PAST AND PROBABLE FUTURE VARIATIONS IN STREAM FLOW IN THE UPPER COLORADO RIVER

by

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Part I
Summary and Conclusions

by

Morris E. Garnsey
Project Director

October 1961
BUREAU OF ECONOMIC RESEARCH
University of Colorado

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Project Director

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SPONSORS

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UNIVERSITY OF COLORADO

BOULDER, COLORADO

PARTMENT OF ECONOMICS

November 10, 1961

Hon. Stephen L. R. McNichols
Governor, State of Colorado

Mr. Ival V. Goslin
Chief Engineer and Secretary
Upper Colorado River Commission

Gentlemen:

In accordance with your desire for the realization of the effective operation of Glen Canyon Dam and for its optimum integration with Hoover Dam together with the auxiliary structures on the upper and lower Colorado, I have the honor to submit on behalf of the Project Research Staff a report "Past and Probable Future Variations in Stream Flow in the Upper Colorado River." This report is printed in five separate parts which are listed on the inside cover of each part.

This project was directed toward a scientific examination of the possibilities of forecasting future variations in the flow of the Colorado River within the Upper Basin. In this study we have undertaken a scientific formulation of the limits of variability in stream flow based on statistical analyses of all available historical flow records. We have also carried out an extensive analysis of the meteorological history of the Upper Colorado River Basin dealing with precipitation, temperatures, wind data, and other available weather records. In addition, we have made some preliminary investigations of phenomena of the Upper Atmosphere as these are related to a specific area such as the Colorado River Basin.

Our major findings follow:

1. A detailed and sophisticated statistical analysis of historical and virgin stream flow records of the Colorado River above Lee Ferry indicates that runoff is very close to random in character.

2. Because of this randomness, probability statements about the mean flow of the Colorado can be made with confidence.

3. Such statements are unaffected by persistence factors if made for a period of five year or longer.

4. It has been established that there is a slight persistence in flow from one year to the next. This finding may be used to give further precision to probability statements about mean flow for periods of one to five years.

5. The statistical analysis of precipitation data has extended knowledge of the ways in which precipitation patterns are related to runoff, thus permitting probability statements concerning runoff within a water year.

All of these findings will contribute to effective probability forecasts of future flows of the river.

The results of our research also point to numerous ways in which the techniques which we have developed can be substantially extended and refined. The report includes, therefore, a number of recommendations for further study and experimentation. A few of the most important of these are:

1. Additional hydrological and hydrometeorological studies should be made in order to improve effective control of the river.

2. Additional synthetic hydrologies should be constructed.

3. Further precipitation studies should be made for the purpose of relating precipitation to runoff. The pilot study of the Gunnison should be extended to other tributaries.

We hope that the proper agencies of state and federal governments will consider these recommendations most carefully.

It should be emphasized that this study does not deal with operating procedures. However, the findings reveal clearly the desirability of further experimentation with operating programs designed to achieve optimum results from the control of the river.

This research project has involved the cooperation of three agencies: the Bureau of Economic Research and the High Altitude Observatory of the University of Colorado, and the Department of Civil Engineering of Colorado State University. Such cooperation was intended to achieve maximum efficiency in research and to avoid needless duplication of work and facilities in state institutions of higher learning. We hope that continued cooperation of this kind will be encouraged and that universities and colleges in other Basin States can participate in future projects.

Sincerely yours,

Morris E. Garnsey

Morris E. Garnsey
Project Director

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ACKNOWLEDGEMENTS

Many persons have been consulted by the staff members of the project and each author has made suitable acknowledgment of his major obligations. The entire staff wishes to make particular acknowledgement to Stephen L. R. McNichols, Governor of Colorado. Without his perceptiveness and his realization of the potential usefulness of the study the project could not have been undertaken. We are grateful, too, to Mr. Don Daily, Chief Administrative Officer to the Governor, for his continuing interest in the project and his effective solution of the recurring problems of finance which circumstances created. Contracting by the state for a research project in pure and applied science was a new experience both for the state and for the project group, which frequently raised unprecedented problems.

We also are indebted to Felix L. Sparks, Director of the Colorado Water Conservation Board (on leave United States Army), Leonard R. Kuiper, Acting Director and R. M. Gildersleeve, Chief Engineer, for their early and continued interest in the research proposal.

The project staff has benefited substantially from two meetings with the entire membership of the Engineering Committee of the Upper Colorado River Commission, at which times the staff presented a report and received valuable advice and criticism from the Committee. The members of the

Committee are: Ival V. Goslin, Chairman, R.M. Gildersleeve, L. R. Kuiper, Stephen E. Reynolds, David P. Hale, H. T. Person, Earl Lloyd, Jay R. Bingham, and Wayne D. Criddle. These meetings were arranged by Mr. Ival Goslin, Engineer, Secretary of the Commission, as only one evidence of his lively interest in the project. Our thanks are due to him and to the members of the Engineering Committee.

We are similarly grateful to Cecil R. Jacobson, Regional River Control Engineer, Bureau of Reclamation, Salt Lake City, and J. R. Riter, Chief Development Engineer, Bureau of Reclamation, Denver, for their interest and advice. We wish to express our appreciation also to Messrs. Luna Leopold and Walter Langbein of the United States Geological Survey who organized a conference of interested scientists in Boulder during the early stages of the project. The project staff found this exchange of views on research methodology and concepts extremely helpful in its subsequent research.

Finally, as project director, I wish to express my sincere thanks to the members of the staff for their effective work and for the successful conclusion of their research. Their names appear upon their respective reports and on the inside front cover of all reports. My special thanks are due to Professor Leslie Fishman, Department of Economics, University of Colorado. Professor Fishman participated actively in the project during its first year, and his continued advice and criticism have been indispensible.

I am also particularly appreciative for the continued interest and cooperation in this project of three members of the HAO staff: Walter Orr Roberts, Director of the High Altitude Observatory and presently Director of the National Center for Atmospheric Research, Robert Low, Administrative Officer of HAO and NCAR, and Grant Athay, Research Staff Member of HAO. A. R. Chamberlain, Administrative Vice President of Colorado State University, participated in the early stages of the project in his capacity as Head of the Department of Civil Engineering at Colorado State University, and I am grateful for his continued interest in it.

I am heavily indebted also to Professor Arthur Maass, Director of the Harvard Water Resources Development Seminar, to Maynard Hufschmidt, Research Director of the Seminar, and to the staff and students of the Seminar. This project stems directly from the work of the Seminar, which I attended in 1957-58 under the grant of a Faculty Research Fellowship in Economics from the Ford Foundation.

Morris E. Garnsey
Professor of Economics
University of Colorado

October 1961

I. INTRODUCTION

This brief volume summarizes the findings and recommendations of the various specialists who prepared the four separate reports which have emerged from the project. The five volumes taken together form a coordinated whole. They have been bound separately in order to facilitate their widest circulation to somewhat dissimilar groups of specialists and technicians.

II. ORIGINS AND PURPOSES OF THE PROJECT

By 1957 the construction of Glen Canyon Dam and Reservoir was well under way and considerable interest was being expressed by officials and the general public in the problems involved in filling the reservoir as expeditiously as possible, while safeguarding the interests of water-users, power producers and domestic consumers in the Lower Basin. This interest was heightened by the realization that the recent annual runoff of the Colorado had been considerably below that of many years in the earlier history of the river.[1] There were

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[1] For example:

Water Year	Runoff at Lee Ferry millions of acre feet
1953	9.2
1954	6.6
1955	7.8
1956	9.2
1957	17.7
1958	14.6
1959	7.3

The Colorado River Compact of 1922 more or less assumed an annual average runoff of 15 million acre feet.

also divergences of opinion concerning the volume of necessary or desirable annual releases. Consequently some estimates of the filling period ran as high as 30 years, or under extreme assumptions of releases to the Lower Basin, even twice that long. It was obvious, also, that in some respects the direct interests of the Upper Basin states were in conflict with those of the Lower Basin. Since the power revenues at Glen Canyon are earmarked under terms of the Colorado River Storage Project Act (April 11, 1956, 70 Stat. 105) for resource development in the Upper Basin, the rapid filling of Glen Canyon and the early generation of large amounts of power would expedite the economic expansion of the four states of the Upper Basin. On the other hand power and water users in the Lower Basin did not wish to contemplate any serious reductions in their revenues, or any obstacles to their own economic growth which might result from limitations on available water.

Under such circumstances it seems quite clear that the interest of both basins would be served best by operating policies which would optimize the total returns in economic values from a fully integrated Colorado River system in which operations at Glen Canyon and Hoover, together with auxiliary reservoirs upstream and down, were treated as a unified whole. Such a policy would also be in the best interests of all of the people of the United States whose taxes had financed most of the control structures on the Colorado. For them only the maximum addition to Gross National Product could be justified, quite apart from the division of benefits among states and economic groups within the Colorado River Basin.

Given this line of reasoning the technical problem of optimizing the economic returns from an integrated Colorado River system turns upon the methods by which "the optimum" can be determined. Discussion of this problem in academic circles was lively during the period 1957-1959, not only among faculty of the universities in Colorado but also at Harvard where the Water Resources Seminar was then in operation. Divergent opinions were expressed, but on one point there was unanimous agreement among economists, meteorologists, hydraulic engineers and others. This was that the degree of effectiveness in determining the optimum over time is dependent in the first instance upon the ability to forecast the amount of water which would be available for control. If those responsible for the actual operating policies and procedures could know with some degree of certainty what future runoff was to be expected, from one month to the next and from one year to the next, such factors as storage, releases, and power head could be managed in such a way as to optimize the returns to the system. If forecasts were non-existent or limited in accuracy it would be highly likely that ex poste analyses of the operating decisions actually taken would reveal unnecessary losses of power and power revenues and poor timing of irrigation releases with diminished crop yields.

Accordingly this project was directed toward a scientific examination of the possibilities of forecasting future variations in the flow of the Colorado River within the Upper Basin. It was also restricted to this area of investigation. No operating procedures have been investigated and no recommendations concerning operating procedures are made.[1] The findings of this project indicate that several forecasting techniques are available which can increase the accuracy of forecasts of stream flow beyond the degree of accuracy previously achieved. It is found, also, that further studies may yield even greater effectiveness in forecasting, and it is recommended that such studies should be undertaken.

The project as originally proposed on March 1, 1959 contained three parts.

> I. A scientific formulation of the limits of variability in stream flow, based on analyses of all available historical flow records. This study was expected to result in an accurate expression of the probability of occurrence of various levels of abundance or drought, the probable durations of such extremes, and other practically important probability statements based on the assumption that past history is a judge of future prospect.

> II. A broader study embracing correlations between stream flow and other weather elements, such as rain-

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[1] See, however, Margaret R. Brittan, "Probability Model for Integration of Glen Canyon Dam into the Colorado River System" University of Colorado, 1960 -- a doctoral dissertation. Copies are available from the Bureau of Economic Research, Department of Economics, University of Colorado. ($3.50)

> fall at official U.S. Weather Bureau Stations, temperatures, wind data, and other weather factors for the basin. This aspect of the research sought to relate stream flow to more conventional and more widely studied weather elements, and to determine the extent to which these better known elements can be relied upon to predict stream flow. If future meteorological research work discovers improved long-range weather forecasting techniques, this part of the program should facilitate their adaptation to prediction of practically useful figures for Colorado River flow.[1]

The third part of the project envisaged a comparison of the general circulation of the high atmosphere (above 15,000 feet) with conventional weather measurements with a view to ascertaining how weather in the river basin is affected by broader world climate trends. This part of the project has been developed only partially, for reasons outlined in the Introduction to the Julian Report. At the same time, however, research specifically designed to encompass the problems of relation of the upper atmosphere to climatic conditions in specific geographic areas is being pursued on a continuing basis by the High Altitude Observatory as a part of its total program of direct and sponsored research.

An important aspect of the project has been its cooperative character. The general form of the project was proposed by economists interested in resources development. Their competence was limited, however, to the sphere of statistical analysis; obviously the competence of meteorologists, hydrol-

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[1] From the Summary of the Proposal submitted to the Colorado Water Conservation Board March 1, 1959.

ogists, and astro physicists was necessary for really effective attack upon the problem of forecasting precipitation and runoff. Fortunately, such persons proved to be interested in the project. Thus, three agencies were involved from the beginning: The Bureau of Economic Research and the High Altitude Observatory of the University of Colorado, and the Department of Civil Engineering of Colorado State University. The results of the research demonstrate that this cooperative effort has been both effective and fruitful.

III. METHODS AND RESULTS

Three of the studies -- Julian, Yevdjevich, and Brittan -- deal primarily with stream flow data. The Julian and Yevdjevich studies differ in method yet complement each other closely. The Brittan study uses straight forward probability techniques to generate synthetic hydrologies for the Upper Colorado. All three studies have yielded significant results, which are in substantial agreement with each other. The Schleusener-Crow report is concerned primarily with analysis of precipitation data per se. Accordingly the methods and results of the entire project will be discussed in three parts:

(1) The hydrometeorological studies of Julian and Yevdjevich,

(2) The synthetic hydrologies of Brittan, and

(3) The precipitation studies of Schleusener and Crow.

(1) Hydrometeorological Studies of Julian and Yevdjevich

In these two papers some fundamental hydrometeorological relations are investigated. Using the equation:

$$\text{Run-off (Effective precipitation} \pm \text{Storage)} = \text{Precipitation - Evapotranspiration}$$

as a starting point, certain significant factors can be pointed out immediately. First, historic data enables one to estimate the storage term by recession analysis and determine effective precipitation. This has been done by Yevdjevich. Second, Julian, roughly estimating the approximate annual precipitation in the Upper Basin, had determined that the proportion of precipitation actually appearing as runoff at Lee Ferry is less than about 20%. Thus, the extreme importance of the evapotranspiration term in the hydrologic process for the basin is obvious.

Two statistical conclusions, semi-quantitative in nature, can also be drawn from the equation. Since runoff and evapotranspiration are not perfectly correlated, the variation of runoff over a period of time must be greater than the variability of either precipitation or evapotranspiration. And the inhomogeniety produced by measurement and sampling errors and the loss of water due to man-made changes in the Basin also serve only to increase the variability of runoff.

A statistical evaluation of the non-randomness of precipitation and stream flow records was carried out by Julian. In all cases gauged discharge records were corrected for such trans-mountain diversion and artificial regulation data as were available. Precipitation data were checked by double-mass techniques and adjusted when appropriate. Two different statistical tests were performed on the data.[1] The question which the tests asked of the data was: Could these data have been drawn independently, that is, at random, from a hat into which all possible values had been placed? Such a question answered in the affirmative would mean that the data resembled random numbers to a degree sufficient that no regularities, cycles, trends, or persistence could be detected. If this question were answered negatively, the historic data do not resemble random numbers.

The results of the analysis indicate that precipitation records (November through April totals) are not significantly different from a series of random numbers.

In his analysis of effective precipitation Yevdjevich employed three statistical methods: distribution of the first serial correlation coefficient, correlogram analysis, and distribution of the range. He also concludes that the fluctuations of effective precipitation in the Upper Basin are very close to the fluctuations of random series.

When stream flow is examined a significant difference emerges. The series of gauged plus corrected stream-runoff data 1914-1957 at Lee Ferry did show that with a risk of being

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[1]Variance spectrum analysis and the Wald-Wolfowitz test. (See the Julian report for details.)

incorrect 5 times out of 100 the data did not resemble a series of random numbers. With the kind of statistical test used it is possible to specify roughly the types of systematic pattern in the data which produced the deviation from randomness. In the case of stream runoff the pattern was one of persistence from year to year, that is, a dry year <u>tends</u> to follow a dry and wet year a wet, but this persistence is small in comparison with the random component.

The Yevdjevich analysis also detects a certain amount of persistence but somewhat less positively than in the Julian analysis. Yevdjevich examined the possible causes of the persistence and concludes that most of it can be explained by storage and inhomogeneity of the records.[1] It should be emphasized that this persistence is a property of the aggregate of the stream-runoff data. Such a property does not <u>insure</u> that a dry year will follow a dry year, but only that on the average or over a period of time such behavior will be realized.

By assuming a simple mathematical model for such a persistence, Julian reaches the following conclusions:

1. Probability limits may be placed on the likelihood of receiving a certain amount of runoff at Lee Ferry in any given period of time.
2. Attempts to define long-term means of the

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[1] The storage factor in the historical record is not related to any control of the river. However, the future operation of storage reservoirs and power plants at Flaming Gorge, Navaho and Curecanti surely will modify the historical persistence revealed in this study.

flow will result in very unstable averages, with only a moderate chance of being reproduced in future periods of years.

3. The variability of the averages of groups of data, say 5 or 10 year means, is increased over what would occur if the data were random.

4. The natural variability of stream-runoff could in some degree account for the observed decrease in runoff efficiency in the Basin.

Physical reasons that can be put forward to account for the persistence are:

1. A carry-over in discharge caused by different kinds of storage.

2. A persistence in evapotranspiration from water-year to water-year.

3. Inhomogeneity produced in the historic records caused by increased loss of water by man's activities, artificial storage, etc., etc.

A complete discussion of points (1) and (3) is found in the Yevdjevich report.

The large random component present in stream-runoff is to be emphasized. The type of persistence detected by the statistical tests was small and shortlived; only adjacent water-years appeared to be linked. However, even the small amount of persistence present in the Lee Ferry data has important effects on conclusions drawn using statistics and probability analysis. As an example, the persistence effect reduces the number of _effective_, that is, independent, observations of water-year runoff at Lee Ferry from 43 (1914-1957) to about

25. It follows that our uncertainty about long-term means and variability as well as the confidence levels attached thereto is greater than it would be if we had a 43-year record without persistence. Thus, the fact that we are dealing with a highly variable quantity is effectively underscored.

Both the Julian and the Yevdjevich reports are in agreement that no statistically significant periodicities, cycles, or trends which could be utilized in any forecasting scheme appear in the water-year virgin flow values. Forecasts of future flows at this stage of our knowledge must therefore consist of probability forecasts and statements concerning the statistical behavior of such flows.

(2) The Brittan Synthetic Hydrologies

The primary contribution of this report is the creation of synthetic hydrologies for the Colorado River. A synthetic hydrology is a hypothetical series of stream flows which provide a large number of possible runoff sequences developed by probability methods. In this report the author examined three approaches to the derivations of synthetic hydrologies, chosen from the recent and growing literature on the subject. Leopold, Thomas and Hurst in recent publications have applied probability analysis to the problem of forecasting runoff.[1] Since their methods differ from each other each one is evaluated in terms of its applicability to Colorado River data.

Dr. Brittan concludes that none of these methods is entirely satisfactory for dealing with the Colorado River runoff series. Consequently, she employs her own variants of previously developed methods. Synthetic hydrologies are developed by two different probability methods. The first method creates a model for generation of sequences of possible runoff by determining the probability of distribution of mean flows in relation to the range. The first step in this method is to describe a theoretical distribution of annual flows by use of the mean and variance. The second step is to examine the data for hidden periodicities by a Fourier analysis. Next the Schuster test is used to determine whether the series differ significantly from a random series. In applying this test experiments were made using groupings of years from 2 to 5. The five-year period was the shortest period which was statistically significant; i.e., the 5-year period is the shortest

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[1] Luna B. Leopold, Probability Analysis Applied to a Water-Supply Problem, U.S. Department of the Interior Geological Survey Circular 410, Washington, D.C., 1959.
Harold A. Thomas Jr. and Myron D. Fiering, "Mathematical Synthesis of Streamflow Sequences for the Analysis of River Basins by Simulation," Ch. XII in Design for Water Resource Systems, by Arthus Maass and others. (Harvard University Press, February 1962)
E. H. Hurst, "Long-Term Storage Capacity of Reservoirs," Transactions of the American Society of Civil Engineers, 116:770, 1950.

period for which it can be safely said that persistence carry-over does not affect the sample. Thus, random selection in clusters of five (the five-year clusters having the same distribution of means, and means to ranges as the observed historical data) was feasible.

On the strength of the above analysis it was decided to generate a synthetic hydrology for the Colorado using five-year periods. This was done by drawing 100 random samples of 5 each, using restraints described in the report.

The final step in this analysis is the expression of the results of the synthetic hydrologies in probability terms. These results are presented in the following table. It should be remembered that neither 0 nor 100 percent refer to absolutes, but to extremely small probabilities of less than 5 chances in 1000.

PROBABILITIES OF AVERAGE ANNUAL INFLOW
TO GLEN CANYON RESERVOIR
BY TIME PERIODS

Average Annual Inflow in millions of Acre-Feet of Water	Probability (Percent chance) of Average Annual Inflow Being Indicated Amount or Less During					
	5 Year Period	10 Year Period	15 Year Period	20 Year Period	25 Year Period	30 Year Period
6	--*	0	0	0	0	0
7	1	--*	0	0	0	0
8	4	--*	--*	0	0	0
9	9	2	1	--*	--*	0
10	16	7	4	3	1	--*
11	25	19	15	17	12	10
12	37	41	37	40	42	52
13	50	64	65	68	78	85
14	65	84	88	92	96	97
15	80	97	98	100	100	99
16	95	100	99	100	100	100
17	100	100	100	100	100	100

*Less than 0.5 percent chance.

(3) The Precipitation Analyses of Schleusener and Crow

This study is concerned primarily with a statistical analysis of precipitation records and it is intended to provide a detailed description of the climate of the Upper Basin. Such a description, or analysis, can reveal characteristics which are significant for short-term forecasting of the runoff of the Colorado River at Lee Ferry.

Some 2000 station-years of record are available in this watershed area. Of these 1660 station-years of daily data from 30 stations were judged to be sufficiently meaningful for analysis. These data were tabulated on punch cards creating a deck of about 608,000 cards.

The next step was to convert the original daily weather data cards into a reduced set which contained only the storm periods that produced all of the precipitation. For purposes of this study, "storm periods" were defined as consisting of a number of consecutive days with precipitation greater than a trace in any 24-hour period. These storm periods could then be counted, starting at any time throughout the year, and the amounts of precipitation accumulated corresponding with any particular time period for which information was desired. A further step in anaylsis was the determination of variability of the time period required to accumulate certain specific precipitation quantities. Another alternative was to leave the time period fixed and examine the variation in quantity of precipitation during that particular period.

The analysis of this sample of data has emphasized decidedly the skewness of precipitation amounts as received in the semi-arid climate of the upper catchment basin of the Colorado River. It was found to be nearly uniform within the entire area that approximately 85% of all storms were required to produce half the annual precipitation. The other half was delivered from the other 15% of all storms. It required approximately 95% of the least productive storms to produce 75% of the annual precipitation. Conversely, 25% of the annual precipitation is delivered in the other 5% of all storms.

It is uniformly true that in this semi-arid climate the median value of monthly precipitation amounts is consistently less than the arithmetic average (mean), which is pulled upward by the few larger storms.

One of the chief advantages of having the precipitation data on punched cards is that they can then be treated on a probabilistic basis with the use of electronic computers. In this particular analysis, four different time periods were treated to show the probability that 5, 10, 15, or 20 inches of precipitation would occur during the balance of the season, starting with October 1, January 1, March 1, and May 1.

Although too little is yet known about evaporation rates, some adjustment for evapotranspiration can be made to relate more closely precipitation to runoff. A part of this study has included the derivation of "adjusted precipitation values." Since evaporation rates are less at cooler temperatures, a variation in "dropout" amounts which could be attributed to evapotranspiration were allowed to vary in three ranges of elevation and for the various months of the year. This reduction of the original precipitation amounts yields a NET quantity which is more directly related to runoff. Some testing of this technique was conducted as part of this project, but it is expected that continuing effort and criticism by hydrologists familiar with precipitation and runoff relationships in this region will lead to further improvement of this general technique. One example of the type of problem which can be treated with computer facilities was prepared, using data of streamflow and precipitation in the Gunnison River watershed. This special analysis of the Gunnison is explained fully in the text of the Schleusener-Crow report.

In addition to the statistical analysis of precipitation data this report includes an investigation of source regions for the moisture which is delivered as precipitation in the upper Colorado River basin. Here it was found that the moisture source for wintertime snows, particularly for higher elevations, was the cooler Pacific Ocean. The path of the air mass moving into the United States from west to east moves air upward and cools it as it passes the Coastal and High Sierra ranges. This removes large quantities of moisture from the lower portion of the air mass and severely limits wintertime snows at low elevations within the upper Colorado River basin. However, winter snow is delivered to the higher elevations of the Rocky Mountain region with a somewhat reliable frequency.

The primary source of moisture for summer thunderstorms is the Gulf of Mexico, and re-evaporation from moist surfaces and transpiration from plants immediately upwind from the shower activity.

During rare occasions, large quantities of warm moist air move from southwest to northeast from the warm Pacific waters lying to the south and west of Los Angeles. When cyclonic storms move through this area from the southwest to the northeast it is possible to deliver large quantities of precipitation over most of the upper basin watershed. Such storms tend to occur in the fall months. Any future plans for attempting to increase precipitation by artificial means must necessarily consider the moisture source, and any operational plans must be based on the primary sources of precipitation available. This means, for example, that attempts at increasing precipitation in the wintertime should exploit the availability of moisture from the Pacific northwest. Conversely, any attempt at weather modification that would plan to use moisture from this region in the summertime would likely be fore-doomed to failure. In addition, any plan which would not recognize the differences between moisture sources in any season would not represent proper planning.

The Schleusener-Crow report also contains a special study of the influence of "major storms" which furnish a large proportion of annual runoff. For purposes of the study a "major storm" is defined as one which produces an 18-station total precipitation greater than 15 inches during a period of four days or less.[1] Such "major storms" typically occur in the period from September through December. Further, if a "major storm" does occur this should be taken as a strong indicator for abnormally high runoff during the water year beginning October 1.[2]

An interesting and significant example of a "major storm" is the one which occurred in September, 1961, too late to be analysed in the report. According to Mr. Crow, precipitation during the four-day period, September 21 to 24, was sufficient to easily classify it as a "major storm" as defined in the current research study. However, in this instance, the four days immediately preceeding this period were also rainy days. The period from September 17 through the 20th received almost enough precipitation to be classed as a "major

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[1] The reader is referred to the text of the report for a more precise definition.

[2] A very early "major storm" might be reflected in runoff before October 1.

storm". The total amount received in Western Colorado during the eight-day period establishes a new record high for any storm period in September.

The month, as a whole, has new all-time records at Fraser, Glenwood Springs, Collbran, Steamboat Springs, and Meeker. Using data from 17 reporting stations in Western Colorado September, 1961, precipitation totals are 365% of the long period median for September (69.26" vs. 19.21").

This heavy September precipitation in 1961 should have important lag effects on runoff measured in the 1961-62 water year. Based on known precipitation which has already fallen and median probabilities of precipitation during the next 12 months, a preliminary estimate at Glen Canyon for the 1961-62 water year would call for streamflow above the long-period median.

IV. SUMMARY OF FINDINGS

The research completed in this report points to five ways in which forecasts of the future flow of the Colorado River in the Upper Basin can be improved materially.

First, probability statements about the mean flow for a five-year period can be made with confidence. Such statements can be given further precision as more knowledge is gained concerning effective precipitation and depletions caused by man's activities. Probability statements can be made also for periods of any number of years.

Second, some water remains in storage (snow, ground water, lakes, etc.) in the river basin at the end of a water year. Such storage gives a tendency for high runoff to follow years of high flow and low runoff to follow years of low flow. This persistence can be used to make probability statements concerning future flows. However, since the water carryover from year to year is small in comparison with total annual flow, the significance of the persistence factor is limited for purposes of forecasting total flow.

Third, careful investigation indicates that precipitation and runoff are governed primarily by chance processes. Thus it is not possible at the present state of scientific knowledge to forecast reliably future annual flows by methods based simply on the extrapolation of hydrological data.

Fourth, the probability of receiving precipitation can be used to refine forecasts of river flow within a water year. Schleusener and Crow have made additional probability analyses of precipitation data in the Upper Colorado River which will assist in making short term forecasts of river flow for operational decisions.

Fifth, the annual forecasts made on April 1 can be anticipated to a significant degree by careful observation of the occurrence or non-occurrence of a "major storm" or storms during the previous September-December. As an example of this finding, the occurrence of such a storm period in September 1961 permits a preliminary estimate in October 1961 of more than 10, 000, 000 acre feet at Glen Canyon for the water year 1961-62.

V. RECOMMENDATIONS

1. To understand better the hydrological characteristics of Colorado River flows, and for forecasting the future runoff at different places, continued hydrological and hydrometeorlogical studies are necessary and useful. Some recommended studies are:

a. Development of methods sufficiently accurate for current use in determining depletion of river flows by man made changes in the river basin. This would improve the accuracy of derived virgin annual flows or of any other homogeneous sample of annual flows.

b. Determination of carryovers of water from one water year to another at the important river gauging stations in the Upper Colorado River Basin by computing natural and artificial water storage at the beginning of each water year. This would permit the computation of effective annual precipitations, which are closer to random fluctuation than annual flows. This would enable the design of statistical models for linkage between annual precipitations and annual flows. This would furnish the basic material for rational application of probability methods in the analysis of Colorado River flows.

c. Selection, improvement, or development of probability methods to be used in hydrological studies of the Upper Colorado River Basin, which might replace the current historical hydrologic method, or the synthetic hydrology methods by more reliable probability methods.

d. Selection and maintenance of some river gauging stations in the Upper Colorado River Basin as virgin flow stations (benchmark stations). This would permit the study of changes in hydrological conditions in the Upper Colorado River Basin with time.

e. Forecasts of future flows by analysis of relationships between physical factors should be made. These should be directed toward searching for relationships between such factors as ocean temperatures, variables connected with activities in the lower and upper atmosphere, and with solar activity.

2. Additional synthetic hydrologies, using techniques presented in this study, should be generated and analyzed.

a. Various operating criteria should be applied to the synthetic hydrologies so that release rules for the dams could be evaluated.

b. The use of five-year clusters for the Markoff Chain Model should be further explored with a transformation applied to the model to bring it more in line with actual experience.

c. Application of monthly serial correlation coefficients to streamflow generation should be explored further. This approach was used by Thomas for the Stillwater River and certainly has application to the Colorado River for operational studies involving monthly flow data.

3. The analysis of precipitation data in the present study suggests both further research and certain operational procedures.

a. Further research should be accomplished to explore different levels of "drop outs" as a means of adjusting observed precipitation data to give observed runoff. Studies such as the one described for the Gunnison River would be of value, not only for the development of prediction equations for seasonal runoff, but also as a means for obtaining a better understanding of the physical processes involved in the rainfall-runoff relationship.

b. It is recommended that short-term planning make use of data that can be obtained on the occurrence of major storms as they happen. In view of the importance of major storms, particularly in the fall, it would be desirable to conduct "bucket surveys" for major storms occuring in the fall of the year. Such "bucket surveys" would give a better measure of the total quantity of precipitation that falls which should be valuable in making estimates of runoff to be expected during the following spring season.

c. In addition, it would be desirable to have additional observing stations for precipitation at elevations greater than 6000 ft. msl., because of the high evaporation-transpiration amounts for elevations below 6000 ft. msl. in the Upper Colorado River Basin, additional stations below 6000 ft. would be of questionable value.