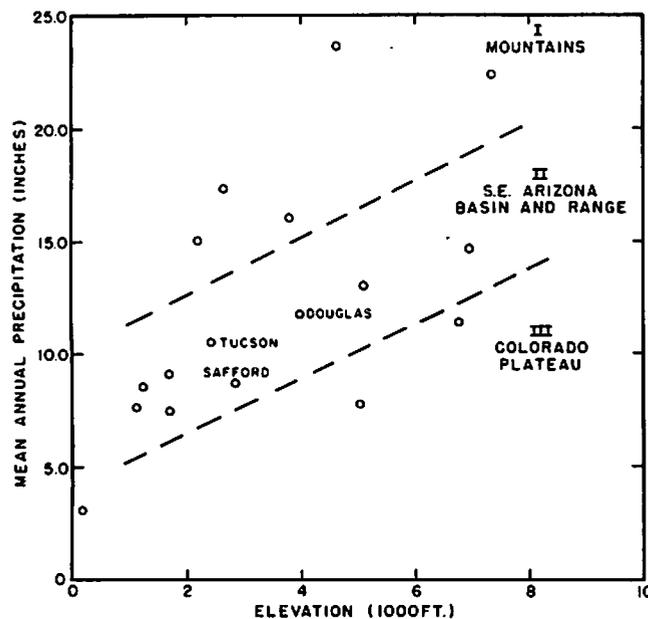alternative is that no research objective be seriously impaired.

Fig. 1. Relation between annual precipitation and elevation for se-
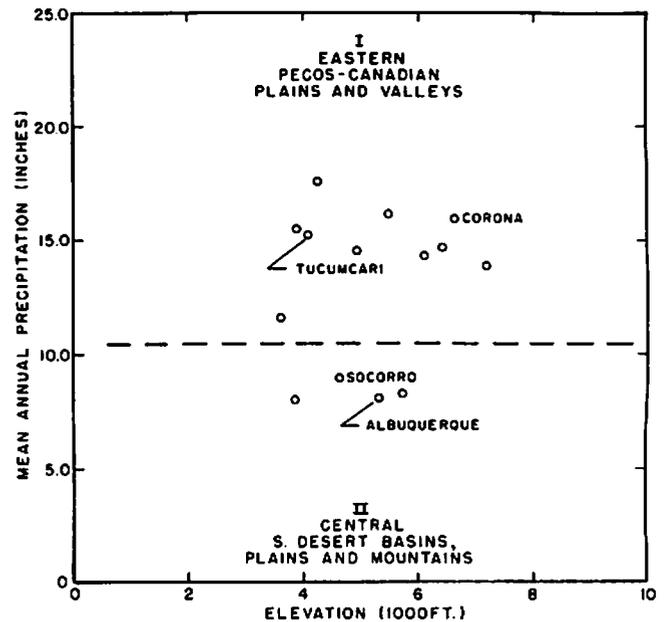lected stations in three Arizona Land Resource Regions.

Fig. 2. Relation between annual precipitation and elevation for se-
lected stations in two New Mexico Land Resource Regions.

The gain to the multidisciplinary program from the data
provided by the resources made available by closing the Saf-
ford and Albuquerque watersheds is expected to be large be-
cause of additional research started and the need for these re-
search results in the agricultural community. These research
programs in erosion and sediment transport, chemical trans-
port, and hydrologic modeling are in the development phase;
the additional resources will enable many new research ques-
tions to be investigated. Compliance with the new water qual-
ity standards, as required by Public Law 92-500, is expected to
be enhanced as a result of this research [Knisel, 1978].

Expansion of the data capabilities of the Safford and Albu-
querque watersheds to include sediment, chemical transport,
evapotranspiration, and groundwater data would require
shifting of resources from other watersheds, notably Alamo-
gordo and Walnut Gulch. Such shifts would be deleterious to
all research programs at Alamogordo and Walnut Gulch be-
cause of the dislocation in the existing data base as well as the
reduction in data collection. On the other hand, the in-
cremental value of expanded data collection at Safford and
Albuquerque is small because of duplication in watershed
characteristics. Also, the diversity of conditions within a large
watershed can be greater than the diversity between small wa-
tersheds [Lane et al., 1977]. Therefore, the net effect on the
multidisciplinary research program of transferring resources
from Walnut Gulch and Alamogordo to Safford and Albu-
querque is negative (Table 3).

The evaluation of the three alternatives is summarized in
Table 3. The alternative most beneficial to the overall SWRC
research program is to close the Safford and Albuquerque wa-
tersheds. The closing will result in a small loss in effectiveness
to the hydraulic research program and a large increase in the
effectiveness of the multidisciplinary research programs.

The alternative of discontinuing the Safford and Albu-
querque watersheds is best, provided it is a feasible solution to
the decision problem. This alternative does not require addi-
tional resources, and it is compatible with the present admin-
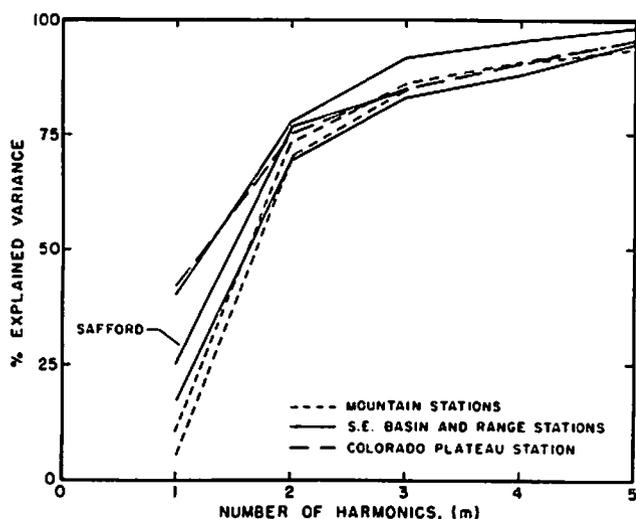istrative organization, thus satisfying the economic and ad-

Fig. 3. Relation between number of harmonics and explained variance for selected Arizona stations in three regions. 2-week mean precipitation.

ministrative constraints. Since it has been shown that the multidisciplinary research objectives have been enhanced by the selection of this alternative, the third constraint is satisfied if it can be shown that the hydraulically oriented research objectives are not seriously impaired. In the next two sections, regional analysis and Bayesian decision theory are used to show that discontinuing these watersheds will not seriously impair the hydraulically oriented research.

Regional Homogeneity

Precipitation and runoff data have been available at Safford and Albuquerque since 1939, and at Walnut Gulch and Alamogordo since 1955. If precipitation and runoff characteristics are similar at Safford and Walnut Gulch, and at Albuquerque and Alamogordo, it is felt that the 40 years of record at the discontinued stations, coupled with the 20 years of record at all stations, and the ongoing record at Walnut Gulch and Alamogordo should provide a satisfactory basis for hydraulic research beneficial to the agricultural community.

The Walnut Gulch Experimental Watershed is located near

Tombstone, some 120 km southwest of Safford, Arizona. Other weather stations in the region include Douglas and Tucson. The Alamogordo Creek Experimental Watershed is located some 250 km east of the Albuquerque watersheds. Other weather stations in the region of Alamogordo Creek include Tucumcari and Corona.

Precipitation characteristics were analyzed for selected National Weather Service (NWS) stations in Arizona and New Mexico. The intent was to determine if some precipitation characteristics were homogeneous over the region including Safford and Walnut Gulch in Arizona and over the region including Albuquerque and Alamogordo Creek in New Mexico. Figure 1 is a plot of mean annual precipitation versus elevation for selected stations in Arizona. Notice that the Tucson, Safford, and Douglas stations appear homogeneous with respect to this relationship. Figure 2 is a similar plot for selected New Mexico stations.

To test for seasonality, Fourier series were fitted to mean 2-week precipitation at selected stations in Arizona and New Mexico. Figure 3 shows the relation between number of harmonics fitted and percent explained variance for some stations in Arizona. In this graph, Safford is shown as the solid line. Figure 4 is a plot of the fitted time series for Tucson, Safford, and Douglas. These graphs indicate that there is a strong seasonality in the region, and although there are scale differences, the three stations have similar seasonal trends. Figures 5 and 6 are similar plots for selected stations in New Mexico. Notice that the seasonal trends are quite different from the Arizona trends, but that except for scale, the New Mexico stations have similar patterns. For the precipitation characteristics examined, there is homogeneity over the region in Arizona that includes Safford and Walnut Gulch and over the region in New Mexico that includes Albuquerque and Alamogordo Creek.

An event-based stochastic model for ephemeral runoff on Walnut Gulch has been developed at the SWRC [*Diskin and Lane*, 1972]. In an attempt to extend information on maximum annual discharge from Walnut Gulch to Safford, this model was applied to watershed 45.002 at Safford. In the first test, model parameters were estimated by using general relationships from a number of watersheds on Walnut Gulch. In the second test, model parameters were estimated by using spe-
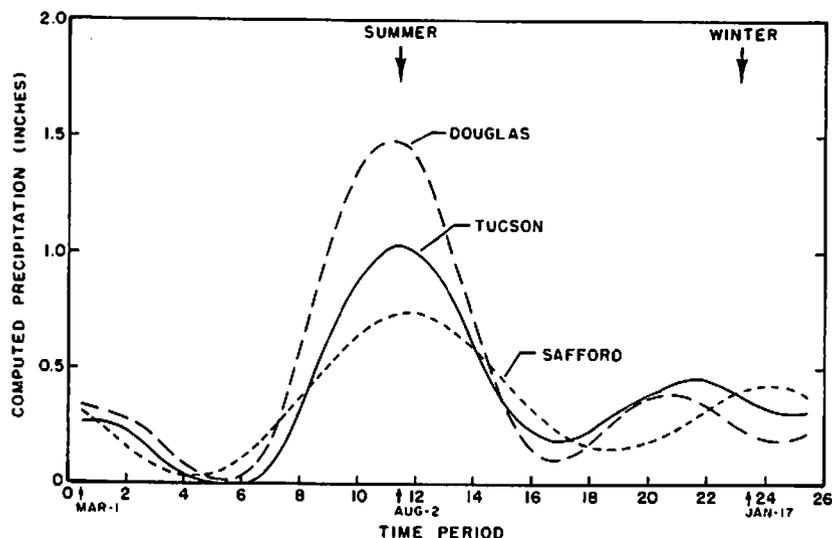

Fig. 4. Fourier series fitted to mean 2-week precipitation for selected stations in Arizona.
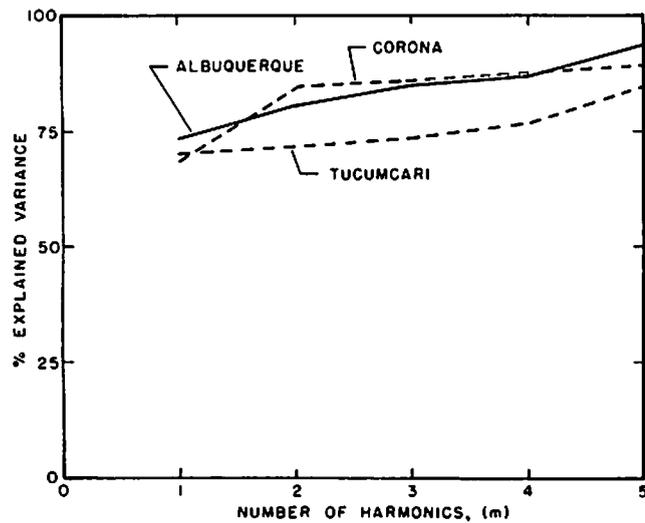
Fig. 5. Relation between number of harmonics and explained variance for selected New Mexico stations. 2-week mean precipitation.

cific value from a single watershed (63.004) which was most nearly like the Safford watershed in terms of drainage area, topography, soils, etc. In each test, 30 years of synthetic data were generated to compare with the observed data. Plots of return period versus maximum annual discharge for the two synthetic and one observed series are shown in Figure 7, the observed data plot between the two synthetic data sets. The upper flood frequency curve represents a generalized relationship for Walnut Gulch based on watersheds with a wide range in size and topography. The lowest flood frequency curve is for the specific watershed on Walnut Gulch which has drainage area, stream channels, topography, and soils characteristics more comparable to the specific Safford watershed [USDA, 1961]. The middle curve, labeled observed data, is the flood frequency curve based on historical observations at the Safford watershed. This suggests that, with respect to maximum annual discharge and this particular model, the Safford and Walnut Gulch watersheds are similar. The above ex-

amples suggest some degree of regional homogeneity in Arizona and in New Mexico.

Are the records at the watersheds where discontinuance is indicated sufficiently long to be a base for further research efforts? In the next section, Bayesian decision analysis is used to estimate the worth of additional data in determining design discharge.

Bayesian Decision Analysis

A method for assessing the value of additional hydrologic record is Bayesian decision analysis [Howard, 1966; Davis and Dvoranchick, 1971; Davis et al., 1972]. In this method of analysis, the data are used to make a specific decision, such as the magnitude of the 100-year flood. Owing to the limited length of record, the decision will most likely be in error because of over- or underestimation. This error, coupled with the natural variability of flow, implies a loss to the decision maker. The loss is not known, but its average value may be calculated by Bayesian decision analysis and is termed Bayes' risk. The Bayes' risk may be reduced by making a decision which explicitly considers the uncertainty inherent in the limited record. Comparison of the decisions made and the Bayes' risks resultant from these decisions, based on hydrologic records of increasing length, gives an indication of the value of having a longer record on which to base the decision making.

As an example, consider the problem of estimating the 100-year flood, Q_{100}, on watershed 45.002 at Safford, Arizona. Annual maximum peak discharge is assumed to follow a log normal probability distribution. The probability density function, pdf, of the log normal distribution has two parameters. Parameters of the pdf are estimated from a sample of length N by two methods. It is first assumed that the sample estimates of the parameter values are in fact correct, that the parameter values are known without error. We then estimate Q_{100} under this assumption. This is the 'no uncertainty' case. Next, we assume that the parameters are random variables with their own pdf's, owing to sampling error, and Q_{100} is determined by Bayesian decision theory. In the Bayesian approach, the procedure is to use a loss function for under- and overestimation of
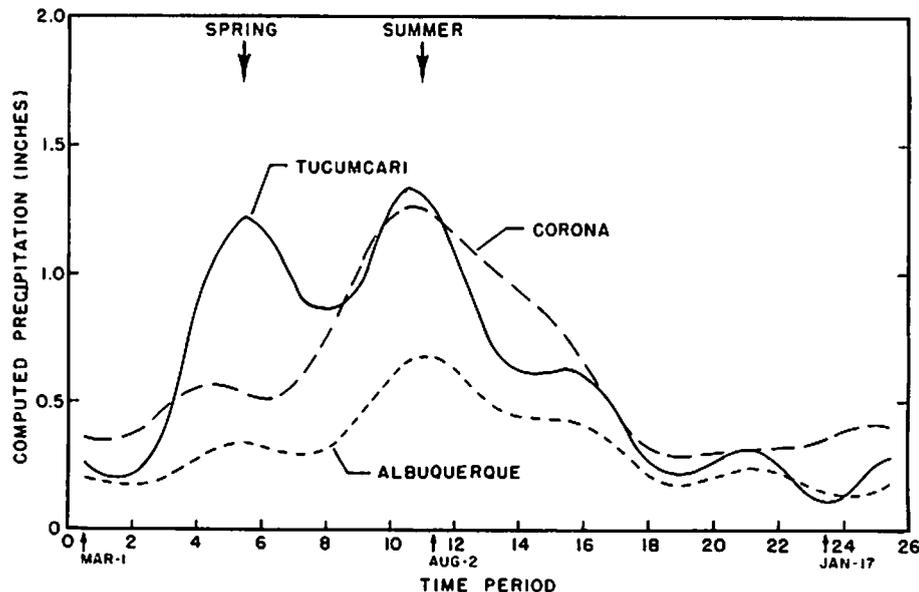

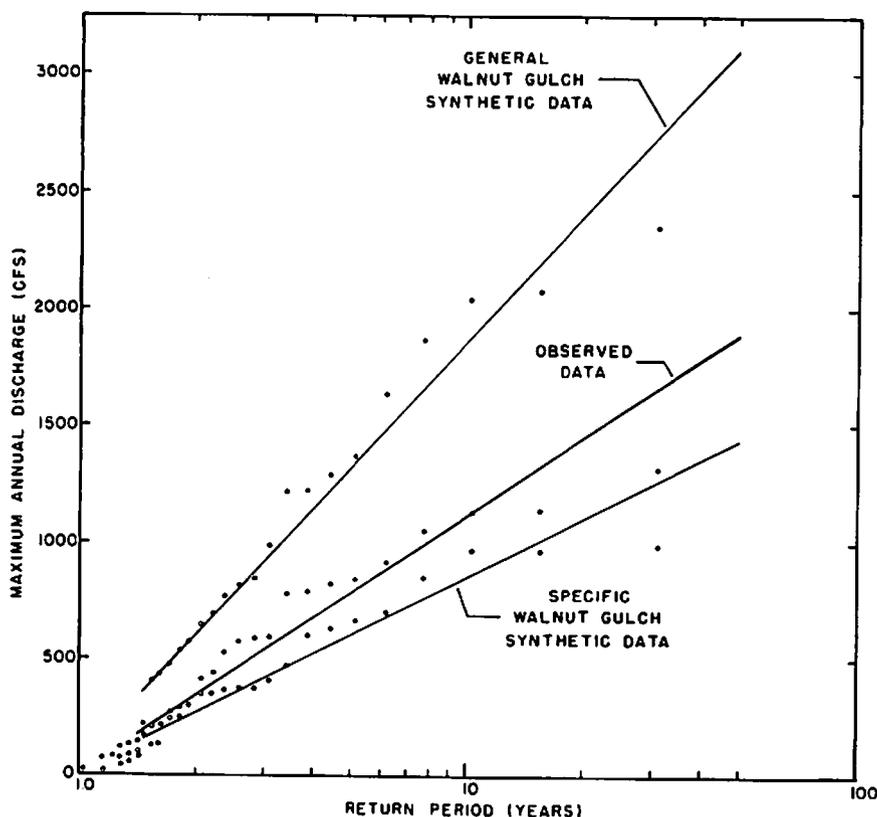Fig. 6. Fourier series fitted to mean 2-week precipitation for selected stations in New Mexico.

Fig. 7. Safford, Arizona, maximum annual discharge (observed and synthetic data).

Q_{100} which does not specify Q_{100} [*Wood*, 1978; equation (6)] and then determine the value of Q_{100}, which minimizes the Bayes risk associated with that loss function. This is the 'uncertainty' case. The difference in Q_{100} with and without uncertainty is a measure of value of perfect information about the parameter. For each particular record length N, we thus have a measure of the value of increased record length in determining Q_{100}. If ΔQ is the difference in Q_{100} estimated with and without uncertainty, then as ΔQ decreases, the value of increased record length decreases.

For a stationary process, as N approaches infinity, the ΔQ should approach zero. This means for very long records, the value of an additional year of data decreases. In our example, this procedure was followed for the 25-year flood and the 100-year flood for $N = 10$, 15, 20, and 25 years, based on the log normal pdf for peak annual flow. A plot of ΔQ versus N is shown in Figure 8. At $N = 10$ years, our estimate of Q_{100} is increased by 70% by assuming that parameters for log normal pdf are random variables based on sample estimates rather than fixed, known values. At $N = 25$ years, this increase is reduced to 25%. Thus at $N = 25$ years, perfect knowledge of the parameters of the pdf would result in a 25% reduction in our estimate of Q_{100}. However, perfect knowledge of the parameters would require an infinite record length. At $N = 25$ years, an additional year of data would only reduce ΔQ by about 1.5%, as can be seen from the slope of the curve in Figure 8. While perfect knowledge of the parameters of the pdf would result in a 25% reduction of Q_{100}, calculation shows that the value of the Bayes' risk would only be reduced by 5%. The reduction in Bayes' risk is small because it is relatively insensitive to changes about the minimum point. An additional year's data would reduce the Bayes' risk by 0.4% for the 100-

year design. The reduction in risk for structural design based on the 25-year flood would be considerably less.

This analysis of the worth of additional record at Safford, for research involving the design of small hydraulic structures, indicates that the sampling uncertainty caused by use of the available record is small, and the effect of this uncertainty on the research objective is minimal. Further, the slope of the curves shown in Figure 8 indicates that expected reductions in the uncertainty with additional data are small. The Bayesian analysis indicates that the 40-year record at Safford is a satisfactory base for further research.
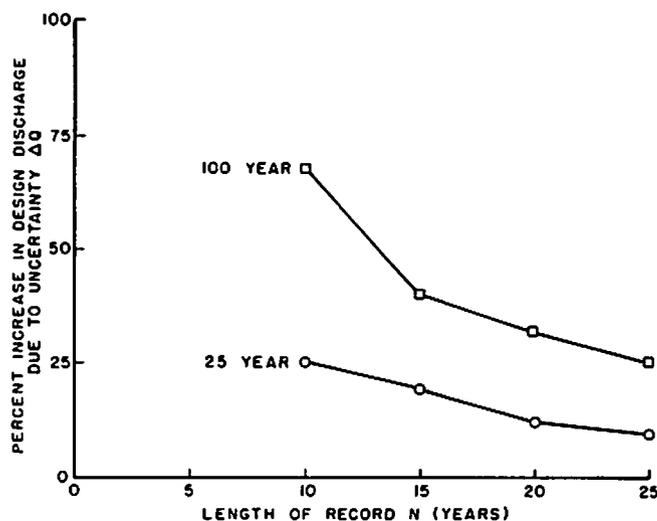

Fig. 8. Relation between record length and increase in design discharge owing to uncertainty for Safford watershed 45.002.

The Bayesian and regional homogeneity analyses have shown that closure of the Safford and Albuquerque watersheds is feasible, in that the closure will not seriously impair the hydraulically oriented research at SWRC.

RESULTS AND CONCLUSIONS

Comparison of the three alternatives for the Safford and Albuquerque watershed indicates that the overall research effort at the SWRC would be improved by discontinuance of these experimental watersheds and use of the resources made available by the closure given for improving the research at other experimental watersheds. The impact of different types of data on typical research programs was determined by a problem-data matrix. Alternative modifications of the data network configuration were evaluated by estimating the effect of future data, or lack of data, on the research results and weighing this effect by the public need for the research, as reflected in the USDA-SEA research priorities. The effect of increasing the resources made available to collect data for the multidisciplinary research programs was shown to be large. The effect of reducing data collection for the hydraulic research programs was shown to be small, owing to similarities in regional characteristics and because of the long record of precipitation and runoff data available.

Closure of the Safford and Albuquerque watersheds was recommended. Data collection at these watersheds was terminated in July 1976. Termination reports summarizing the hydrologic findings at these locations are in preparation. Operation of the research programs at the SWRC in the 3 years following closure has confirmed the analysis; the added resources have strengthened the multidisciplinary program, while the hydraulically oriented research is progressing satisfactorily [*SWRC*, 1979].

Experimental watersheds that were established a considerable number of years ago may not be collecting the data required to conduct research on problems that have a current high public need. Further the value of the data collected from these watersheds can decline over the years on account of increasing record length and because of the availability of data collected at other watersheds having similar characteristics. In such cases, evaluating the data collection program and associated research may indicate closure of the data collection activities at these watersheds. Owing to the complexity of this evaluation, classical optimization procedures are difficult to apply. In such cases, the theory of bounded rationality is useful in understanding the actual decision process.

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