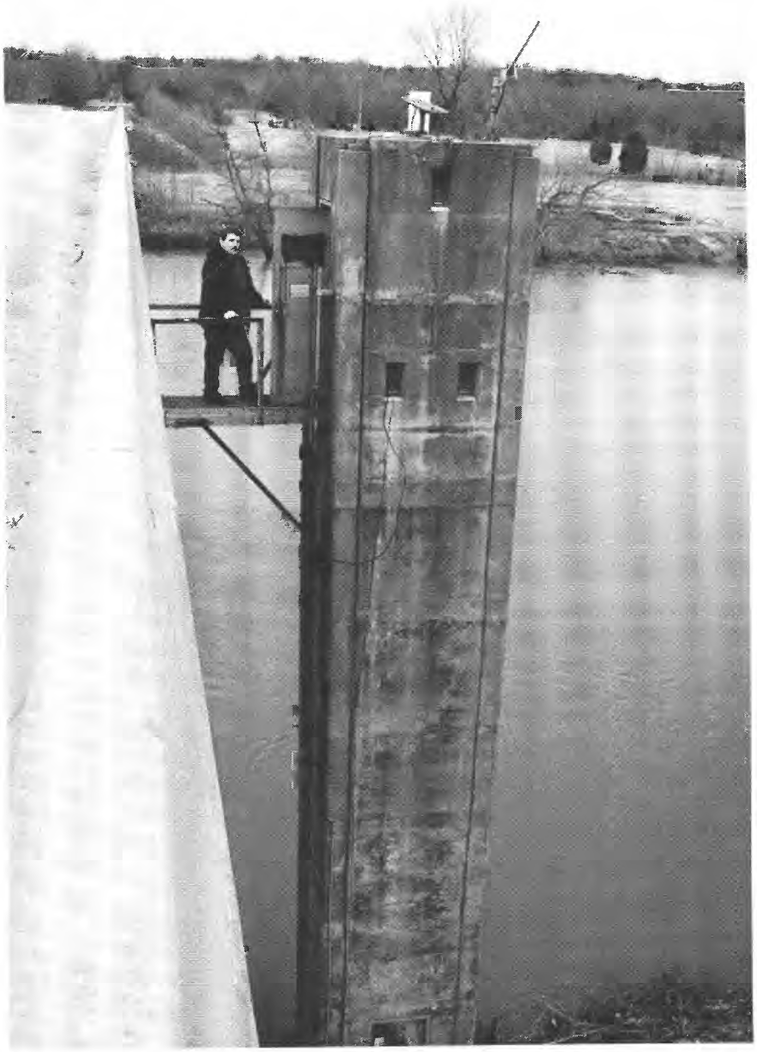
STREAM-GAGING PROGRAM OF THE U.S. GEOLOGICAL SURVEY



U.S. GEOLOGICAL SURVEY CIRCULAR 1123

Front cover—Stilling well and shelter for measuring the stage of a river
Cable car, current meter, and weight used for measuring the discharge of a river from a cableway
Photography by David F. Usher

THE STREAM-GAGING PROGRAM OF THE U.S. GEOLOGICAL SURVEY

By Kenneth L. Wahl, Wilbert O. Thomas, Jr., *and* Robert M. Hirsch

U.S. GEOLOGICAL SURVEY CIRCULAR 1123

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FIGURES

CONVERSION FACTORS

Multiply	By	To obtain
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
acre-foot (acre-ft)	0.001233	cubic hectometer

Stream-Gaging Program of the U.S. Geological Survey

By Kenneth L. Wahl, Wilbert O. Thomas, Jr., *and* Robert M. Hirsch

Abstract

The U.S. Geological Survey (USGS) stream-gaging program provides streamflow data for a variety of purposes that range from current needs, such as flood forecasting, to future or long-term needs, such as detection of changes in streamflow due to human activities or global warming. The development of data on the flow of the Nation's rivers mirrors the development of the country. From the establishment of the first stream-gaging station operated by the USGS in 1889, this program has grown to include 7,292 stations in operation as of 1994. Data from the active stations, as well as from discontinued stations, are stored in a computer data base that currently holds mean daily-discharge data for about 18,500 locations and more than 400,000 station-years of record. The stream-discharge data base is an ever-growing resource for water-resources planning and design, hydrologic research, and operation of water-resources projects.

More than 600 State, Federal, and local agencies provide funding for the stream-gaging program. More than 50 percent of the 7,292 stations operated by the USGS are funded through the Federal–State Cooperative Program whereby the USGS provides up to 50 percent of the funds and the State or local agency provides the rest. The USGS provides full support for fewer than 10 percent of the stations that it operates.

The uses of streamflow data are described, and the growth of the stream-gaging program is related to legislation and the need to manage the Nation's water resources better. The dynamic nature of the stream-gaging program is illustrated by noting the changes in the program from 1981 through 1986 and from 1985 through 1994.

A brief description is provided of techniques for measuring stage and discharge, computing streamflow records, and disseminating the data through published reports and electronic media. A brief history is provided of the nationwide evaluations of the stream-gaging program that were undertaken to ensure that the program was keeping abreast of changes in objectives and technology and meeting the needs of the data users. Finally, challenges for the future are identified. These challenges includemaintaining a long-term and consistent data base, upgrading the stream-gaging structures and equipment, providing ready access of streamflow data to users, and training and maintaining a skilled staff to operate the stations in the stream-gaging program.

INTRODUCTION

The growth and development of the United States has been dependent on the availability of water resources. In colonial times, springs, shallow wells, streams, and rainwater collected in cisterns provided water for domestic and livestock uses. These supplies were subject to the uncertainties of droughts and were vulnerable to contamination. Major population centers developed along rivers and streams that provided water for public supply and transportation. Urban growth in the Eastern United States, particularly after 1800, caused the quality of many city water supplies to deteriorate noticeably. Shallow ground-water supplies often were contaminated by household privies that commonly were located near family wells. Rainwater stored in cisterns was subject to contamination by accumulations of soot, dust, and street debris that collected on roofs and in gutters. The use of water for washing streets increased because it was believed that the epidemics of yellow fever, typhoid fever, cholera, and smallpox were related to the filthy conditions of the streets. As a result, early in the 19th century, such cities as Boston, New York, and Philadelphia began looking for ways to ensure reliable water supplies. Development of such supplies required the use of storage reservoirs, aqueducts, and distribution systems.

As the population grew during the 1880's, people moved west and away from perennial water supplies. The westward expansion also moved population into more arid regions of the country where the flow of rivers and streams was much less dependable than in the humid East. Dependence on water storage and transmission increased as the distances from reliable water sources increased.

During the first two-thirds of the 20th century, water planners and managers sought to develop the Nation's water resources to meet the growing needs of the country. Large reservoirs and aqueducts were constructed to provide water for public supply, industry, irrigation, and hydropower; to provide flood control; and to foster regional economic development. By the 1960's and the 1970's, concerns about the environmental effects of large reservoirs, as well as increasing construction costs and the scarcity of suitable storage sites, curtailed the construction of significant additional reservoir capacity (fig. 1).

The development of data on the flow of the Nation's rivers mirrored the development of the country. Increasing need for reliable water supplies quickly led to the need for streamflow data with which to

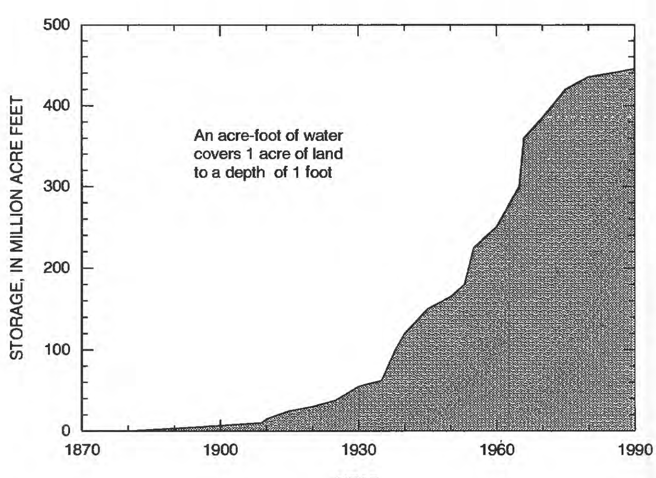


Figure 1. Cumulative reservoir storage in the United States (from U.S. Geological Survey, 1990).

design storage and distribution facilities. In 1889, the first stream-gaging station operated in the United States by the U.S. Geological Survey (USGS) was established on the Rio Grande near Embudo, New Mexico. The establishment of this early station was an outgrowth of efforts to train individuals to measure the flow of rivers and streams and to define standard stream-gaging procedures. As the need for streamflow data increased, the stream-gaging program of the USGS has grown to include (as of 1994) 7,292 continuous-record stream-gaging stations (herein referred to as "stations") in the United States, Puerto Rico, and the Trust Territories of the Pacific Islands (fig. 2). More than 90 percent of these stations are operated with at least partial support from other Federal, State, and local agencies. This report briefly describes the evolution and current status of the stream-gaging program of the USGS, the uses of streamflow data, the data-collection process, evaluations of the stream-gaging program, and challenges for the future.

OVERVIEW OF THE STREAM-GAGING PROGRAM

The stream-gaging program of the USGS does not represent a single "network" of stations, but is an aggregation of networks and individual streamflow stations that originally were established for various purposes. Because the data from about 4,200 of the 7,292 stations are telemetered by an earth-satellite-based communications system, those data are available in realtime for many agencies to conduct water-resources projects and for the National Weather Service (NWS) to forecast floods. Data from the active stations, as well as from discontinued stations, are stored in a computer data base that currently holds mean daily-discharge data for about 18,500 locations and more than 400,000 station-years of record, or more than 146 million individual mean daily-discharge values. Additional data are added to the data base each year. The stream-discharge data base is an ever-growing resource for water-resources planning and design, hydrologic research, and operation of water-resources projects. Increasing the length of individual station records is valuable for at least two reasons. Additional years of record provide ever-improving accuracy of estimates of streamflow characteristics, such as the magnitude of extreme infrequent floods or low flows, and an opportunity to determine how streamflow characteristics are

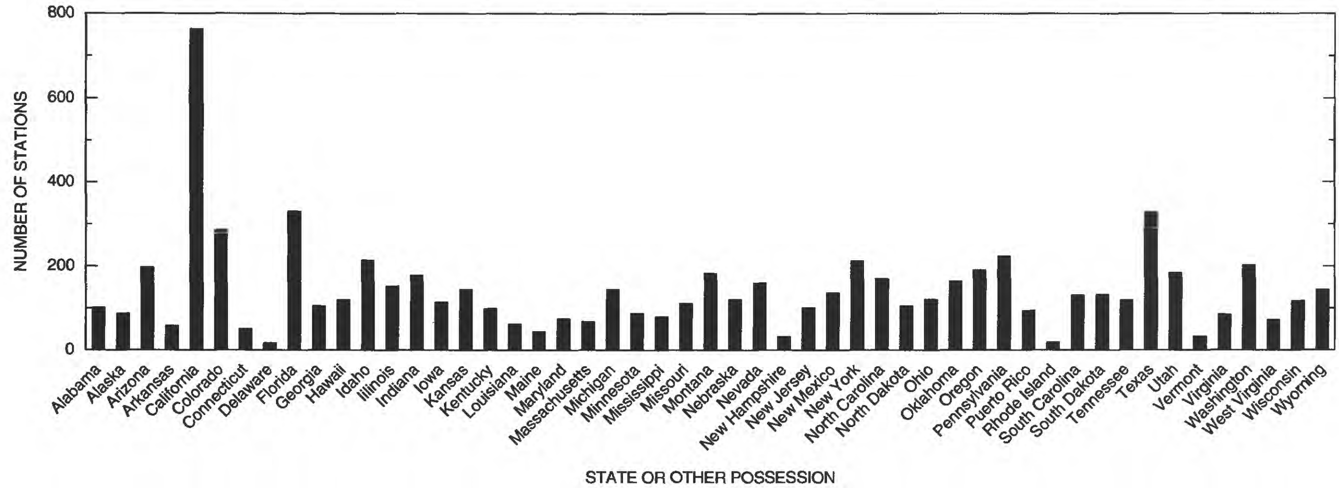


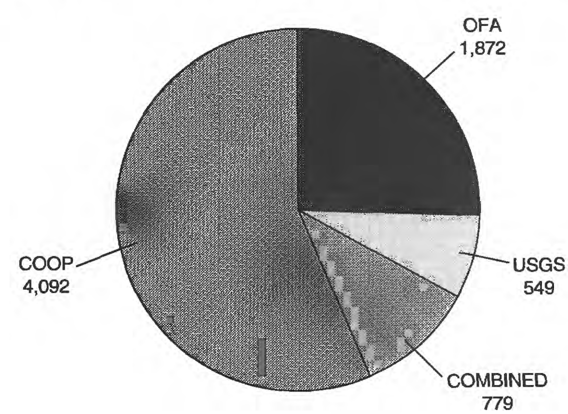
Figure 2. Number of stations operated by the U.S. Geological Survey in 1994, by State or possession.

changing over time due to such causes as agricultural practices, urbanization, ground-water development, or climate change.

Funding the Program

Just as the network of stations represents an aggregation, so does the program funding. Operating funds for individual stations in the program may come from a blend of Federal funds appropriated to the USGS, funds from State and local agencies, and funds appropriated to other Federal agencies (Condes, 1994). Federal funds used for hydrologic data-collection activities of the USGS come from the following primary sources: funds made available by Congress to the USGS for matching State or local agency offerings under the USGS Federal–State Cooperative Program (herein referred to as the "Cooperative Program"), transfer of funds from other Federal agencies to meet their water-resources-data needs, and funds appropriated by Congress and designated specifically for use by the USGS for collection of streamflow and water-quality data.

More than 50 percent of the 7,292 stations operated by the USGS are funded through the Cooperative Program (fig. 3). Under that program, the USGS provides up to 50 percent of the funds, and the State or local agency provides the remainder. Currently, more than 600 State and local agencies participate in the stream-gaging program. Other stations in the program are operated by the USGS and funded by other Federal agencies, such as the U.S. Army Corps of Engineers (COE) and the Bureau of Reclamation (BOR), to provide those agencies with the hydrologic data needed for planning and operating water-resources projects. Additionally, some of the stations are funded by the USGS to support national programs of water-resources investigations; to collect data required by court decree, treaty, or compact; and to conduct hydrologic research. The USGS provides full support for fewer than 10 percent of the stations that it operates. Many of the stations funded primarily by State or local funds are critically important to USGS-funded programs, such as the National Water Quality Assessment (NAWQA) Program (Leahy and Thompson, 1994). As



SOURCES OF FUNDS

COOP	Combination of USGS and non-Federal agency
OFA	Other Federal agencies
USGS	USGS appropriations
COMBINED	A combination of any two or more from OFA, USGS, and COOP

Total stations in 1994 is 7,292

Figure 3. Number of stations and sources of funds, 1994 fiscal year.

discussed below, continuous streamflow data are essential to water-quality studies. The NAWQA Program could not be conducted without the stations funded by the Cooperative Program or other Federal agencies.

Because many of the stations are funded from multiple sources (Federal, State, and local agencies), each agency that participates in funding the stream-gaging program has a proprietary interest in the activity. State agencies, for example, view the data-collection activities in the Cooperative Program as a shared governmental responsibility in which they have a large, long-term financial investment and vested interest. The investment and the vested interest are carefully guarded, and changes in data-collection activities must be negotiated to mutual satisfaction. As a result of the strong vested interest, changes in the way the program is carried out require sensitivity to user reactions, thereby inhibiting unilateral action by the USGS.

> We believe that the U.S.G.S. basic water quantity data collection activities are: 1) essential, because the value of hydrologic data increases with both the length and continuity of the record; 2) the logical responsibility of the Federal Government, because the States cannot possibly assume the support and leadership role of U.S.G.S. for interstate water systems; 3) cost-effective, because coordinated water data collection eliminates overlapping and duplicative efforts.
>
> Data analyses as well as research and development of new predictive techniques can be accomplished by innumerable public or private water-resource agencies, as the need arise, if the long-term basic data exists. If the data is lacking, no one, including the U.S.G.S., can manufacture it. Accordingly, this activity must be one of U.S.G.S.'s highest priorities [Statements of William J. Carroll, President-elect, American Society of Civil Engineers, before the Subcommittee on Interior and Related Agencies, Committee on Appropriations, U.S. House of Representatives, March 10, 1988].

Because interests in and the need for hydrologic data varies in time and space, stream-gaging networks are continually changing with time. The USGS attempts to balance availability of funding support with the needs of all interested parties to ensure that essential information is provided to all users. Budget constraints at State and Federal levels have forced many cooperators to reduce funding support for hydrologic data-collection activities. In some instances, monitoring activities at a particular site are discontinued because the needs of the supporting agency have been met. When funding support for a monitoring site is withdrawn, the USGS attempts to notify all potentially interested agencies of the impending changes to allow users of the data an opportunity to make alternative arrangements for funding the collection of data that are critical to their needs.

> In the summer of 1994 the USGS learned that the California Department of Water Resources would be unable to fund their share of support for 85 cooperatively-funded stations in California. This situation raised considerable concern among Federal, State, and local agencies in California. In a letter to the USGS, U.S. Senator Barbara Boxer said she understood "that a number of California state and county agencies, including the Department of Fish and Game and the Division of Water Rights are dependent upon this long-term, uninterrupted data for interpreting and satisfying water resource demands....". Senator Boxer went on to say that she was "concerned that the loss of these stream gaging stations would deal a serious blow to the reliable, science-based management of our water resources.....". Despite tight budgetary times throughout the State of California, State and local agencies offered cooperative funds sufficient to continue streamflow data collection at 73 of the original 85 stations scheduled for closure [James Mullen, U.S. Geological Survey, oral commun., January 1995].

Uses of Streamflow Data

The USGS stream-gaging program provides hydrologic information needed to help define, use, and manage the Nation's water resources. The program provides a continuous, well-documented, well-archived, unbiased, and broad-based source of reliable and consistent water data. Because of the nationally consistent, prescribed standards by which the data are collected and processed, the data from individual stations are commonly used for purposes beyond the original purpose for an individual station. Those possible uses include the following:

- Enhancing the public safety by providing data for forecasting and managing floods
- Characterizing current water-quality conditions
- Determining input rates of various pollutants into lakes, reservoirs, or estuaries

- Computing the loads of sediment and chemical constituents
- Understanding the biological effects of contamination
- Delineating and managing flood plains
- Operating and designing multipurpose reservoirs
- Setting permit requirements for discharge of treated wastewater
- Designing highway bridges and culverts
- Setting minimum flow requirements for meeting aquatic life goals
- Monitoring compliance with minimum flow requirements
- Developing or operating recreation facilities
- Scheduling power production
- Designing, operating, and maintaining navigation facilities
- Allocating water for municipal, industrial, and irrigation uses
- Administering compacts or resolving conflicts on interstate rivers
- Defining and apportioning the water resources at our international borders
- Evaluating surface- and ground-water interaction
- Undertaking scientific studies of long-term changes in the hydrologic cycle

Data for one or more of these purposes are needed at some point in time on virtually every stream in the country, and a data-collection system must be in place to provide the required information. The general objective of the stream-gaging program is to provide information on or to develop estimates of flow characteristics at any point on any stream. Streamflow data are needed for immediate decisionmaking and future planning and project design. Data, such as that needed to issue and update flood forecasts, are referred to as "data for current needs." Other data, such as that needed for the design of a future, but currently unplanned, bridge or reservoir or development of basinwide pollution control plans, are referred to as "data for future or long-term needs." Some data, of course, fit into both classifications; for example, a station that supplies data for flood forecasting and also provides data to define long-term trends.

Data for Current Needs

Streamflow data are needed at many sites on a daily basis for forecasting flow extremes, making water-management decisions, assessing current water availability, managing water quality, and meeting legal requirements. These activities require streamflow information at a given location for a specified time. These needs generally are best satisfied by operating a station to produce a continuous record of flow. The locations of the stations and the periods of operation are dictated by the uses to be made of the data.

More than one-half of the USGS stations provide current information (mostly by way of satellite telemetry) to agencies that operate water-resource systems and forecast floods. The NWS is charged by law with the responsibility of issuing forecasts and warnings of floods to the Nation to help save lives and to help mitigate property damage. The NWS uses data from USGS stations to forecast river stages and flow conditions on large rivers and their associated tributaries. Flood forecasts are issued at about 4,000 locations strategically located throughout the Nation. The reliability of flood forecasts depends on having reliable current data for precipitation and streamflow. The USGS collects the streamflow data, and the NWS collects the precipitation data and combines both types of data when making the flood forecasts. The NWS does not fund stations, but relies on the data from stations operated by the USGS for other agencies.

> The U.S. Geological Survey stream gaging network is vital to the National Weather Service's river forecast and warning program and the goal to reduce flood damages and loss of life. Without data from this network, this nation would experience increased losses from floods of both life and property [Elbert W. Friday, Jr., Assistant Administrator for Weather Services, National Weather Service, written commun., January 19, 1995].

During the 1993 Mississippi River floods, USGS field personnel made more than 2,000 visits to stations in the flood-affected areas to verify that the instruments were working properly, to make repairs as needed, and to make direct measurements of the streamflow. Data from these stations were provided continuously to the NWS and the COE and formed the basis for flood forecasts that allowed people to be evacuated from areas about to be inundated. The COE and local agencies used the streamflow information to protect lives and property and to focus flood-fighting activities where they were most needed. As a national organization, the USGS was able to move staff from other offices into the disaster areas. Because these hydrologists and technicians were already familiar with the equipment and procedures, they could begin to work immediately upon arrival in the area. This same experience with the realtime use of USGS streamflow data is repeated several times each year as catastrophic floods strike various sections of the Nation.

Data for Future or Long-Term Needs

The collection of data to meet future needs often represents a larger challenge than does collection of data for current needs because the future needs are seldom known precisely and, in fact, may be impossible to anticipate. Because operating stations at all points on all streams is physically and economically impossible, mechanisms must be available to transfer streamflow information from stations to points where there are no streamflow data (ungaged sites).

Transfer of streamflow information for unregulated streams may be accomplished in many ways, ranging from the simple to the complex. Simple methods are interpolation between or extrapolation from gaging points on the same stream on the basis of drainage-area size. More complex methods may involve transferring information from basins with similar hydrologic characteristics, mapping station data to define approximate lines of equal runoff values, or correlating short records with long records. A statistical technique known as multiple-regression analysis has proven to be effective for defining equations (mathematical models) that relate streamflow characteristics to the basin and climatic characteristics that affect streamflow. The resulting equations usually are referred to as "regional relations" because they can be applied to ungaged streams within a defined hydrologic area or region. An example of a regional relation for estimating flood discharges for central Ohio is as follows (Koltun and Roberts, 1989):

$$Q_{50} = 148\, A^{0.757}\, S^{0.276}\, (St+1)^{-0.355},$$

where

Q_{50} is the 50-year flood discharge, in cubic feet per second, that has 1 chance in 50 (0.02 probability) of being exceeded in any given year;

A is the drainage area (or size of the watershed), in square miles;

S is the main-channel slope, in feet per mile; and

St is the percentage of the watershed occupied by lakes, ponds, and swamps.

The above equation was computed by using values of Q_{50}, A, S, and St at 180 stations in central Ohio. The streamflow characteristic, Q_{50}, was computed at each station by using streamflow records, and the basin characteristics A, S, and St were measured from topographic maps. To estimate Q_{50} at an ungaged site, the user determines the values of A, S and St for a specific site of interest from a topographic map and substitutes the values in the above equation. A compilation of regional relations for estimating flood discharges (like Q_{50}) for rural and urban streams throughout the United States was given by Jennings and others (1994).

Studies of the uncertainties of these regional relations have been used to guide the USGS and its cooperators in determining how to change the stream-gaging program to reduce the uncertainty in estimates of streamflow characteristics. These studies permit the analyst to evaluate ways of reducing the uncertainty in the regional relations by adding new stations with certain ranges of basin characteristics, continuing operation of existing stations, or some combination of both approaches (Medina, 1987).

Regardless of the methods used to transfer information, actual streamflow data are required. The stations that supply these data must be representative of the streams in the region. The data provided serve as the basis for defining and calibrating the equations (models) that serve as the transfer mechanism.

> A modeling approach does not decrease the amount of data required; in fact, it increases it. Modeling is not a replacement for observation [National Research Council, 1992, p. 14].

Some applications of data require long-term records to achieve a specified accuracy. The natural variation that is inherent in the flow of rivers produces uncertainty in estimates of the characteristics of those flows. The uncertainty is dependent on the variability of streamflow in the region and the length of streamflow record; uncertainty decreases as the record length increases. This is true no matter what is being discussed; for example, flood characteristics or the long-term average flow of the river. The relation between the standard error of estimate (a measure of uncertainty) and the record length for the mean-annual flow and the 50-year flood for Minnesota is shown in figure 4. If errors are normally distributed, then the standard error of estimate is the error to be expected for about two-thirds of the streamflow estimates.

The relation in figure 4 shows that given a 20-year record at a station, the 50-year flood can be estimated for that site with a standard error of about 35 percent. As the record length increases, the standard error or uncertainty in the 50-year-flood estimate decreases.

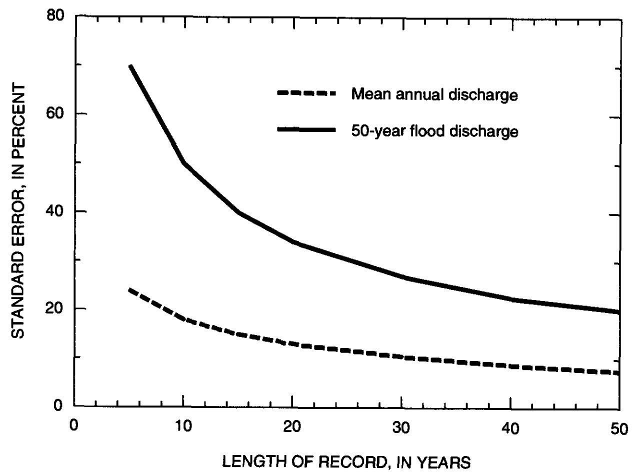


Figure 4. Relation between standard error of estimate and record length for Minnesota (from Benson and Carter, 1973).

When streamflow characteristics from stations are used to define a regional relation for use at ungaged sites, the error in the streamflow characteristics is a part of the total error in the regional relation. For example, note the scatter around the regional (regression) relation between the 50-year flood and the drainage area for rural streams in eastern Massachusetts (Wandle, 1983) (fig. 5). The scatter about the regional relation includes the error that results when drainage area alone is used to estimate the 50-year flood, as well as the error in estimates of the 50-year flood at the individual stations. Thus, it is imperative that the data used in defining the equations be as accurate as possible, and that can be achieved only with long

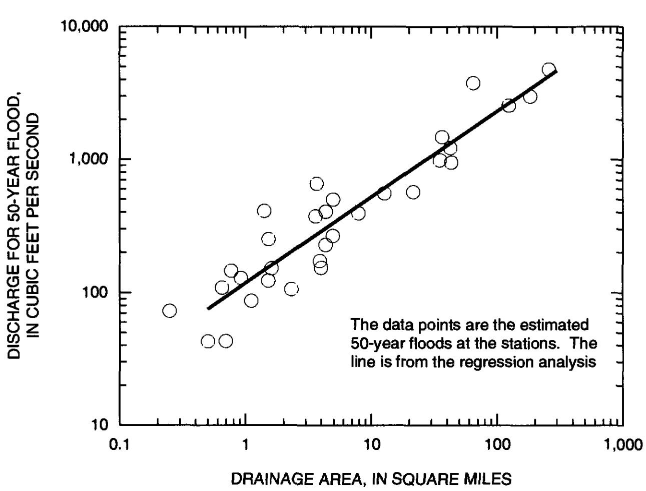


Figure 5. Relation between drainage area and 50-year flood for small rural streams in eastern Massachusetts (from Wandle, 1983).

records. Note in figure 5 that a tenfold increase in drainage area results in about a fivefold increase in flood size. This is typical for flood characteristics, although the specific relation varies with hydrologic region.

Trend analysis is another application that requires long records. Concern is widespread that increased greenhouse-gas concentrations in the atmosphere are affecting the climate and the hydrology of the Earth. Analysts have used actual streamflow records to determine whether streamflows are beginning to change as a result of human activities or global warming. Natural climatic episodes of wetter or dryer than normal and lasting longer than a decade have been observed. Given the occurrence of such episodes and the inherent variability of streamflow, record lengths of more than 50 years are essential if real trends are to be detected. Slack and Landwehr (1992) reviewed the USGS data base to identify streamflow records that reflected natural conditions and could be useful in trend analysis. They identified 1,659 stations that could be used for this purpose in the United States and its possessions. The distribution of record lengths for these stations is shown in figure 6. More than 500 stations identified by Slack and Landwehr (1992) have record lengths in excess of 50 years.

> Detection of hydrologic change requires a committed, international, long-term effort and requires also that the data meet rigorous standards for accuracy [National Research Council, 1991, p. 220].

Specific Categories of Use

A recent nationwide evaluation of the USGS stream-gaging program identified uses of the data for individual stations in the program (Thomas and Wahl, 1993). Between 1983 and 1988, uses of data were defined for 6,238 of the approximately 7,000 stations then operated by the USGS. Individual stations were identified as belonging to one or more of nine categories on the basis of the principal uses made of the data. The uses of data were determined through a survey of cooperators and other known users of the data. These users were recognized as representing only a limited sampling of all users of streamflow data. Many other organizations and individuals use data from the stream-gaging program, but these uses cannot be easily documented. Many times those users (and uses) become known only when a station is discontinued.

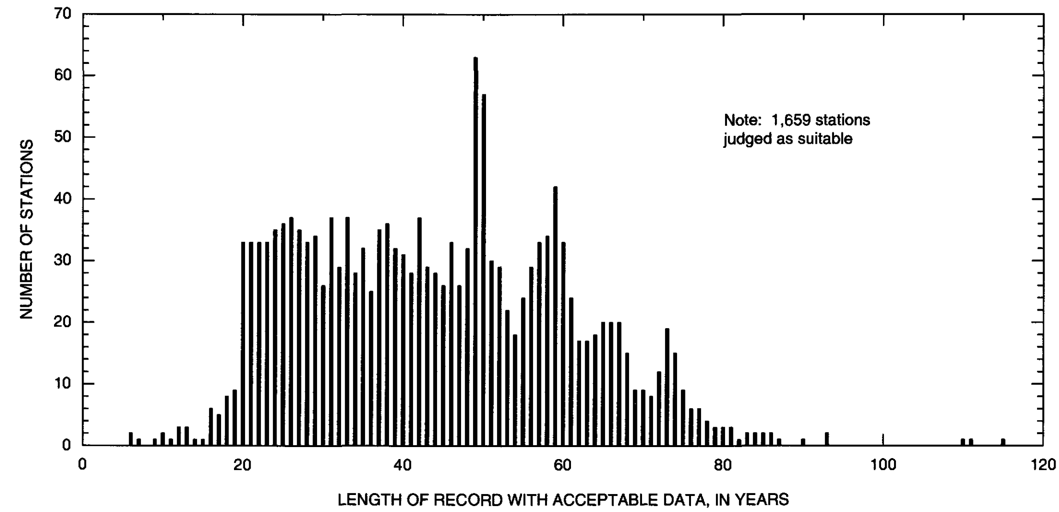


Figure 6. Number of stations and record lengths with acceptable data for studying climate fluctuations (from Slack and Landwehr, 1992).

The station on the Green River at Warren Bridge, near Daniel, Wyoming, was started in 1932. It was funded under the Cooperative Program with the Wyoming State Engineer, but because of funding cuts by the Wyoming legislature, it was discontinued, along with several other key stations, in 1992. That station, however, was also used by numerous other agencies: Bureau of Reclamation for planning reservoir operations downstream, both the National Weather Service and the Natural Resources Conservation Service in flood and water-supply forecasting, several researchers for trend studies, and it was identified as part of the USGS Hydro-Climatic Data Network by Slack and Landwehr (1992). The station was restarted in 1994 and is presently funded by the Bureau of Reclamation [Joel Schuetz, U.S. Geological Survey, oral commun., January 1995].

- *Hydrologic systems.*—One of the more common uses of streamflow data is to account for and monitor the flow through a river basin or to define the general hydrologic conditions in the basin. Development of water resources has so altered the hydrology of some streams that station data at a given point primarily reflects the human manipulations. Data from about 4,200 stations operated by the USGS are used to understand and evaluate the resource, diversions, and return flows (water that has been used for some application and is being returned to the stream) that must be accounted for. Data from these stations also are useful in estimating hydraulic characteristics of aquifers, ground-water recharge, and evapotranspiration and in calibrating ground-water models. At State and interstate levels, many of the stations serve a key role in the process of allocating and regulating water rights. These stations provide data to satisfy current and future needs.

I am writing you on behalf of the Missouri River Basin Association, a coalition of eight states and twenty-eight Indian Tribes in the Missouri basin. For years, we have been working closely with the federal agencies that have jurisdiction in the basin to improve management of the basin's water resources. As you know from your years with USGS, good water management depends upon good data. An important source of good data has been USGS's Coop Program [Excerpt of letter from J. Edward Brown, President, Missouri River Basin Association, to Gordon P. Eaton, Director, U.S. Geological Survey, February 14, 1994].

- *Regional hydrology.*—Stations supplying data that are largely unaffected by manmade storage or diversion furnish much of the data needed for future or long-term needs. Because they provide data that reflect natural conditions, these stations serve as the basis for defining the characteristics of streamflow and for developing the regional relations described in a previous section of this report. Data from about 3,800 stations operated by the USGS can be used for this purpose. Designers and planners of water-control and water-related facilities increasingly use the statistical characteristics of streamflow rather than the flow for specific periods in the past. For example, many highway bridges are designed on the basis of the flood that will be exceeded on the average of once in 50 or 100 years. Determining the appropriate design flood for a highway bridge is critical to balancing construction costs against risks to human safety and potential damage to property. Using too small a design flood can lead to a bridge design that causes water to back up and inundate the road itself or property along the flood plain upstream from the bridge. Too large a design flood can lead to a design that is wasteful and requires an unnecessarily wide opening, an unnecessarily high roadway, or both. By using long-term streamflow records, storage reservoirs can be designed on the basis of the probability of deficiency of storage to meet given discharge rates from storage. The water available for dilution of treated wastewater releases or other similar purposes may be stated in terms of the mean flow or probability of nonexceedance of flow magnitudes for periods of a year, season, month, week, or day. For example, if estimated low flows are understated, then there would be a requirement for additional costly wastewater treatment to meet water-quality standards. However, if low flows are overstated, then the treatment requirements would lead to unacceptable water quality when low flows occur.

- *Project operation.*—Data from stations in this classification are used on an ongoing basis to assist water managers in making daily operational decisions. These decisions include managing daily and hourly flows through gates and hydropower penstocks, pumping water into diversion systems or hydroelectric reservoirs. They also include extensive balancing of uses among multiple sources of water in regional systems, including many reservoirs and ground water supplies. Such decisions are a daily reality when dealing with water requirements for municipal, industrial, and agricultural uses; hydroelectric power generation; and space for flood control in reservoirs. For example, data from about 2,900 stations operated by the USGS are used by the COE, the BOR, and others to operate more than 2,000 flood control, navigation, and water-supply reservoirs. Data from stations in this category satisfy a current need.
- *Hydrologic forecasting.*—Data from stations so classified provide information for flood and water-supply forecasting. These stations play a key role in efforts by Federal, State, and local agencies to protect the lives and welfare of the general public through the evacuation of people from areas about to be inundated. More than 3,000 of the stations operated by the USGS are used in the NWS's flood-forecasting system. These data supply an immediate and high-priority current need. Because these stations are located at critical points on streams, they also generally provide valuable information on the statistics of flows that will be quite useful for meeting future needs.
- *Water-quality monitoring.*—The stations discussed in this paper are only a part, albeit the largest part, of the USGS hydrologic data-collection program. Other program components provide data on the chemical quality of water resources, sediment in streams and lakes, surface- and ground-water resources, and water use (fig. 7). Although the various program components are funded separately, they are highly interdependent and complementary. The programs on water quality and sediment provide information on the concentrations of chemical constituents in the water. The sediment and chemical quality of a river is intimately linked to the streamflow. Rapid variations in streamflow due to rainfall or snowmelt typically are associated with rapid variations in sediment or chemical concentrations. Consequently, understanding the movement of sediment and chemicals in a river depends on the availability of water samples at these times of rapid flow variation. One of the ways this is accomplished is to equip the station

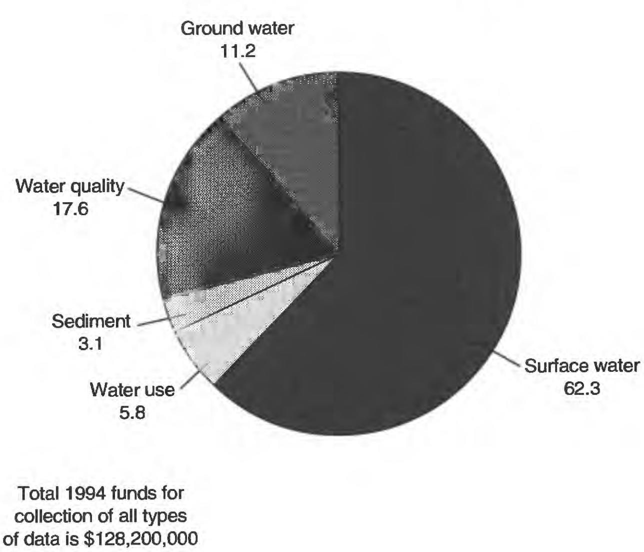


Figure 7. Percentage distribution of funds for U.S. Geological Survey hydrologic data collection, 1994 fiscal year.

with an automatic pump sampler that is activated by a microcomputer programmed to call for samples based on stage, changes in stage, concentrations of chemical constituents, time since the last sample, or some combination of the above. These automatic sampling systems are vital to the study water-quality impacts of urban or agricultural land uses in small watersheds. The stations in this category also provide the flow data required to convert concentrations to loads (the total amount of the material transported by the water). The load transported by the flow is needed to understand fully and monitor the movement and fate of the material in flowing water. The approximately 2,700 stations operated by the USGS that provide discharge data for water-quality monitoring are fulfilling a current need. However, these data also may fulfill a future need if they are used to examine long-term trends in water quality or to determine the relative importance of various sources of pollution to a water body such as a reservoir, lake or estuary.

> The USGS operated a gaging station on the Garcia River from 1962 to 1983 as part of their cooperative program with the State. A stream gaging station on the Garcia River would provide essential hydrologic data to properly manage in-stream gravel mining operations on the Garcia River. Significant bedload transport oc-curs only during larger runoff events. Prudent management of in-stream mining calls for limiting or curtailing mining during drought years. A stream gage operated by the USGS would provide an objective record of the yearly flood events. Mining operations would be requested to suspend operations in years when the annual flood was less than a specified size. Therefore, it is imperative that the data be collected by an impartial and respected agency such as the USGS [Excerpt from a letter to Senator Barbara Boxer, California, from Dennis Jackson, Mendocino County Water Agency, Ukiah, California, October 29, 1993, requesting assistance in getting the USGS to reestablish a stream-gaging station on the Garcia River in Mendocino County].

- *Planning and design.*—Data from about 1,100 stations operated by the USGS in this category are needed to plan and design a specific project, such as a reservoir, levee, water-treatment facility, or hydroelectric powerplant. Because these data relate to a specific project, they generally are filling a current need.
- *Legal obligations.*—Data from these stations satisfy a legal responsibility of the USGS or of signatories of treaties, compacts, and decrees. The USGS operates about 250 stations in support of 17 interstate compacts, 2 Supreme Court decrees, and 1 international treaty.

> The U.S. Supreme Court in a 1954 decree required that the USGS monitor flows in the Delaware River at Montague, New Jersey and the diversions out of the Delaware River basin through the Delaware and Raritan Canal. The decree settled a water-rights suit in which four States were involved. The USGS operates two stations to monitor the flows as identified in the U.S. Supreme Court decree [William Carswell, Jr., Delaware River Master, U.S. Geological Survey, oral commun., January 1995].

- *Research.*—Data from about 700 stations operated by USGS are collected for a particular research or water-investigation study. As such, the data supply a current need. The length of time that the data will be needed is dictated by the particular project. Some research needs, such as detection of hydrologic trends, can be met only by long-term, high-quality streamflow records.

> Detection of hydrologic change requires long-term data sets of greater quality and reliability than are normally needed in the investigations of processes [National Research Council, 1991, p. 223].

- *Other.*—These stations supply data for uses that do not fit into any of the eight categories above. These include, for example, recreational purposes, such as providing data for canoeists, rafters, and fishermen. Data from about 700 stations operated by the USGS supply a current need for water-resource information.

> The USGS in New Mexico instituted a direct-dial telephone number and recording for current streamflow information. The "Streamflow Hotline" was established to provide river rafters, fisherman, ranchers and farmers, and other interested parties with a telephone number that they could call 24 hours a day to obtain current streamflow information on major rivers in New Mexico. The hotline is updated daily during the spring runoff period, and depending on river releases, at least two to three times a week the remainder of the year. Calls to the hotline during the spring runoff period of April through June average about 1,000 per month and about 100 per month during November through February. The number of stations included on the hotline has increased to 18 due to requests from individual users and other agencies [John Borland, U.S. Geological Survey, oral commun., January 1995].

A growing number of stations are used for purposes that do not fit readily into one of the above nine categories. Data needed to define instream uses are good examples. Instream use refers to water that is used, but not withdrawn, from a surface-water source. Instream uses can be broadly characterized as streamflows required to meet human, ecological, or environmental needs. Human needs include recreation, hydroelectric power generation, transportation, waste assimilation, aesthetics, and cultural-resource preservation. Ecological or environmental needs include fish and wildlife habitat, wetlands preservation, freshwater dilution of saline estuaries, and maintenance of the riparian zone. Thus, these uses cut across most of the nine categories discussed above.

Quantitative estimates for most instream uses are difficult to compile. However, because such uses compete with offstream uses and affect the quantity and quality of water resources for all uses, effective water-resources management requires that methods, definitions, and procedures be devised to enable instream uses to be assessed quantitatively. The need to maintain some flow in streams has long been recognized as an important requirement for healthy stream ecosystems. In recent years, many court and compact decisions also have recognized the importance of instream flows and often have mandated an increase in instream flows to meet various environmental, recreational, and water-quality needs. Data from stations are critical to determine whether mandated instream flows are being maintained.

> In New Jersey, the USGS operates 25 stations downstream from water-supply reservoirs and pumping stations. These station monitor whether the streamflow rates are being maintained at or above a permitted minimum flow. This minimum passing flow is selected by the State in order to protect the ecology of the streams and also the water rights of downstream users [Robert Schopp, U.S. Geological Survey, oral commun., January 1995].

History and Growth of the Stream-Gaging Program

The USGS, which was created in 1879, was authorized in 1894 to survey irrigable lands in arid areas and to measure the flow of rivers and streams. As noted in an earlier section, the first USGS station was established on the Rio Grande in 1889. In 1895, the first Cooperative Program in the Nation began in Kansas through an agreement with the newly established Kansas Board of Irrigation Survey and Experiment (now known as the Division of Water Resources of the Kansas Department of Agriculture). This agreement provided for measurement of streamflow at seven sites to ascertain water-supply potential. In 1995, 100 years after the inception of the Cooperative Program, the USGS operates 166 stations in Kansas, 84 of which are operated in cooperation with 10 State, city, or local agencies (fig. 8). The other stations are supported by either Federal agencies or funds appropriated to the USGS.

> Virtually every business day in this country consulting engineers in the private sector, in addition to engineers working at all levels of government, rely on the unbiased and objective scientific information and data provided... One could even argue persuasively that certain aspects of the USGS should be strengthened and expanded. For instance, in the Federal/State Cooperative Program for Water Data Collection Analysis—the critical backbone of the nation's essential surface water data gathering network....[Excerpt from a letter from Stafford E. Thornton, President, American Society of Civil Engineers, January 26, 1995].

The initial growth of the stream-gaging program was slow. At the turn of the century, only 163 stations were in operation. Most of the stations were in the West and were used to satisfy needs for irrigation. Growth of the program after 1900 was more dramatic, as shown by the number of active stations in each decade from 1900 to 1990 (fig. 9).

The growth and evolution of the USGS stream-gaging program was related to increased concern about floods and droughts, the increased use of water for irrigation and hydroelectric power, and specific legislative acts. The Federal Power Act was passed in 1920; during the next 20 to 30 years, planning for hydroelectric power development caused increased need for data. Congress passed legislation in 1929 that officially recognized the Cooperative Program in which costs are shared with State and local agencies, and in the ensuing years, cooperative stream-gaging programs were established with many State and local agencies. Also, the severe midcontinent drought in the early 1930's and the floods in 1936–37 in the Ohio and the Potomac River Basins increased the awareness among Federal, State, and local agencies that management of the water resources requires comprehensive, reliable streamflow data.

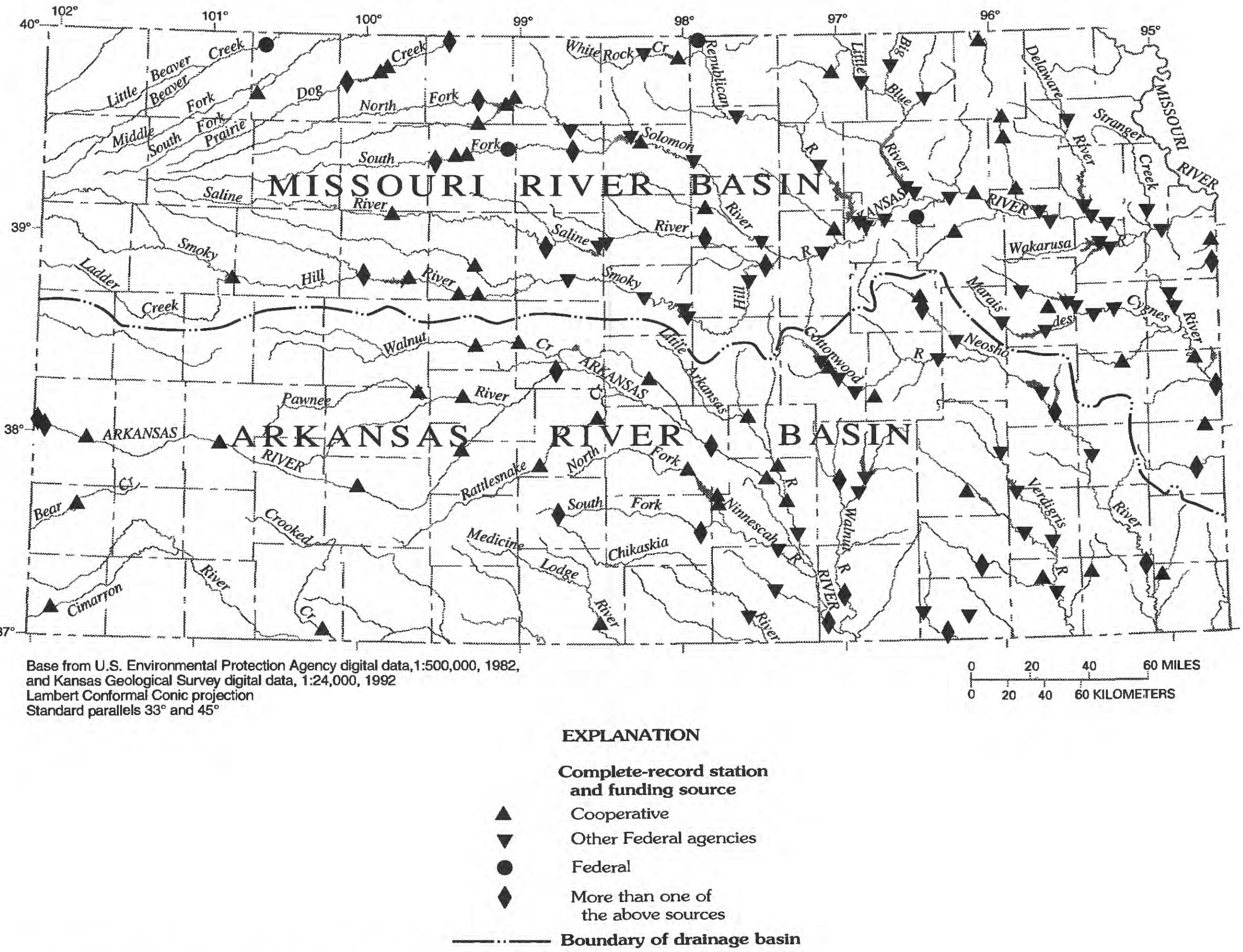


Figure 8. Areal distribution of stations for Kansas, by funding source.

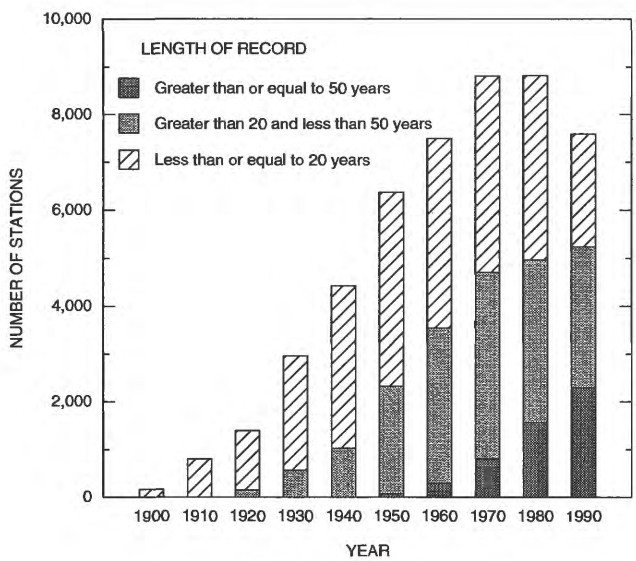


Figure 9. Number of stations in the U.S. Geological Survey data base, 1900–90.

Passage of the Watershed Protection and Flood Prevention Act of 1954 and construction of the interstate highway system in the 1960's increased the need for streamflow data for small watersheds. Some of this need was provided by partial-record stations that recorded data only for flood peaks, but the numbers of continuous-record stations also increased. The need for data at the thousands of points where the highway systems crossed streams created an immediate need for methods to estimate flood magnitudes at ungaged sites. This need was satisfied by streamflow data to calibrate the regional equations used to make those estimates. The National Flood Insurance Act of 1968 increased emphasis on flood-plain mapping and emphasized the need for reliable flood-frequency data.

The Surface Mining and Control and Reclamation Act of 1977 also increased the need for data on streams affected by surface mining and other energy development. However, the additional stations constructed in the 1970's generally were offset by reductions in other areas of the network. Reevaluation of the program in the early 1970's (Benson and Carter, 1973), the beginning of stringent financial constraints on the parties to the program, and the completion of many water-development projects were factors in limiting expansion of the program.

The major factors that have affected trends in the network since the late 1970's appear to be related to economic concerns and energy programs. In the 1970's, the oil crises gave impetus to a large expansion of research in coal and oil shale as sources of energy. Definition of the effects of such energy development on streamflow and water quality required streamflow data. Numerous stations were installed to provide those data. As concern for energy sources waned in the early 1980's, many of those stations were discontinued.

In 1987, a poll was made of USGS offices to identify stations discontinued or started from 1981 to 1986. This poll was taken in response to NWS concerns that the number of stations in the USGS stream-gaging program was declining. Between 1981 and 1986, 873 stations were added, but 1,744 stations were discontinued; thus, there was a net loss of 871 stations from the program. This illustrates the complexity of change; stations that were added and then deleted during the period (125) were not counted in this poll.

A more recent poll of USGS offices in Delaware, Georgia, Iowa, Idaho, Maryland, Michigan, Oklahoma, and South Dakota showed little net change in numbers of stations between 1985 and 1994. These States, which were selected as a representative sample, had 832 stations at the beginning of the period. During the period, 189 stations were added, and 170 were dropped; this represents about a 20-percent turnover rate in 10 years. An additional 29 stations were started and dropped. Of the stations that were dropped, record lengths were more than 20 years at 97 stations and more than 40 years at 30 stations.

DATA-COLLECTION PROCESS

The basic piece of data obtained at a station is the stage, which is the height of the water surface above a reference elevation. If the stage of the streambed is known and is subtracted from the water-surface stage, then the result is the depth of water in the stream. Although stage of a stream is useful in itself in planning uses of flood plains, most users of streamflow data need to know the discharge of the stream. Discharge is defined as the volume of flow passing a specified point in a given interval of time and includes the volume of the water and any sediment or other solids that may be dissolved or mixed with the water. The units of discharge usually are measured in cubic feet per second (or cubic meters per second, if metric units are used). Discharge is derived from the stage data through the use of a relation between stage and discharge. The stage-discharge relation for a specific stream location is defined from periodic discharge measurements made at known stages.

Standard methods of data collection are used as described by Rantz and others (1982) and in the publication series Techniques of Water-Resources Investigations of the U.S. Geological Survey. Those methods are briefly described in the following sections.

Measuring Stage

Perhaps the most common method of measuring the stage of a river is through the use of a stilling well. Stilling wells are located on the bank of a stream or on a bridge pier and are topped by a shelter that holds recorders and other instruments associated with the station. The well is connected to the stream by several intakes such that when the water level changes in the stream, the level simultaneously changes in the well (fig. 10). Thus, the water surface in the well is main-

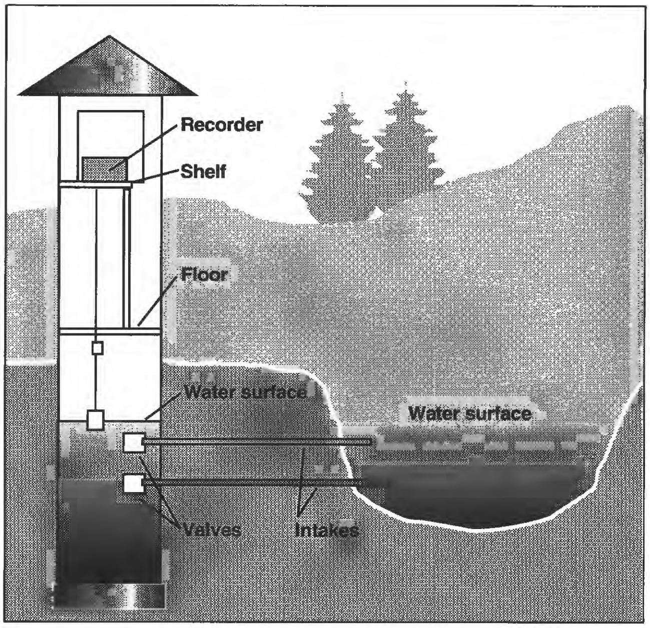


Figure 10. Schematic of a stilling well and shelter.

tained at the same level (stage) as the water surface in the stream. The well damps out the momentary fluctuations in the water surface in the stream due to waves and surging action that may be present in the river. An outside reference gage, typically a graduated staff gage, is read periodically to verify that the water level in the well is indeed the same as the water level in the stream and that the intakes are not plugged. As the water level in the well rises or falls, a float in the well also rises or falls. A graduated tape or beaded cable attached to the float and with a counterweight on the other end is hung over a pulley. This pulley drives a recording device. Historically, the recording device would have used a pen that recorded a graph of the river stage as it changed with time. Graphic recorders are still in use; today, however, the stage is more commonly recorded on a punched paper tape or an electronic recorder or is transmitted to the office by means of satellite.

In many cases, stilling wells are impractical because of difficulties either in installation or operation. Stations that use a bubbler system are an alternative because the shelter and recorders can be located hundreds of feet from the stream. In a bubbler system, an orifice is attached securely below the water surface and connected to the instrumentation by a length of tubing. Pressurized gas (usually nitrogen or air) is forced through the tubing and out the orifice. Because the pressure in the tubing is a function of the depth of water over the orifice, a change in the stage of the river produces a corresponding change in pressure in the tubing. Changes in the pressure in the tubing are recorded and are converted to a record of the river stage.

Measuring Discharge

The most practical method of measuring the discharge of a stream is through the velocity-area method. This method requires the physical measurement of the cross-sectional area and the velocity of the flowing water. Discharge is determined as the product of the area times the velocity. Velocity is measured by using a current meter. The meter consists of a propeller that is rotated by the action of flowing water. The rotation depends on the velocity of the water passing by the propeller. With each complete rotation, an electrical circuit is completed and recorded in some fashion. Given the number of revolutions in a given time interval, velocity can be determined for the location of the current meter.

Measuring the average velocity of an entire cross section is impractical, so the method uses an incremental method. The width of the stream is divided into a number of increments; the size of the increments depends on the depth and velocity of the stream. The purpose is to divide the section into about 25 increments with approximately equal discharges. For each incremental width, the stream depth and average velocity of flow are measured. For each incremental width, the meter is placed at a depth where average velocity is expected to occur. That depth has been determined to be about 0.6 of the distance from the water surface to the streambed when depths are shallow. When depths are large, the average velocity is best represented by averaging velocity readings at 0.2

Current meter and weight suspended from a bridge crane.

Wading rod and current meter used for measuring the discharge of a river.

Crane, current meter, and weight used for measuring the discharge of a river from a bridge.

and 0.8 of the distance from the water surface to the streambed. The product of the width, depth, and velocity of the section is the discharge through that increment of the cross section. The total of the incremental section discharges equals the discharge of the river.

When the stage is low and the stream can be waded, the measurements are made by wading with the current meter mounted on a wading rod. The meter is positioned at the appropriate depth on the wading rod, which also is used to measure the water depth. If the water is too deep for wading, then the measurement is made either from a bridge or cableway across the stream. If the measurement is made from a bridge or cableway, then the meter is suspended on a thin cable wound on a reel. A torpedo-shaped weight is attached below the meter to permit it to be lowered into the water and to hold it in position once submerged. If measuring from a bridge, then the reel is mounted on a wheeled frame (or crane) that permits the lowering of the meter assembly over the bridge rail; from a cableway, the reel is mounted in a cable car suspended from the cableway that crosses the river. The basic procedure of measuring width and velocity is the same, however, whether the measurement is made by wading or from a cableway or bridge. The USGS makes more than 60,000 discharge measurements each year. The distribution of measurements made in 1993 is shown in figure 11.

Determining a Continuous Record of Discharge

Measurements made over the range in stage of the stream are plotted against the corresponding stages to define the stage-discharge relation that is used in conjunction with the recorded stage record to determine the discharges throughout the year. The procedure would be fairly straightforward were it not for all the natural processes that occur in streams. Flowing water moves sediment and other material that if eroded from or deposited on the streambed or banks, can alter the cross-sectional area of the stream at a given stage. Growth of vegetation along the banks and aquatic growth in the channel itself can impede the velocity, as can deposition of downed trees in the channel. Processes like these will alter the stage-discharge relations and are characteristic of most streams. In addition, ice and snow can produce large changes in stage-

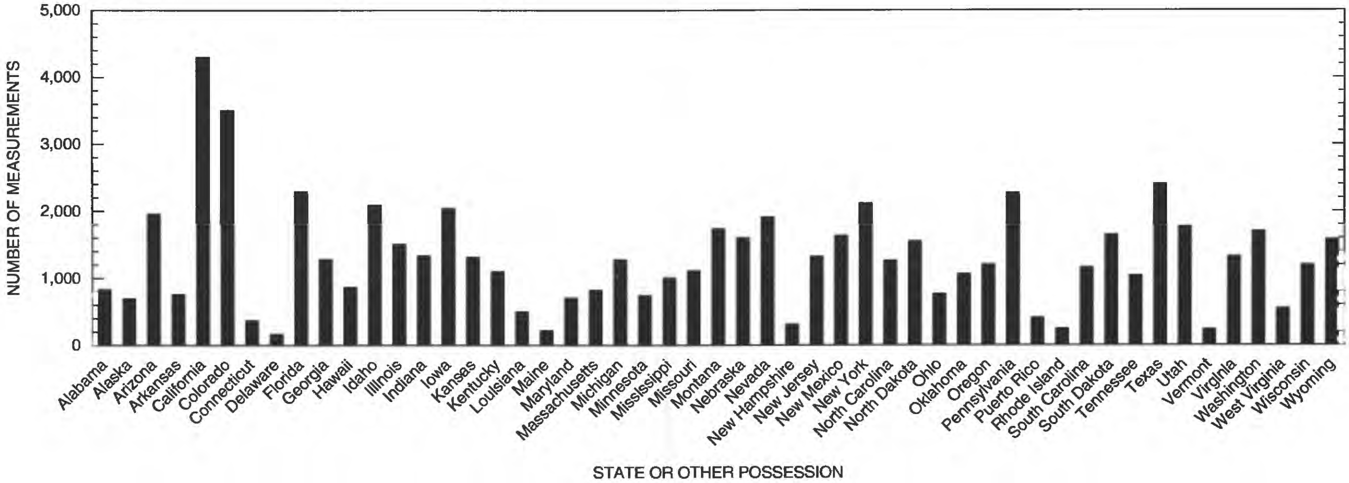


Figure 11. Discharge measurements made in 1993, by State or possession.

discharge realtions, and the degree of change can vary dramatically with time.

The stage-discharge relation will be stable if the hydraulic characteristics of the general reach of stream are unchanging and the bed material does not move appreciably. On a stable stream, periodic measurements are made every 6 to 8 weeks to verify that the relation has not undergone some unrecognized change. The stage-discharge relation will be unstable, changing with time and with the flow conditions, if the streambed or the hydraulic roughness is changing (as might occur with a sand-bed stream). In such cases, frequent measurements (about weekly) are needed to define how the rating is changing and to define its present condition (fig. 12).

Sometimes, current-meter measurements are not possible during large floods. However, the stage and discharge of those floods are essential in defining the

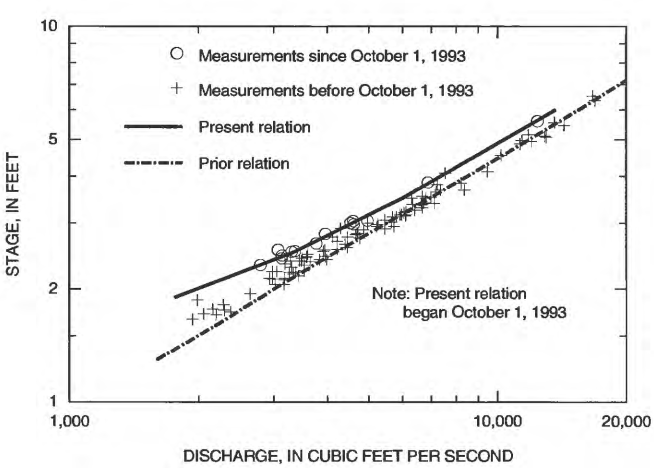


Figure 12. Sections of stage-discharge relations for the Colorado River at the Colorado–Utah State line.

rating for the range of flow. Therefore, the discharge is determined indirectly by surveying the high-water marks left by the flood and by using hydraulic formulas to calculate the discharge for the peak stage.

Because the relation between stage and discharge may vary with time, the discharge is known only with certainty at the time of discharge measurements. If the relation is changing, then judgement must be used to determine the most probable status of the stage-discharge relation for times between discharge measurements. In fact, changes in the stage-discharge relation may not be evident until a whole series of measurements are available for analysis. Therefore, the computational process usually goes through the following steps:

1. Following a measurement, a preliminary evaluation is made of the degree to which the stage-discharge relation has changed on the basis of measurements made up to that time. Provisional discharges are determined, assuming that the most recent measurements define the channel condition.

2. This process is repeated following each measurement. However, with each measurement, more measurements are available to evaluate the stage-discharge relation. This may lead to changes in the provisional discharges that had been computed for previous months.

3. At the end of the year, all measurements are available for review. The entire set of measurements are used to reevaluate the rating conditions for the year. Final decisions are made about the stage-discharge relation that were in effect

during the year and the record is refined or recomputed as necessary. This record is then passed through a rigorous review process and, once approved, the data are considered final and are placed in the archives and published.

Data Collected by Other Agencies

Other agencies, most notably State agencies, collect some streamflow data, as do a number of cities, local governments, and other Federal agencies. The primary differences between the USGS networks and those of the other agencies are the purposes for which the data are collected. Other agencies, whether they are Federal, State, or local, often collect only those parts of the data needed for a specific mission or task. For example, data collected by other agencies to fulfill permitting requirements associated with wastewater or treated water commonly do not include the full range of flows. These data, while vital for that specific mission, generally have little transfer value and are, therefore, of limited value in addressing issues of national and regional scope (Hren and others, 1987; Childress and others, 1989). Consequently, these data are not usually placed in accessible archives and made readily available to others.

Some data collected by other agencies, however, have value beyond the specific purpose for which the data were collected. Data from stations operated by other agencies are reviewed by the USGS, published in the annual State Water Data Reports series compiled by the USGS and entered in the USGS data base (see fig. 9). In 1990, data from about 400 stations were provided to the USGS by other agencies.

Dissemination of Data

Currently, daily-discharge data are published on a water-year basis for each State in the USGS report series Water Resources Data—[State Name]. A water year is the 12-month period from October 1 through September 30 and is designated by the calendar year in which it ends. Thus, the 1994 water year ends September 30, 1994. Because of the need for review of the completed computations, these reports generally are published from 6 months to 1 year after the end of the water year. The present report series, in which the data are released on a state-boundary basis, began with the 1971 water year.

Before the introduction of the present publication series, water-resources data were published in USGS Water-Supply Papers. Before September 1960, data for each major river basin were published in annual Water-Supply Papers. From 1961 through 1970, the data for the major river basins were published in 5-year summaries.

Many streamflow-data users must make operational decisions daily. For these users, streamflow records are computed and made available on a provisional basis. Today, more than one-half of the currently operating stations have equipment that permits immediate transmission of data by means of satellite from the data-collection site. By using the telemetry, data are transmitted around the clock by means of two geostationary operations environmental satellites (GOES) that are positioned above the Earth at an altitude 22,300 miles above the Equator over the eastern Pacific Ocean and Brazil. The satellites are operated by the National Oceanic and Atmospheric Administration. These data then are retransmitted by means of a domestic satellite, and the resulting signal is received by the USGS and other users (fig. 13). The transmission and receipt of the signals are automated, as are the provisional discharge computations that are available for meeting current data needs.

Automated telemetry provides the water-data users with provisional stage and discharge information in a timeframe that meets water-management needs. This technology permits the USGS field offices to monitor the operation of the hydrologic stations continuously, time visits to stations to coincide with times of maximum need for data (such as during floods), and to service equipment at the stations.

> In northeastern New Jersey, the USGS operates 18 satellite data transmitters at stations as a part of the Passaic Flood Warning System. The Passaic River Basin is one of the most flood-prone basins in the United States with an estimated annual average flood damage of 84 million dollars [Robert Schopp, U.S. Geological Survey, oral commun., January 1995].

In addition to the published record, the data collected by the USGS are archived in the National Water Data Storage and Retrieval System, which is a computerized data base widely known by the acronym WATSTORE (Hutchinson, 1975). The WATSTORE system contains the data and a number of programs that can be used to analyze and produce statistical summaries of the data contained therein.

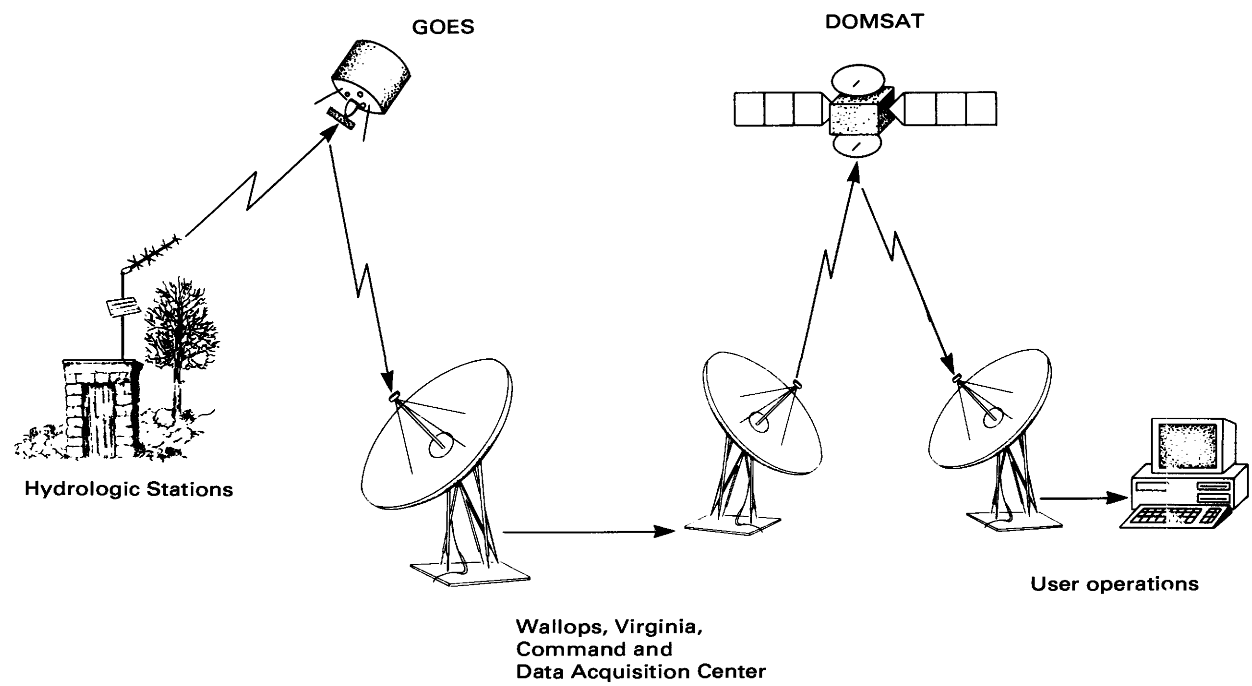


Figure 13. Schematic of the data flow for realtime operations.

Beginning with the 1990 water year, Water Data Reports also are available on Compact Disk–Read Only Memory (CD–ROM). The Water-Supply Papers, the Water Data Reports, and the CD–ROM's are distributed to participating agencies and libraries; they also are available for sale by the USGS Earth Science Information Center, Denver, Colorado. The USGS currently is developing procedures to allow access to streamflow data by means of Internet. Historical mean daily-discharge data for about 18,500 stations will soon be available through this source. The USGS "Home Page" on the World Wide Web is

http://www.usgs.gov.

EVALUATING THE PROGRAM

The stream-gaging program of the USGS is continually changing because the needs for data and the abilities of the many entities to fund their components of the program are changing. Any activity of long standing needs to be reexamined periodically to verify that the program is keeping abreast of changes in objectives, technology, and (or) external constraints. This is especially true for the national stream-gaging program because it also is an aggregation of many local or regional programs that have a variety of primary objectives.

The USGS has a long history of analyzing and evaluating the stream-gaging program. The first known nationwide review of the stream-gaging program was conducted between 1953 and 1958. The purpose of the review was to design a hydrologic network of stations in accordance with principles described by Langbein (1954). During this review, stations were classified according to the primary uses of the data as either water management or hydrologic network (regional hydrology). Within the hydrologic network, the concept of primary and secondary stations was developed. The primary stations were used for long-term sampling of streamflow, and the secondary stations, which were operated for 5 to 10 years, were used to obtain geographic coverage of streamflow characteristics. Estimation of long-term statistics at the secondary stations was based on the correlation of monthly flows with the long-term primary stations. Recommendations were made for improving the stream-gaging program.

The second national study of the streamflow data-collection program was conducted in 1969–70. The stations were classified on the basis of the principal uses of data as providing data for current use (water management), planning and design (regional hydrology), and defining long-term trends and the stream environment. The goals of the program for planning and design data were to provide information that is equivalent to 25 years of record for principal streams (which drain 500 square miles or more) and 10 years for minor streams (which drain less than 500 square miles) (Carter and Benson, 1969). These data were to be provided by either a gaged record or equations that relate streamflow characteristics to basin characteristics. In general, these goals were met only in the humid Eastern United States. The results are described in a series of statewide reports entitled "A Proposed Streamflow Program for [State Name]." A summary of the nationwide study, including recommendations for improving the program, is provided by Benson and Carter (1973).

The most recent nationwide evaluation was conducted during the mid-1980's to define the cost effectiveness of the operation of the stream-gaging program (Thomas and Wahl, 1993). The objective of the nationwide study was to define and document the most cost-effective methods of furnishing streamflow information. The study involved the following phases: an analysis of the data uses and availability and documentation of the sources of funding for each station; an evaluation of the utility of using less costly alternative methods, such as hydrologic-flowrouting models and statistical methods, to provide the needed streamflow information; and an analysis of the cost-effective operation of the stream-gaging program that relates the accuracy of the streamflow records to various operating budgets. A prototype study for the nationwide analysis was described by Fontaine and others (1984). Statewide analyses were performed by hydrologists in the USGS State Offices. The reports that described the analyses for the individual States were summarized and referenced in Thomas and Wahl (1993).

The results of the poll on data uses are summarized in figures 14 and 15. The categories were described earlier in this report in the section on "Uses of Streamflow Data." The percentages in figure 14 total more than 100 percent because data uses for a given station may be included in more than one category.

Although stations usually are established for a specific reason, the data collected are useful for many purposes. On average, there are more than two categories of data use per station. The uses of data from only about 20 percent of the stations fall into a single data-use category. The greatest number of the stations in only a single data-use category are in regional hydrology (34.4 percent) and hydrologic systems (30.2 percent). More than 1,500 stations (25 percent) have four or more data-use categories.

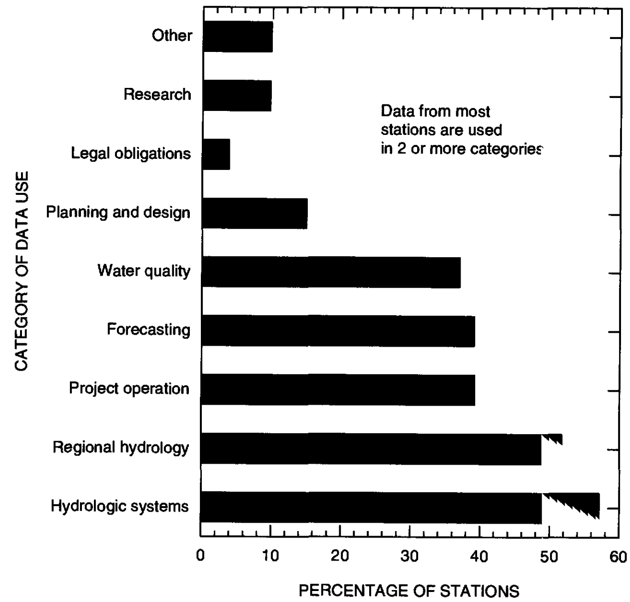


Figure 14. Percentages of stations by category of use (from Thomas and Wahl, 1993).

The nationwide analysis documented that multiple uses were being made of data collected at stations in the stream-gaging program, simulated flows from hydrologic-flow-routing models and statistical methods generally were not of sufficient accuracy for most uses, and the program was being operated in an efficient and cost-effective manner (Thomas and Wahl, 1993). Network analyses and program evaluation will continue to play a prominent role in the management of the program. Future directions will likely involve the development of techniques for a more coordinated analysis of water-quality, ground-water, and streamflow networks.

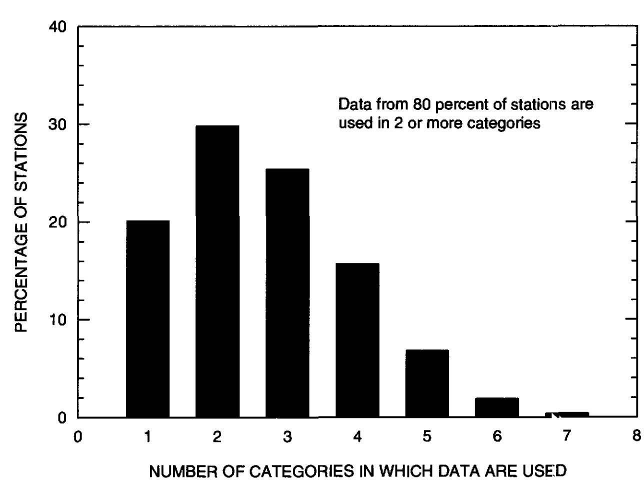


Figure 15. Distribution of stations as a function of the number of data-use categories (from Thomas and Wahl, 1993).

> The existing data networks should be viewed by hydrologic scientists as opportunities upon which they can build. To optimize these opportunities, it is first necessary to define the characteristics of the data sets that hydrologic scientists need. These characteristics include the variables to be measured and the locations, frequencies, durations, and accuracies of the measurements. They should be derived from knowledge about the hydrologic phenomena to be explored and from the hypotheses to be tested [National Research Council, 1991, p. 221].

CHALLENGES FOR THE FUTURE

As we approach the 21st century, the limited water supply and established water storage and distribution systems must be managed effectively to meet increasing demands. Evidence abounds, however, that the era of building large dams and conveyance systems has ended. Thus, "new" future supplies likely will come from conservation, reuse, and improved water-use efficiency rather than from ambitious water-supply projects. The Governors of the Western States issued a policy statement that called for sharply enhanced efficiency in water use; and the President signed into law the Energy Policy Act of 1992 (Public Law 102–486), which calls for government agencies to take the lead in water-use efficiency measures and sets new standards for water-conserving plumbing fixtures. A supply that has ecological and economic limits cannot be continuously expanded to try to meet insatiable demands. Comprehensive streamflow data are needed to account for the water in the Nation's hydrologic systems and to quantify the stress on existing supplies. Just as managers needed supply information during the dam-building era, they now need more comprehensive streamflow data to assess the effectiveness of various management options and to monitor mandated instream flows.

> Water management will be increasingly looking for flexible policies which can quickly adapt to a variable climate. Such policies require comprehensive monitoring of changing drought conditions to provide lead-time to water managers [National Science Foundation, 1990].

Perhaps the biggest challenge that confronts the stream-gaging program, and indeed of the hydrologic community, is that of maintaining long-term and consistent nationwide data sets. Agreement is widespread about the need for such data sets. Because of the manner in which the data program is funded, the networks of stations are dynamic. Interest in and the need for hydrologic information vary in time and space. This variation of interest, coupled with the budget limitations, means that all needs simply cannot be met. In some instances, monitoring activities at a particular site are discontinued because the needs of the supporting agencies have been met. In other cases, even though the needs have not yet been met, budget allocations dictate reductions for hydrologic data-collection activities. Since the late 1960's, reductions have been sharp in the number of stations that provide data that are appropriate for studies of climate variability (fig. 16). This is but one striking example of how budget constraints have caused a reduction in the availability of the streamflow data needed to address an important current issue.

> The U.S.G.S. basic water data collection program is of vital importance to water resource planning, design, and operation in the United States. Reductions in surface water data collection will have long-term adverse effects on the efficiency and certainty of planning, design, construction, and operation of projects. Civil engineers rely on surface water data for numerous projects, including flood control, pollution control, transportation, and navigation. Of particular concern is the need to maintain the length and continuity of the hydrologic data record, because interruptions in data collection can cause extreme hydrological events to go unrecorded" [From American Society of Civil Engineers Policy Statement on Surface-Water Data Collection, October 24, 1993].

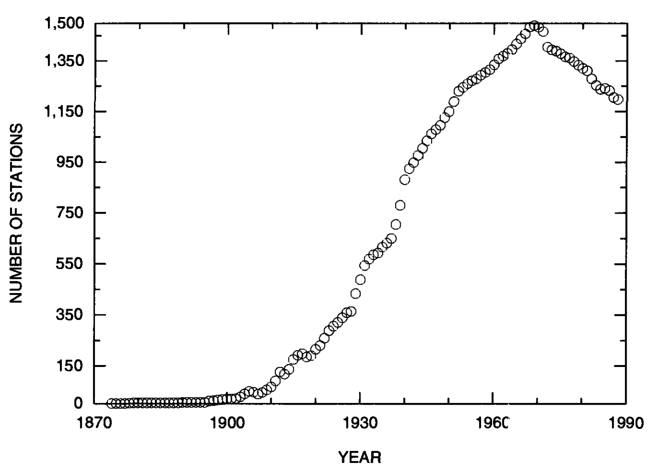


Figure 16. Number of stations in a given year with acceptable data for studying climate fluctuations (from Slack and Landwehr, 1992).

> Despite the increasingly recognized importance of data records of long duration, only a few dedicated research organizations have successfully maintained high-quality data collection efforts over periods of 50 to 200 years. Furthermore, these organizations have experienced difficulty in committing limited research monies year after year to an activity that is frequently termed "monitoring," often with pejorative overtones [National Research Council, 1991, p. 222].

Maintaining the stations and equipment needed to gage the Nation's streams also will pose a large challenge for the future. Of the 7,292 stations in operation in 1994, many have been inplace for more than 20 years. Because of the streamside locations, the stations and cableways, as well as the associated recorders and equipment, require significant amounts of upkeep. In addition, the changes in technology related to water-level sensors and data recorders in recent years have been phenomenal. Replacing existing sensors and recorders with equipment based on the newer technology will not only be costly, but will require fundamental changes in modes of operation. Past improvements in sensors and recorders have increased the reliability of the streamflow records (Thomas and Wahl, 1993) and decreased the frequency of visits to the station for equipment repair. Further improvements in technology should result in savings in labor required to operate the stream-gaging program and improved accuracy of streamflow records. For example, the use of satellite telemetry or cellular phone technology provides USGS staff with knowledge of equipment failure and unusual flow conditions so that costly field visits can be scheduled when they are most needed, thereby reducing the average number of visits to the station.

One of the most pressing and immediate challenges relates to the mechanisms for releasing interim data. Traditionally, the stream-gaging program has been oriented towards producing data to be placed in the archives for use in future analyses. Those persons or agencies with an immediate need for data generally participated in the collection of the data and, therefore, had ready access to the interim data. With the advent of data transmission by means of satellites, the needs for and uses of realtime data have significantly increased. Forecasters and managers now rely on interim data received in near realtime to make operational decisions. The data upon which those decisions are based must be the best that can possibly be produced in a short timeframe.

A related problem is that of access to the archived data. Historically, data have been archived in the WATSTORE data base. It evolved from the computer technology of 20 to 30 years ago and was designed initially for experienced users of the data base. Interest in and need for access to that data base is much broader than is possible through the WATSTORE system and technology. As noted earlier, the USGS will soon make the data accessible by means of Internet. When that is accomplished, many potential users would have ready access to the archived data.

> The immediate, unrefined products of observation and experimentation are scientific data. These are obviously available to those who collect them, but their primary value is often realized by others at a later date and in a quite different scientific context. For hydrologic science to move forward it is essential that data sets, once acquired, be properly identified and described...be catalogued and archived (including archival maintenance), and be made available to the scientific community at reasonable cost and effort [National Research Council, 1991, p. 310].

Finally, operation of the stream-gaging program is dependent on a committed and talented staff of hydrologic technicians who maintain and service the gages, make the measurements that define the rating curves, and compute the discharges that compose the data base. Maintaining and training the skilled staff necessary to do these tasks will be one of the largest challenges

> In the history of the hydrologic sciences as in other sciences, most of the significant advances have resulted from new measurements. Yet today there is schism between data collectors and analysts. The pioneers of modern hydrology were active observers and measurers, yet now designing and executing data programs, as distinct from experiments carried out in a field setting with a specific research question in mind, are too often viewed as mundane or routine. It is therefore difficult for agencies and individuals to be doggedly persistent about the continuity of high-quality hydrologic data sets. In the excitement about glamorous scientific and social issues, the scientific community tends to allow data-collection programs to erode [National Research Council, 1991, p. 214].

The USGS continues to be committed to collection and dissemination of high-quality streamflow data as a critical part of its overall mission of providing earth science information for the wise management of the Nation's natural resources. The maintenance of a viable stream-gaging program is an integral part of managing these natural resources.

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