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COLLECTION AND USES OF HYDROLOGICAL AND HYDROMETEOROLOGICAL DATA FOR SYSTEM OPERATION AND PLANNING

Presented by the United States Department of the Interior, Bureau of Reclamation

NOTE: This text is subject to editorial revision.

COLLECTION AND USES OF HYDROLOGICAL AND HYDROMETEOROLOGICAL DATA FOR SYSTEM OPERATION AND PLANNING

By United States Department of the Interior
Bureau of Reclamation

SUMMARY

Careful assembly of all data on temperature, rainfall, snow accumulation and stream runoff throughout the widespread climatic and geographical conditions of the Colorado River Basin is made by the Bureau of Reclamation, employing the services of many U.S. Government agencies. These data are analyzed to enable the several reservoirs and hydroelectric power plants on the river to be operated in coordination to accomplish optimum flood control, irrigation and generation of power.

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The assembly and uses of hydrological and hydrometeorological data are considered to be among the most important phases of the work in planning and operation of multiple-purpose projects in the western United States. The climate of the western United States is such that extreme variations occur in precipitation, temperature, and stream discharge from year to year and in different geographical locations. In planning the development of multiple-purpose projects, we are fortunate in having available to us the records that have been collected over the past sixty years, but we are aware that this period of record does not provide us with a complete background of data for perfect project design.

The western United States is a relatively new area, and the science of record collection was not started until the latter part of the nineteenth century. Even then only sparse records were collected, as it was not feasible to establish a large network of measurement and observation facilities, nor was the need for records apparent at that time. Most of our records date back to the early 1900's. Data on precipitation and temperatures are the most complete and longest in duration. As the requirement for water resource development occurred, measurements of stream discharge were expanded. Many measurements of stream discharge were begun in the 1920's, which fortunately provides us with a usable period of record on which to base project design. By correlation of stream discharges with comparable records from other areas, and with precipitation and temperature records, we have managed to develop data of stream discharge in many areas where few records are available.

In planning multiple-purpose projects in the western United States, we endeavor to design the project to serve adequately through a drought cycle. The period of the 1930's was apparently a severe drought period in the United States. We are fortunate in our present-day planning to have records showing the severity of that drought and can design our projects accordingly. Many of our large multiple-purpose developments in the western United States are designed and constructed on the basis of data that were collected for the 1930 drought period.

For the purpose of this discussion the Colorado River has been selected as an example of a major international stream on which the collection and uses of hydrological and hydrometeorological data play a most important role. The Colorado River drains an area of about 243,000 square miles, beginning at elevations in excess of 14,000 feet on the west slope of the Rocky Mountains and ending in the Gulf of California. The weather elements of the basin are the extremes in the United States. More often than not, the daily maximum and minimum temperatures of the entire United States are reported from stations within the basin. Precipitation varies from near the maximum for the country at the high elevations to practically nothing in the desert regions of the lower part of the basin. Stream discharges are erratic from year to year due to variations of weather over the country and the basin. Taken as a whole, the Colorado River presented one

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of the most complex problems for multiple-purpose development of any major river in the western United States. That main river development was initiated by the construction of Hoover Dam by the Bureau of Reclamation in 1935 and later by construction of Davis, Parker and Imperial Dams downstream. Presently, new work is proceeding under the Colorado River Storage Project upstream from Hoover Dam. A considerable amount of work remains to be done, but eventually the basin will be developed and operated to obtain the maximum practicable multiple-purpose benefit.

The collection and uses of hydrological and hydrometeorological data also play a very important part in the operation and in the planning for operation of structures which form the multiple-purpose projects on the Colorado River. In the planning and in the operation, use is made of records of precipitation, temperatures, water equivalent of snow, stream flow, evaporation, sediment, and water quality.

The flow of the Colorado River presently is controlled by Lake Mead behind Hoover Dam, by Lake Mohave formed by Davis Dam, and by Havasu Lake which is formed by Parker Dam. All of these dams are located in the lower basin of the Colorado River. Presently under construction in the upper basin of the Colorado River are three more dams--Glen Canyon, Navajo and Flaming Gorge. Glen Canyon Dam will form reservoir, Lake Powell, with a capacity of about 28 million acre-feet which is very nearly the same as that of Lake Mead. These upper basin reservoirs will be ready to commence storing water in about two years.

Hoover Dam and Lake Mead, of the Boulder Canyon Project, now form the principal multiple-purpose storage project on the Colorado River. The Boulder Canyon Project Act states that Hoover Dam and the reservoir which it creates shall be used: "first, for river regulation, improvement of navigation, and flood control; second, for irrigation and domestic uses and satisfaction of present perfected rights in pursuance of Article VIII of said Colorado River Compact; and third, for power." As you can see, flood control has first priority for space in Lake Mead. The principal reason for this is the manner in which the runoff occurs on the Colorado River. In the late summer season it is not unusual for the flow of the Colorado River to be 2,000 to 3,000 cfs, and again it is not unusual during the April-July period for the flow of the Colorado River to be 100,000 to 120,000 cfs. The large storage space in Lake Mead regulates these flows such that they can be beneficially used for irrigation in the areas below Hoover Dam. Prior to the construction of the dam, the agricultural development was limited by the magnitude of the low flows of the river and the development along the river was limited to areas which would not be flooded by the higher flows of the early summer months.

The second priority of use of storage in Lake Mead is for irrigation. By storage of large quantities of water during the high runoff years irrigated areas can be developed on an average runoff condition rather than on the low runoff condition. Storage is used during the low runoff years and refilled during high runoff years.

The last priority of use is for the production of power. Although this feature has the last priority it is by no means the least important. Revenue from the power features of the Boulder Canyon Project is repaying with interest the cost of construction and paying the cost of operation and maintenance. When Unit N-8 installation is completed, Hoover Power plant will have an installed capacity of 1,344,800 kw.

Downstream from Hoover Dam is Davis Dam which was built for two principal purposes. One of them is to regulate the releases from Hoover Dam by withdrawing from storage in Lake Mohave water to meet irrigation orders during periods of low power releases from Hoover Dam and refilling that storage during periods of high power releases from Hoover. The other principal purpose is that of giving closer regulation of flows at the International Boundary so that water may be delivered in compliance with provisions of the water treaty between the United States and

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the Republic of Mexico. Davis Dam also produces hydroelectric power by means of a 225,000-kw powerplant. The revenue from the power and energy is repaying with interest the cost of construction.

The next structure downriver from Davis Dam is Parker Dam which forms Havasu Lake. This reservoir was created for the principal purpose of forming a forebay for Colarado River Aqueduct of the Metropolitan Water District of Southern California. The Colorado River Aqueduct delivers water to the coastal area of Southern California. Havasu Lake has a further function in that it is used to control the floods of the Bill Williams River Basin. The storage space within the top ten feet of this reservoir is reserved to the United States for controlling these floods. The Bureau has three observers in strategically located positions in the Bill Williams drainage basin who make observations of precipitation and stream stages. These observers report stages on streams where there are no regularly maintained Geological Survey gaging stations. Each observer has a radio transmitter-receiver set in a River Control radio network. They report their observations to the River Control office each day, or oftener if a storm is in progress or the streams are in flood stage. Estimates are made of the flood runoff from the basin and adjustments are made in the releases from Davis Dam and Parker Dam to provide space in Havasu Lake to contain the flood runoff in a manner to eliminate or reduce the flood flows downstream from Parker Dam to non-damaging magnitudes. Ordinarily, because of this flood-warning network in the drainage basin the level of the lake is not lowered very much more than four feet. Parker Dam contains a 120,000-kw powerplant which produces hydroelectric energy with the releases of water to the lower river.

Use is made of basic data in planning and in operating all multiple-purpose projects. Although the Bureau of Reclamation makes use of these basic data, most of the measurement and recording is performed by other agencies. The Weather Bureau of the United States Department of Commerce collects records and reports precipitation and temperature data at a large number of stations throughout the country. In the outlying areas these weather stations may consist only of a standard rain gage and maximum and minimum thermometers operated and recorded by cooperative observers, whereas in the larger centers the weather bureau station has many scientific instruments in addition to these basic ones. The data collected are published periodically and made available to all using agencies. The Bureau of Reclamation makes use of the published data to the extent possible, but it also has agreements with the Weather Bureau to receive current data as soon as available from locations which affect the Bureau's operations. Another function of the Weather Bureau is the collection of evaporation loss data by means of keeping accurate accounts of losses from evaporation pans which can be converted to loss from free water surface by applying a factor.

The Soil Conservation Service of the United States Department of Agriculture is the agency which coordinates the snow survey program and makes most of the snow measurements. This agency works in cooperation with other agencies in the collection and publication of snow data. These data are furnished to the Bureau of Reclamation as soon as possible for its use in streamflow forecasting. The amount of water stored as mountain snow varies from place to place, so it is important that snow courses be located in a way to determine, to the greatest extent practicable, the snow crop over the area in question. A snow survey consists of a series of about ten samples taken with specially designed snow sampling equipment along a permanently marked line, about 1,000 feet in length, called a snow course. The use of the snow sampling equipment provides a record of snow depth and water-equivalent values for each sampling point. The average of these values is reported as the snow survey measurement for a snow course. Snow surveys are made monthly or semi-monthly, beginning in January or February and continuing through the snow season until April, May or June. Presently, in the Colorado River Basin we are making use of records of about fifty snow courses in our streamflow forecast procedure. The published reports are made available to any agency or water user for use in planning operation of reservoirs for control of floods, for hydroelectric power systems and irrigation systems. In addition to the snow measurements, the Soil Conservation Service also makes measurements of soil moisture at selected locations over the drainage area. The amount of moisture in the soil has a bearing on the runoff produced by the melting snow. More moisture in the soil under the snow pack results in more runoff when the snow melts. This is one of the new refinements that is being tried in attempting to improve the reliability of the procedures for forecasting streamflow runoff.

Still another Federal agency has the authority for streamflow measurements. That is the Geological Survey, an agency of the United States Department of the Interior. This agency measures and publishes records of streamflow throughout the United States. It keeps the Bureau of Reclamation informed of current streamflow data in areas where it is needed. The Bureau of Reclamation also requests the Geological Survey to obtain streamflow records in areas of particular interest to it. Through these cooperative efforts the Bureau of Reclamation obtains basic data wherever and whenever it has need for them.

The network of stream gaging stations covers all of the major streams in the United States and most of their tributaries, and special records are obtained on intermittent or other particular streams when the need arises for an investigation in that area. Most of the gaging stations are equipped with continuous stage recorders, and these are supplemented by observations of a Hydrographic Engineer at regular intervals. The Hydrographic Engineer makes measurements of rates of flow during his regular visits to the station in order to rate the channel section controlling the flow past the recorder. Daily records of the flow at each station are computed from the continuous records of stage and station rating to give monthly and annual flows which are published for each station. Preliminary records may be obtained upon request from the field offices of the Geological Survey for immediate use by anyone interested in a particular record. Special installations have been made cooperatively by Bureau of Reclamation and Geological Survey at stations where it is necessary to obtain instantaneous readings of stage at particular times in order to compute the flow at the station. Two such installations are in operation on the Lower Colorado River System. These are radio-equipped stations by which the stage from the recorder is transmitted in code at regular times during the day. These stations operate automatically and are installed as auxiliary equipment to the regular continuous stage recorder.

The Geological Survey has accumulated records at many main stream stations since it was established. In water supply investigations, it is often advantageous to correlate these records in order to predict or fill in periods of missing records on similar, adjacent, or near-by streams. Considerable work has been done in this regard by the Geological Survey in recent years using a graphic method of correlation which materially reduces the amount of work involved. This correlation procedure has been developed to the point that many stations can be discontinued and their record of flow closely predicted by use of correlation with stations on similar streams. This work permits establishment of new stations on streams where additional runoff records are needed. The Geological Survey also makes independent studies, and cooperates with other agencies, in the field of evaporation loss.

In the initial planning of multiple-purpose projects, all hydrological and hydrometeorological data for the area are assembled to ascertain the adequacy of data for performing the water supply studies of the project. The capacity of the storage system for all water uses, the capacity and extent of the water distribution system, the installation capacity of the hydroelectric power plant; and other associated phases of the project, are all developed from the historical records of stream discharge. The first prerequisite of the study is to develop as long a record of stream discharge as possible. If extended periods of record are not available, short-term records are extended by correlations with records from near-by similar streams, or by correlation with precipitation records, snow-survey and temperature data, or by combinations of those elements in any logical method that results in the derivation of a stream flow record. Generally, the study is conducted in monthly quantities, but occasionally daily studies will be required.

Water requirement

Water requirement studies are an integral part of all water supply projects. The derivation of the water requirement for irrigation is based upon temperature and precipitation; the water consumed by plants is directly proportional to temperature. One method employed by the Bureau of Reclamation to determine consumptive use by crops is the Lowry-Johnson method, which relates consumptive use to the number of day degrees above 32 degrees Fahrenheit between killing frosts in the spring and fall. Another method developed by Blaney and Criddle of the Department of Agriculture relates consumptive use to mean monthly temperature, daylight hours or latitude, and a constant for each crop. The consumptive use thus derived is corrected for effective precipitation by analyzing the rainfall pattern of the area over a long period of years and allowing a percentage effectiveness for rains of different intensities. After this adjustment is made the consumptive use of water to be supplied by irrigation is known. Increments of water are added to account for farm waste and deep percolation losses, lateral losses, and main canal losses to arrive at a diversion requirement from the source of supply.

Evaporation losses to be expected from free water surfaces must be computed as a water requirement of the project. Evaporation pan data are available at several stations operated by the Weather Bureau, Soil Conservation Service, Geological Survey, and other agencies. These data are converted to free water surface evaporation by the application of a factor derived for the type of pan whether it is a land pan, a floating pan, or another type. Evaporation is a function of temperature, wind, and vapor pressure. These elements are measured at a greater number of stations, and generally for longer periods, than evaporation loss from pans, so evaporation can be computed from various formulas when pan data are not available, or comparisons can be made of the alternate methods of deriving evaporation loss estimates.

After obtaining the necessary stream flow data, water requirements, and evaporation loss estimates a hypothetical project operation can be made for the historical period for which records are available. This study of inflow, outflow, and storage change indicates the amount of storage necessary to meet various daily, monthly, or annual demands with the given set of inflow conditions. The final determination of storage space for conservation purposes also necessarily depends upon economic conditions as it may not be feasible to develop storage space in addition to an optimum amount if only a small increase in irrigated area can be achieved. This is likewise true for power projects, and the economic height of dam can be determined by ascertaining the height at which the incremental return from power sales decreases to equal the incremental cost of the investment.

Requirements for flood-control space in multiple-purpose reservoirs are determined by an analysis of flood discharges from stream-flow records on the stream being considered, or from records on adjacent streams with similar characteristics. Benefits to be derived by controlling record floods are calculated from surveys of flood damages that would result from such floods. The amount of flood-control space that can economically be provided is thereby determined.

Spillway designs are based upon synthetic flood determinations from storms of record or from synthesized storms based upon maximum possible water-holding capacities of air masses typical in the region. This entails a long and tedious study of climatological data to develop these hydrometeorological data. This maximum possible storm is converted to an inflow hydrograph after a thorough study of the terrain of the watershed and the infiltration capacity of the soils. The inflow represented by the hydrograph is routed through the reservoir to determine the necessary spillway capacity, in addition to other outlet capacity, that will protect the dam from over-topping.

After the

After the structures are planned and designed, it then becomes necessary to formulate operating procedures to obtain the maximum possible benefit from the water supply available. One of the most important operating tools is the ability to forecast the project inflow sufficiently far in advance to permit scheduling the operation to meet the demands for water and power and to provide the flood protection for which the project was designed.

About two-thirds of the annual runoff of the Colorado River occurs during the four-month period, April through July, and is the result, principally, of melting of the winter's accumulation of snow. It is this four-month period for which we have a principal need for streamflow forecasts, and it is for the preparation of these forecasts that we require the collection and use of records of precipitation, water equivalent of snow, and streamflow. Without these data it would be practically impossible to prepare a usable forecast of the streamflow. The derivation of the forecasting procedure to obtain an estimate of the April-July discharge of the Colorado River at the Grand Canyon station required several months of work by a large staff. All hydrological and hydrometeorological data in the basin were assembled and missing data were developed. A detailed analysis was made of the effect of snow reports, precipitation, temperature, wind, evaporation, stream discharge, and other elements. Multiple correlations of these various elements were tried to relate their effect upon stream discharges. After a few analyses it was possible to discern the more important elements and concentrate on them. These elements were snow, precipitation, and antecedent runoff conditions. The study resulted in two separate forecast procedures, one for the January through March period, and another for April through June.

The early forecasts are based on only accumulated seasonal precipitation since it was evident from the analysis that the dependability of the early forecasts could not be significantly improved by inclusion of snow measurement and antecedent runoff data. Thirteen precipitation stations were selected for the best representative coverage of the total basin above the Grand Canyon gaging station. For the early months a single forecast is made for the April-July inflow at Grand Canyon. These January through March forecasts are made from correlation equations using recorded accumulated seasonal precipitation for the thirteen index stations and recorded inflow.

Forecasts issued during April through June are derived from a summation of three tributary forecasts. Each of the tributary forecast equations is based on a multiple correlation analysis using precipitation, snow and antecedent runoff data, and April-July runoff. The antecedent runoff factor is an index of fall soil moisture conditions. The three subbasins used to obtain the forecast of the flow at Grand Canyon are as follows:

1. Green River above Greenriver, Utah

2. Colorado River above Cisco, Utah

3. Remaining basin below Greenriver and Cisco, Utah

The subdivision of the basin was made to achieve greater climatic continuity throughout the subbasin than could be realized if the entire drainage area above Grand Canyon were considered as a whole. Consideration was given to nearly all precipitation stations and snow courses that have complete records. Records from a total of 72 precipitation stations and 49 snow courses are used for the tributary forecasts. The precipitation stations and snow courses were assigned weights which give consideration to each station's representative catchment area, elevation, and in some cases to the station's distance from the mouth of the tributary basin. Instead of using the record of precipitation as a single total for the effective season, it has been separated into three periods (fall, winter, and spring) serving as independent variables, using the 20-year period 1936-55.

The equations

The equations for the three subbasins were similar, each considering the three separate factors of precipitation, antecedent runoff and April 1 snow data. Each equation contains a fall, winter, and spring term. The fall term consists of precipitation for September through December and antecedent runoff for the low-flow period of September through December. The winter term consists of precipitation for December through March and the water equivalent of the April 1st snow survey. The spring term consists of April and May precipitation and is used as an estimate in the April and May forecasts.

Measurements of precipitation and snow measurements are forwarded to the forecasting office as soon as possible after the first of each month, generally arriving by about the 7th or 8th day. Data are immediately placed in the forecast equations and the mechanics of working the equation are accomplished within another day. Operating plans are then adjusted with the new forecast.

Development of a forecast procedure acceptable to all concerned enabled us to obtain a modification of the flood-control regulations at Hoover Dam. The United States Army Corps of Engineers is the agency in the United States that is responsible for flood-control operations of all flood-storage space in reservoirs. Prior to developing the forecast technique it was necessary to have 9.5 million acre-feet of storage space below elevation 1229 on April 1 of each year. This requirement often necessitated the evacuation of space that was not needed during low years of runoff. With the forecasting procedure now available the evacuation rate of storage space is related to the inflow forecast and the inviolate space below elevation 1229 has now been changed to 2.5 million acre-feet for August through October; 2.675 million acre-feet on November 1; 3.963 million acre-feet on December 1; and 5.350 million acre-feet on January 1. Tables of minimum average releases for flood-control purposes have been developed for each month from January through June, which dictate the required release to be made for any given forecast and reservoir content. With this technique we only provide the space necessary to regulate the maximum of the forecast of inflow.

Early in June each year an integration committee, made up of a representative of the Secretary of the Interior and one from each of the two operating agencies of Hoover Powerplant, meets and plans the operation of the reservoir and powerplant for the coming twelve-month period. The streamflow forecast forms the basis for planning this operation. Also taken into consideration are the flood-control requirements of Lake Mead, the irrigation requirements both in the United States and Mexico, and the power and energy requirements of the Hoover Dam power allottees. Also considered in making these plans are the other sources of power and energy of the allottees. Another principal feature of the planning is the integration of the operation of Hoover Powerplant with that of the powerplants at Davis Dam and Parker Dam.

The annual plan of operation adopted at the June integration meeting is followed throughout the year until such time as changing runoff conditions may require a change in the plan of operation. At that time another integration meeting would be held to adjust the program of operations to meet the then-current conditions. Sometimes a plan adopted at the June meeting is followed throughout the year, while in other years the plan may be changed as many as four or five times during the year. All the time, precipitation records and streamflow forecasts play an important part in making and revising the operating plans.

Current streamflow records play an important part in determination of river losses and uses along the stream and in adjusting routing procedures to meet irrigation and power commitments at downstream points. It is with these current records that we keep informed as to how our operations are proceeding and, through them, we are able to make adjustments to meet the changing conditions. The Geological Survey keeps current records of streamflow on the main stream and records of diversions to the irrigated areas, and these records are reported to our operating offices daily from stations which are visited daily. We also have two remote stream-stage stations which report by radio each day. By use of these automatic reporting stations we can keep informed on streamflow at inaccessible points and thus provide more knowledge and better regulation of the flows of the river.

This discussion has mainly been concerned with the collection, assembly, and uses of precipitation, temperature and streamflow data. The importance of records such as sedimentation, evaporation, quality of water, and others cannot be overlooked. Data on sediment and water quality are generally obtained at selected stations concurrently with stream discharge measurements. Sediment data are extremely important in the planning and design of new reservoirs and in the operation of river systems. Sediment concentrations of the Colorado River above Hoover Dam are extremely high, but below Hoover Dam the concentrations are low. Low sediment concentrations in storage releases cause degradation of the river below a storage dam and aggradation of the river upstream from the next downstream storage reservoir. This problem has been of sufficient importance on the Colorado River to establish the Colorado River Front Work and Levee System to perform maintenance dredging work on the river. This will be a continuing program until the river becomes stabilized under the effects of the relatively silt-free water.

Quality of water becomes a problem in all multiple-purpose systems to some degree. As water is used and re-used for irrigation and municipal purposes, it naturally assumes a different quality. The Public Health Service of the Department of Health, Education, and Welfare, along with the Geological Survey, collects data on water quality and makes recommendations for corrective action when conditions warrant.

Evaporation of water from the surface areas of the reservoirs and the river is a major loss of water from the system. Because of the large area of Lake Mead and the high rate of evaporation, the loss has a large magnitude. During 1952 and 1953, intensive investigations of the evaporation loss from Lake Mead were made and a specific method was developed for determining this loss. The Geological Survey makes these computations with data collected cooperatively by them, by the Bureau of Reclamation, and by the Weather Bureau. Currently, the Geological Survey is investigating methods of determining evaporation loss from Lake Mohave and Havasu Lake.

Because of the large loss of water by evaporation from free water surfaces the Bureau of Reclamation is conducting investigations of materials and methods for reducing the evaporation loss. From studies made on small reservoirs it has been determined that an important reduction in evaporation losses can be made by application of materials which form a monomolecular film on the water surface. Studies of materials, methods of application and methods of maintaining the film are being conducted at the present time.

New techniques in the collection of basic data are being developed continually, including improvmment of instrumentation, transmission of data and the effects of other data such as solar radiation upon snowmelt. Automatic devices for recording and transmitting precipitation, temperature, and stream discharge are becoming more common. Similar devices will soon be available for automatic analyses and transmission of water qualities. The science of snow surveying is continually being improved by new equipment for reaching remote snow courses, and by automatic reporting equipment. Although the Bureau of Reclamation takes only a minor part in the collection of data, we have taken an active part in working with the collecting agencies to develop new instruments for measuring and reporting data. We foresee the time when a major part of the hydrological and hydrometeorological data will be collected automatically and fed into some of the presently available electronic computing machines for computation of forecasts and integration of forecasted streamflow with multiple-purpose project operation.

In the meantime, we plan to continue to obtain records in the customary manner and to encourage expansion of facilities to cover all foreseeable requirements for hydrological and hydrometeorological data.

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