# 2
# Gaging the Nation's Streams

The U.S. Geological Survey (USGS) has a long tradition of studying the nation's streams. The first USGS gaging station was established on the Rio Grande in 1889 (Wahl et al., 1995). However, since the USGS's inception, its mission and programs have sometimes come under scrutiny by Congress or by the USGS itself, and as a consequence the mission and programs have adapted to changing needs and mandates. The National Streamflow Information Program (NSIP), as it is presently known, is being examined at the request of the USGS with a view to ensuring that it meets the nation's needs.

In this chapter, the committee traces the history of river studies and streamgaging at the USGS, summarizes what a USGS gaging site generally looks like, briefly consider the role of other U.S. agencies in supporting streamgaging, looks at streamflow network design in other countries, and examines the value of a national streamflow information program.

## A HISTORY OF THE STUDY OF RIVERS AT THE USGS

A brief history of river studies at the USGS, in its various manifestations, provides background for review of the program. The following discussion was gleaned from a more general history of the USGS's first century of operation (Rabbitt, 1989). The picture that emerges is that of a program that traditionally has provided information to a host of users, funded as much by users as by federal government appropriations. Information includes hazard (flood and drought) estimation and warning and water supply information for irrigation (food supply), power generation, flood control, defense, and resource protection.

The USGS mission when it was formed in 1879 was "classification of the public lands." The federal government owned more than 1.2 billion acres, most of it west of the Mississippi River, and less than 20 percent of this land was then surveyed for mineral wealth or agricultural potential. John Wesley Powell in 1878 showed that most of this land was arid, and only a fraction of that could be irrigated. Water was clearly the limiting resource for development of the arid region, so Powell recommended organizing the arid lands into irrigation districts.

Irrigation and flood relief were tied together in an investigation by the USGS into using flood-generating water surpluses from the Rocky Mountains to irrigate dry areas west of the Rockies. A drought in 1886 seized the nation's attention, and in 1888 Congress authorized a survey of the western lands for irrigation potential. Sites were to be selected for reservoirs for storing water and at the same time alleviating downstream floods. This congressional authorization gave Powell, then USGS director, a long-awaited opportunity to map watersheds and measure streamflow (Figure 2-1).

Powell wasted no time in starting, even though he had to train hydrologists. Land purchases were put on hold until Powell's irrigation survey was complete, in order to prevent land speculation. (Many parcels of dubious value might be bought up by a company that would reap large profits once a water supply was demonstrated.) Western developers, understandably, were unhappy. Six new states that were given "dowry" lands could not settle them, giving them no tax base. In 1890, in response to pressure from these states and the developers, Congress repealed the withdrawal of lands and discontinued the irrigation survey. The USGS fell out of favor with Congress, and the next few years saw cuts in appropriations except for activities of immediate practical use, such as mineral resources surveys. The Senate appointed a committee to investigate the "efficiency and utility" of the USGS, an action directed at Powell.

The USGS survived this scrutiny, and Powell's vision survived in the sense that geology now included the study of water. A small appropriation in 1894 was earmarked for "gauging the streams and determining the water supply of the United States." Groundwater and water-use investigations became part of the USGS, and appropriations were increased regularly. The federal need for water information was fully recognized in 1896, when a Public Lands Commission was recommended, to include the director of the USGS. This commission was to be responsible for determining, among other things, the water supply of the public lands.

Theodore Roosevelt outlined a water policy in his first State of the Union message in 1901. The Newlands Act in June 1902 promoted reclama-

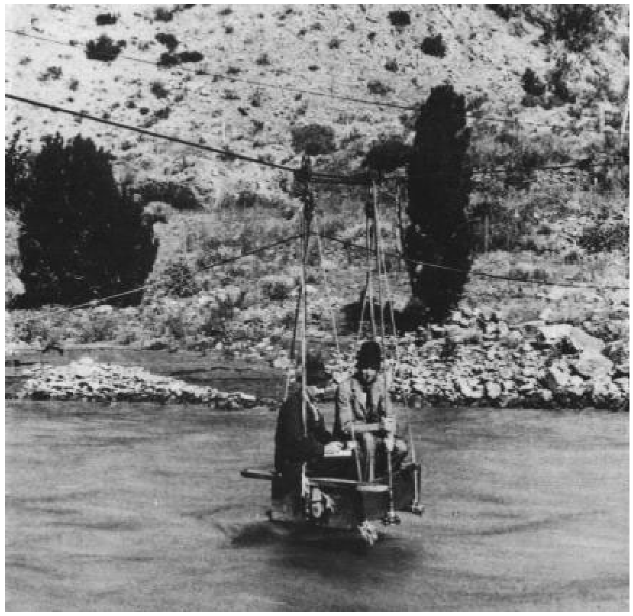

FIGURE 2-1 Streamgaging by the USGS in 1890. SOURCE: Rabbitt (1989).

tion of the arid lands, and the Reclamation Service, then an adjunct of the USGS, was established. The USGS Hydrographic Division separated from the Geologic Branch and became the Hydrographic Branch. Appropriations increased for water resources investigations over the years, in response both to irrigation needs and to several major floods (Figure 2-2). Streamflow measurement and analysis came into its own, linked to the development of waterpower, irrigation, and flood hazard estimation.

Waterpower interests increased after World War I, when USGS engineers conducted a national survey for waterpower sites. In 1920, the Federal Water Power Act established the Federal Power Commission, which could license the development of waterpower on federal lands. The USGS was given the task of measuring streamflow and examining proposed waterpower projects (Figure 2-3).

Cooperative funding drove the majority of investigations. Cooperators included the U.S. Army Corps of Engineers, who needed streamgaging for flood control projects, and the Department of State, which had international water issues to resolve. States also became important partners during

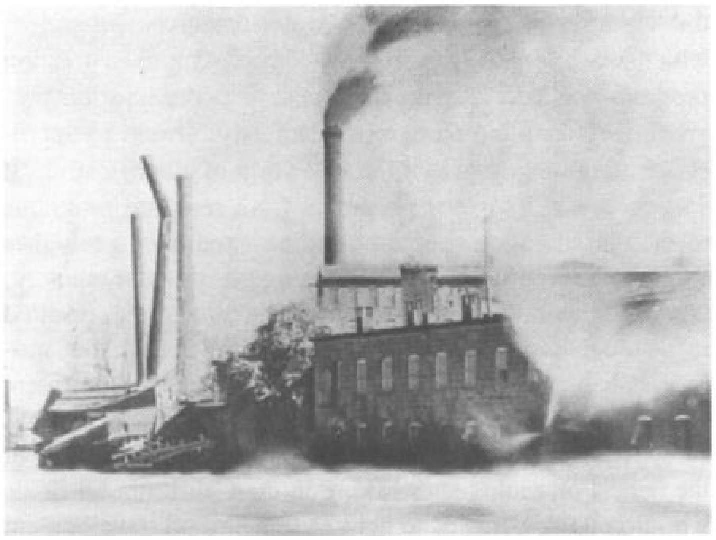

FIGURE 2-2 Devastating floods such as this one in New Jersey, in 1902, highlighted the need for streamgaging for warning, stream studies, and hazard estimation. SOURCE: Rabbitt (1989).

FIGURE 2-3 A USGS geologist surveys a western river for power generation potential in 1920. SOURCE: Rabbitt (1989).

this period. In 1905, Congress appropriated funds specifically for cooperative studies, and in 1928, Congress gave formal recognition to the federal-state partnership that became the Federal-State Cooperative Water Program (now known simply as the Cooperative Water Program). While Congress increased the water resources funding at that time, it stipulated that the maximum federal contribution to such projects would be 50 percent. As discussed later in this report, this limiting stipulation has had a major impact on the design of a federal streamflow information program.

The Hoover presidency (1929-1933) was important for the USGS because President Hoover believed in both conservation of resources and basic research to understand them. For example, the destruction of ground cover by overgrazing had worrisome implications for water supply. In response to such concerns, the Water Resources Branch expanded. The depression heralded a sober era for the USGS in which basic research was conducted in the shadow of practical hydrology. Overall, Franklin Roosevelt's programs actually led to growth in the USGS. The Tennessee Valley Authority and the Public Works Administration both required intensive streamgaging, but the grants also supported research. The USGS made great strides in quantitative hydrology, researching rainfall-runoff relations and analyzing flood frequencies. Streamgaging instrumentation also improved. With these new program funds, federal appropriations now accounted for only one-quarter of total USGS support.

After World War II broke out, the USGS Water Resources Branch had responsibility for providing information on water for military and industrial installations. The USGS wrote more than 15,000 reports for the war effort. After the war, the USGS focus shifted back to irrigation, flood control, and highway drainage. The agency also took on the task of determining water needs for industry, starting with the steel industry. These tasks resulted in a very active USGS by 1954 (its seventh-fifth year), at which time 6,400 gages were active. New research activities in the next decade set the tone for the rest of the century. The USGS researched stream sediment transport, including measurement methods, bedload, controls on channel aggradation, and effects of sediment on flow. It conducted basic process research on river hydraulics in the field and in flumes, from the large scale (stream networks) to the reach scale, investigating relationships among discharge, channel geometry, drainage basin size, and water velocity. It initiated studies to answer management questions, such as effects of reservoirs on flow and impacts of wetlands and groundwater pumping on streamflow. USGS scientists also studied flood hazards; water supply issues, including water resource assessments; snowpack and snowmelt, annual runoff estimates for major basins; and effects of rainfall and drought on flow. By 1962, the Water Resources Division of the USGS was involved in "fundamental and applied research in water hydraulics, limnology, hydrology of ground water and surface water, geochemistry of water, stream-channel development and morphology, sediment production and transport, evapotranspiration and evaporation suppression, physical and chemical interrelations of precipitation and water above and below the land surface, and the effects of man-made environmental changes on water and water supplies" (Swenson, 1962).

The 1960s onward could be characterized as an era of USGS participation in public issues. As the nation began to confront its industrial and radioactive wastes and their human health hazards, the USGS took a larger role in these areas as well as natural hazards. Geochemists shifted from mainly mineral prospecting to exploring the distribution of potentially hazardous natural substances. The 1964 federal budget gave the USGS the task of creating a national network for collecting water data to address accelerating demands on resources and movement of Americans into water-poor or flood-prone areas. The goal was a 50 percent increase in collection of basic water data by 1973. The network would be supported by the development of digital recording equipment, computerized data processing, and central data distribution through the new Office of Water Data Coordination. The value of basic research was also emphasized, and the plan called for a water-resources program that was 25 percent research. Scientists were needed to do this work, so the USGS helped develop hydrology curricula at major universities. Although the Vietnam War pulled attention and resources away from many domestic programs, environmental problems stayed in the public eye. The 1960s and 1970s saw passage of the Water Quality Act, the Solid Waste Disposal Act, and the National Environmental Protection Act.

By 1971, the USGS collected streamflow data at more than 11,000 gaging stations and measured water quality at 4,000 stations. Multidisciplinary studies had increased in number, and information became increasingly accessible. Hazard prediction (including flood prediction) was given high priority. A technological breakthrough came in 1972 with the availability of what is now called Landsat satellite data. The USGS built a data center in South Dakota to distribute satellite and other remotely sensed data and immediately began exploring how the new information might address hydrologic issues. In 1975, the Land Information and Analysis Office consolidated several multidisciplinary land resource and environmental programs. One of its main objectives was to interpret and display land resource information for a wide audience.

In 1977, the National Water-Use Information Program was created, and its five-year reports continue to be the most widely used USGS products. In 1984, the program also started publishing the National Water Summary, which annually described hydrologic conditions and events (such as floods) for each state.

The 1980s were a time of downsizing and increased private access to federal lands for mineral and energy development, in order to increase domestic energy and mineral production. As a result, the USGS reverted to its initial task of classifying public lands, and some of its other duties were placed in other agencies. The primary task of the Water Resources Division was to provide hydrologic information for the best use and management of water resources. Mapping advances benefited the Water Resources Division; by 1988, the Mapping Division completed the 1:100,000-scale digital database including hydrology of the United States.

USGS publications from the last few decades reflect emerging technologies and changing societal values, linking streamflow to water quality, land use, and watershed management. Desired flow characteristics reflect changing values and are increasingly related not just to power supply, flood protection, and human water supply, but also to biological functions of rivers, including riparian habitat. The USGS has also taken advantage of technological breakthroughs in computational capacity, satellite communications, geographic information system (GIS) technology, and remote sensing. Computer flow models are used to estimate sediment transport, estimate streamflow highs and lows from precipitation, extend flow records, reconstruct natural flows, forecast future water demand, and predict effects of climate change on streamflow. The USGS has paid considerable attention to the statistics of streamflow and has developed field methods and mathematical tools to minimize the uncertainty of its numbers. It has also sought to make its information rapidly and readily accessible to the public, especially through the Internet.

The present-day NSIP developed in response to critical national needs—irrigation water supply (with national interest heightened by severe drought), flood warning and flood estimation, public water supply, water-power generation, water conservation, national defense, and industrial water supply. Now the streamflow program serves the additional needs of protecting water quality and aquatic and riparian habitat, watershed management, and providing information for river recreation. A tension has always existed between applied hydrology to provide specific kinds of information for a specific purpose at a given location, and basic hydrologic science to understand streamflow. Project-based funds have been augmented to a greater or lesser degree by federal appropriations that in some cases could serve basic research needs. Whenever possible, the USGS has strived to maintain hydrologic research in the interests of the long-term water supply and hazard prevention.

The next two sections discuss the streamgaging network and its "nodes," the individual gaging stations that define the network. It should be noted that NSIP is not the only network within this larger set of gages. Other important networks include gages used in three streamflow and water quality networks: the National Water Quality Assessment (NAWQA) program, National Stream Quality Accounting Network (NASQAN), and Hydrologic Benchmark Network. The component gages of these and other networks overlap with those of NSIP and each other. Thus, the NSIP network includes gages funded by these and other programs, including those supported by matching funds provided by other federal, state, and local agencies. Data from all USGS gaging networks are gathered into the National Water Information System (NWIS) database of the USGS, accessible via NWISWeb.

## WHAT IS A GAGING SITE?

The USGS's stream science program rests on the data collected with the streamgage network of about 7000 gages. A streamgage's main purpose is to measure a river's *discharge*. Recorded as a volume of water per unit time (usually in cubic feet per second), the discharge is crucial information about water available for drinking, irrigation, industry, energy, engineering, recreation or wildlife, or on the other hand, the downstream flood risk. River discharge is labor-intensive to measure, so gaging stations instead record a river's water level, or *stage*. Changes in stage originally were recorded by using a float attached to a rotating drum and, more recently, have been recorded by using pressure transducers that convert water pressure to an electronic signal. A sturdy housing protects most USGS gages; even during severe floods the gages must continue to function and transmit information or they lose their value for flood warning.

Stage is then converted to discharge with a *rating curve*. Building the rating curve is part of the cost of streamgaging, because discharge measurements must cover the whole range of stages that a river might reach. USGS personnel must visit the gaging station numerous times at various discharges and measure both stage and discharge directly. Discharge is typically measured with a current meter (Figure 2-4). The river width is divided into intervals, and for each interval the water depth and a representative water velocity (usually the velocity recorded at 60 percent of the total depth) are measured. Multiplying the area of each interval (square feet) by the velocity (feet per second) provides a discharge for each interval; the sum of these is the total discharge for the river.

FIGURE 2-4 Measuring discharge by means of a bridge crane. The current meter, or "fish", is lowered into the river to measure current velocity. The crane is wheeled along the bridge to obtain measurements at multiple sections. SOURCE: USGS (*http://water.usgs.gov/wid/FS_209-95/mason.figure.id.1.gif*).

Such direct measurements of discharge are consistent and robust. They have not changed fundamentally in a century. They have the disadvantage that for practical reasons, flows cannot be measured at every possible point of interest within the river system. The theory to extrapolate flows from measured points to other points of interest is poorly developed. An opportunity exists to put flow estimation on a more theoretical footing by constructing numerical models of streamflow hydraulics at gaging station sites.

The rating curve may shift with time in channels that are eroding or aggrading. Shifting rating curves introduce error into discharge measurements. To minimize such errors, the USGS attempts to locate gages at relatively stable *control sections*, such as near bridges. In general, however, channel sedimentation or erosion can be expected, so the USGS must make frequent measurements, especially at high discharges, to keep the rating curve up-to-date or it loses its value.

As might be expected, very high stages and discharges are rare but are of great interest for flood warning. The USGS strives to amass data on high discharges whenever and wherever they occur, in order to extend rating curves into the high-flow range. These high-flow conditions are hazardous, so techniques and tools continue to be developed to keep USGS personnel out of harm's way.

Once the rating curve has been constructed, raw continuous measurements of stage are transmitted to the USGS, where they are aggregated, converted to periodic discharge, and delivered in real time to users via the Internet. Not all data are disseminated: many are archived by the USGS, either digitally or otherwise, including notes by field hydrologists, rating curves, and so-called unit values of discharge.

Gaging and data retrieval innovations have led to variability among the 7000 USGS gage stations. The simplest gage station may be a temporary or one-time measuring point, in some cases simply a tube filled with cork crumbs to record the highest stage by leaving a bathtub ring of cork in the tube. The "crest stage" so measured is increasingly seen as a biologically critical streamflow parameter (e.g., Bovee and Scott, 2002; Scott et al., 1997). Other gage stations consist of webcams and simply show hourly photos of flashflood-prone rivers such as the Santa Cruz River in Arizona (Figures 2-5 and 2-6). At the other end of the spectrum is the fully automated multi parameter gage station that transmits data in near real time from a remote location via satellite (Figure 2-7). The great majority of USGS gages are now equipped with these systems. Data are transmitted by two geostationary operational environmental satellites (GOES) operated by the National Oceanic and Atmospheric Administration (NOAA). Data are retransmitted by domestic satellite to the USGS and other users.

The hazards associated with streamgaging and the need for intensive data collection during rare high-discharge events have led the USGS and others to develop "non-contact" technologies, such as pulsed Doppler radar to measure surface velocity, and ground-penetrating radar to measure channel cross section (Costa et al., 2000; Haeni et al., 2000; Melcher et al., 1999; and Spicer et al., 1997; also see Chapter 5 of this report). These technologies can be deployed at a particular station or on a mobile unit for measuring conditions at many stations during a high-flow event. Thus far, they have not been widely used (Table 2-1).

The preceding discussion raises the question of whether the existing gages are technologically optimal. Are national needs being met at critical sites? Can innovation reduce long-term labor costs? Some of the issues that face the USGS in effectively gathering streamflow information are listed below, and several are discussed in more depth in later sections.

- *Personnel*: need for frequent site visits to build and update rating curves, with an even greater need during large regional floods

FIGURE 2-5 Gaging station on the flashflood-prone Santa Cruz River in Arizona includes a webcam to transmit hourly photos to warn of floods in the otherwise dry channel. SOURCE: USGS (*http://az.water.usgs.gov/webcam/9482500_cam/cam_09482500.html*).

FIGURE 2-6 Arizona's Santa Cruz River, normally dry, in flash flood, 1983. SOURCE: USGS (*http://az.water.usgs.gov/webcam/9482500_cam-/cam_09482500.html*).

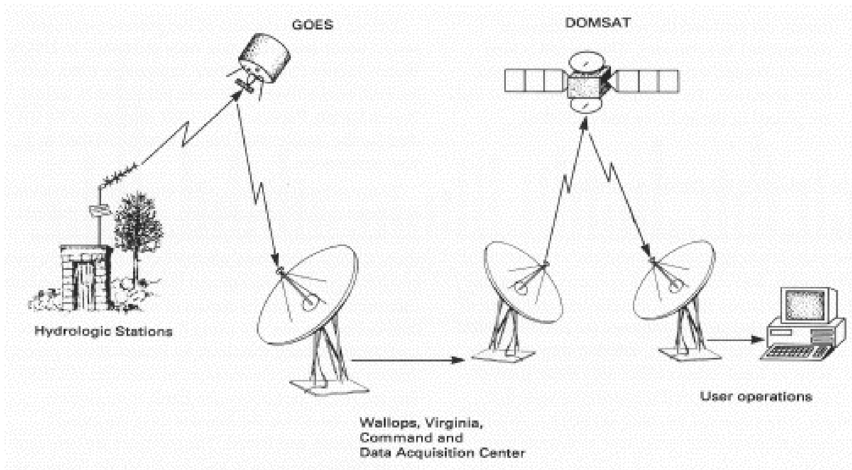


FIGURE 2-7 Most USGS gage stations transmit data on river stage in real time, using two satellite links. SOURCE: USGS (http://*md.water.usgs.gov/-publications/presentations/md-de-dc_rt98/sld025.htm*).

- *Safety*: need for technology to measure discharge quickly and remotely
- *Communications*: need for information to reach the affected public quickly, despite possible interruptions in communication lines
- *Durability*: need for gages and transmission devices to continue to function even in severe conditions
- *Water supply security*: need for information on *low-flow* conditions to provide decision makers and water managers with information to manage needs for drinking water, power generation, recreation, defense, industry, and instream habitat
- *Distribution and coverage*: need for knowledge of conditions at any time, whether measured directly or interpolated
- *Continuity*: need for long records in order to understand extreme events and assess stationarity of streamflow
- *Cost optimization*: need to optimize the balance between spatial coverage and long records, given that resources are limited

TABLE 2-1 Summary of Hydrologic Stations [a]

| | | | | | Costs | |
|---|---|---|---|---|---|---|
| | **Feature** | **Number Active** | **Percentage of Total** | **Number Inactive** | **Technology** | **Labor** |
| Data collected | Continuous stage | 7,273 | | 12,151 | | |
| | Crest stage only | [b] | | [b] | | |
| | Discrete (event) data | [b] | | [b] | | High |
| Data retrieval | By site visit | 1,260 | 17.3 | | Low | High |
| | By satellite | 6,013 | 82.7 | | High | Low |
| | By camera | 0 | 0 | | High | Low |
| Remote sensing | Ground-penetrating radar | 0 | 0 | 0 | High | |
| | Doppler | 200-300 | | | High | |

[a] The numbers of gages recording stage maxima or discrete events are not tracked because of their inherently changing nature.
[b] Data on numbers of these nonstandard measurements are not readily available. SOURCE: J. Michael Norris, USGS, written communication, March 2003.

## THE NSIP GAGING NETWORK

A discussion of streamgaging must include not just *what* is measured and *how* it is measured, but *where* it is measured. The benefits provided by gages exist only where the network covers a particular area. The loss of a gage may represent an information loss to the network, but perhaps more critically it represents a loss of coverage for certain communities or for certain gaging needs.

The USGS, faced with constraints, has designed the NSIP to provide full coverage for certain needs (e.g., interstate compacts, compliance with international water treaties, estimating major river basin outflows). The prioritization that the USGS appears to have used, even if not stated explicitly, has been not by gage but by federal gaging needs. The question has not been, Do we need this additional gage? but Do we need this kind of coverage? This question is examined more closely in Chapter 4.

If one views the gaging network as a coverage problem, locating a streamgage at a site is just one way of achieving coverage. Periodic site visits, temporary gages, statistical estimation, GIS models, or other new technologies might also achieve coverage. What is needed is coverage, not gages per se. A more detailed discussion of principles and trade-offs of streamflow network design is contained in Chapter 4.

Another aspect of the gaging network is that it is reassessed periodically. Gaging is therefore an example of adaptive management, in which the fundamental goal is to obtain coverage either directly or indirectly for the priority gaging needs.

## ROLE OF OTHER AGENCIES IN SUPPORTING STREAMGAGING

Many city, county, state, and federal agencies collect streamflow data. The primary differences between USGS networks and those of the agencies are the purposes for which data are collected. Other agencies generally collect only those data needed for a specific mission or task. For example, data collected to fulfill wastewater permitting requirements often do not include the full range of flows. These data, while vital for their own goals, are generally of limited value in addressing issues of national and regional scope (Hren et al., 1987). As a result, these data are usually not placed in accessible archives and made readily available. One possible solution would be for the USGS National Water Information System to contain pointers to sources of streamflow information other than those contained in USGS archives.

Some data collected by other agencies, however, have value beyond the specific purpose for which they were collected. Data from some stations operated by state and federal agencies are quality assured by the USGS, published in the annual state Water Data Reports series compiled by the USGS, and entered in the USGS database. In 1990, data from about 400 stations were provided to the USGS by other agencies (J. Michael Norris, USGS, written communication, 2002). In fact, the many interests served in federal programs (e.g., the Environmental Protection Agency's [EPA's] Total Maximum Daily Load [TMDL] program and the Federal Emergency Management Agency's [FEMA's] Flood Insurance Program) by the USGS streamflow information are a strong argument for federal support of the NSIP.

## STREAMFLOW NETWORK DESIGN IN OTHER COUNTRIES

It is useful, in assessing the way in which the United States gathers and disseminates streamflow information, to look at how other countries manage the collection and dissemination of this information. Examples of some of these arrangements are summarized below.

### Australia

In Australia, the responsibilities for water resource assessment and management are vested in the states under the Constitution of the Commonwealth, and state or territory governments currently fully fund these networks (Ross James, Commonwealth Bureau of Meteorology, personal communication, 2002). Only the climate and weather networks operated by the Australian Bureau of Meteorology are maintained with Commonwealth funding because meteorology is a Commonwealth responsibility. The bureau also provides a national flood warning service under collaborative arrangements with state or territory and local governments. As a result of these arrangements, the bureau does operate some stream monitoring stations. However, the state or territory and local governments operate the majority of stream stations used by the bureau's flood warning service.

Up until the mid-1980s, some Commonwealth funding was provided to the states for streamgaging networks. An attempt to identify specific stations that made up a national monitoring network for which funding would be provided resulted in Commonwealth funding support being redirected toward "project-based" initiatives rather than a national monitoring system.

Currently, Australia is in the process of completing a National Land and Water Resources Audit (*http://www.nlwra.gov.au/*), which is funded by the Commonwealth government with considerable matching support from the states and territories. The need for improved monitoring, ongoing monitoring, consistent data management standards, and improved access to data and information products has featured prominently in audit reports. These issues, and the role the Commonwealth government will play in addressing them, still have to be addressed as part of the plans for ongoing audit activities.

National streamgaging information is available on-line at the Bureau of Meteorology site as a catalog of the water quality monitoring stations operated by the state and territory water agencies. However, only descriptions of the data are provided. The observations on streamflow must be obtained from the agency operating the station.

## Canada

Canada's Hydrometric Program is carried out under formal agreements (signed in 1975) between Environment Canada and each of the provinces and Indian and Northern Affairs Canada, representing the territories under the Canada Water Act. The agreements provide for the collection of surface water quantity and sediment data on a national basis, and the costs of the program are shared according to specific interests and needs. Over the years, a number of interpretations of the agreement articles have occurred. Currently, the program operates 2,290 water-level and streamflow stations. An additional 413 stations are operated outside of the program (Table 2-2).

According to national guidelines for designating water quantity survey stations, federal stations (i.e., those funded 100 percent by the government of Canada) support programs of primary interest to Canada which include the following:

1. *Federal Departmental Programs*. These are stations required under statutory obligations that have developed in response to federal legislation and priorities and as a result of programs of various federal government departments or agencies to provide quantity information on inland waters. They include stations operated in support of specific federal works, benchmark basins, studies or investigations, and research projects and to meet navigational requirements and management responsibilities. A station may be so designated where Canada has formally accepted responsibility for continued operation of the station under an implementation agreement.

TABLE 2-2 Canada's Streamgaging Network

| Category (funding) | Number of Stations | Percentage of Active |
|---|---|---|
| Federal | 671 | 25 |
| Federal-provincial or federal-territorial | 863 | 32 |
| Provincial or territorial | 756 | 28 |
| Fully cost-recovered from other parties | 94 | 3 |
| Contributed by other organizations | 319 | 12 |
| Total active stations | 2,703 | 100 |
| Total inactive stations | 5,300 | — |

SOURCE: Environment Canada.

2. *Interprovincial Waters.* These are stations required for monitoring waters flowing across or forming part of provincial or territorial boundaries where federal responsibility has been established by an agreement or justified by an interjurisdictional concern.

3. *International Waters.* These are stations associated with federal responsibilities arising from international agreements, treaties, orders, or studies, including the following:

- Stations specifically named under the Boundary Waters Treaty and those approved officially as "international gauging stations"
- Stations specifically stipulated under International Joint Commission Orders, or required to support such orders, to provide for control of waters crossing or forming part of the international boundary and for International Joint Commission related study, surveillance, flow regulation, or apportionment purposes; such stations may also be required for similar studies carried out under unilateral or bilateral mechanisms and undertaken in anticipation of the need for formal orders
- Stations related to international treaties and agreements that involve waters crossing or forming part of the international boundary and specifically stipulate the reaches of streams required to be monitored or special arrangements that have to be made to meet water quantity survey needs
- Stations on streams flowing across or forming part of the international boundary for which Canada has determined that monitoring is required for water management purposes

4. *National Water Quantity Inventory.* These are stations that provide information for a national inventory of surface waters. They consist of those stations required to determine water quantity trends in the major drainage basins in Canada that serve to provide an assessment of the total surface water resources and to measure significant discharge to the oceans.

In many respects, the Canadian program resembles the U.S. program.

## United Kingdom

The United Kingdom maintains a network of more than 1,300 gaging stations. Responsibility for these stations rests primarily with the Environment Agency in England and Wales, the Scottish Environment Protection Agency, and in Northern Ireland, the River Agency. The data are archived by the Centre for Ecology and Hydrology with funding from the Natural Environment Research Council.

## Brazil

The federal government of Brazil provides 100 percent federal funding for 5,000 stream gages as a part of the water quantity and quality monitoring program. All hydrologic data obtained through this program are made available free of charge to all interested parties and individuals. The collection of the related meteorological data is also fully funded by the federal government, and administered by the Meteorology Institute of Brazil. However, the meteorological data are not available free of charge because the institute requires additional income to support its operations. The issue of charging for the meteorological data is subject to some debate within the Brazilian federal government.

## Germany

In Germany, three institutions or organizations that are responsible for the streamgages (H. Gerhard, 2002; Hessian Agency for the Environment and Geology, personal communication, 2002; A. Sudau, Bundesanstalt für Gewässerkunde, Referat Geodäsie, personal communication, 2002):

(1) the federation represented by the Federal Waterways and Shipping Administration,

(2) the federal states (the Länder), and

(3) regional water associations and communities (used for dams and water works).

The legal basis is the Water Management Act (*Wasserhaushaltsgesetz*). There are 260 federal streamgages in Germany that are fully funded by the German federal government. The Federal Local Waterways and Shipping Offices operate these gages. The other gages are funded either by the federal states or by contributions to the associations. All data (such as high or low waters, mean daily or yearly discharges or water levels) are published in books related to the large rivers (e.g., the Rhine River Hydrologic Yearbook).

Currently, there is a federation committee that deals with the problem of optimization of gaging station networks in Germany. However, the main task of this committee is to optimize gaging networks in coastal areas, which include tidal rivers and estuaries. The committee developed a small brochure, but it is available only in German. The committee also reviewed the literature on network design and found that the majority of literature comes from the United States and was generated during the 1970s. The review of literature is also available in German (C. Blasi, LAWA Committee for Developing Criteria Catalogue of Gauging Stations in Coastal Areas, personal communication, 2002).

In summary, the streamflow information programs in other countries show that there is recognition worldwide of the vital importance of streamflow in serving public interests. Other countries have greater streamflow information coverage, in some cases because population densities have exerted greater pressure on resources than in the United States. Yet Canada, with a lower population density, has better coverage. The Australian case is particularly interesting because the Bureau of Meteorology provides a federal link to valuable streamflow data from states and territories.

## European Environmental Agency

The design of a water resources monitoring network for the European Environmental Agency (EEA) (Nixon, 1999) identified seven different types of monitoring stations related to the type of information provided. These also correspond closely to the NSIP network design goals. In considering European Union (EU) water quality monitoring needs, the possible station types identified by the EEA:

- statutory stations to provide data for legal commitments, either regulatory, international transboundary waters, or obligations from EU directives;
- benchmark (or reference) stations to characterize catchments undisturbed by man;

- boundary stations to characterize fluxes at legal boundaries or across media;
- impact stations aimed at controlling human impacts associated with well-defined pollution sources;
- representative stations to provide summary information on larger areas with long records;
- operational stations for day-to-day management by local, regional, or national agencies; and
- research stations installed and operated during scientific projects.

Three general types of water quality monitoring stations were judged most relevant to the EEA monitoring network:

1. reference stations, supporting the analysis of natural or pristine water quality and trends across Europe;
2. flux stations; and
3. representative stations.

Additionally, two broad categories of stations were identified for inland water quantity monitoring:

1. statutory and operational monitoring to provide information for the business and operational needs of regulators, suppliers, and other users; and
2. surveillance monitoring to characterize and allow appraisal of the state of water resources and, with water quality and biodiversity information, the state of the EU water environment.

Surveillance monitoring stations include:

- reference stations that characterize undisturbed conditions;
- baseline stations that capture regional hydrology to characterize ungaged sites;
- representative Stations with long records to support regional and national assessments; and
- impact stations selected to characterize the effects of man's interference with the natural regime.

Motivated by a very different set of institutional drivers (such as EU directives), the station types identified for an EEA monitoring network are nonetheless quite similar to the goals proposed for the NSIP streamgage network. Although the EEA is not a primary collector of data, the information sought from the EEA monitoring network reflects EU member nations' need for unbiased scientific information to support assessment, management, and policy making—a need mirrored in the United States.

## VALUE OF A NATIONAL STREAMFLOW INFORMATION PROGRAM

Four areas in which streamflow information clearly has value to society are (1)optimizing hydropower and water supply, (2) reducing impacts of flooding, (3) reducing impacts of droughts, and (4) reducing pollutant loads to waterbodies. Other areas where streamflow data can have high value include national defense, food and fiber production, recreation, and wildlife habitat and diversity including Endangered Species Act requirements. The relationship of streamflow information to aquatic habitat is examined in Chapter 6. The formal definition of information gain from gaging, and how it can be valued, is addressed in Chapter 4.

### Optimizing Hydropower and Water Supply

An analysis in New South Wales, Australia, showed that the benefit of streamgaging in aggregate is about ten times the cost involved, but may be hundreds of times the cost for particular gages where water storage or flood mitigation is planned (Cloke and Cordery, 1993; Cordery and Cloke, 1992). In terms of power generation benefits on the Columbia River, long-lead streamflow forecasts allow alternative operation of reservoirs for hydropower production that result in an increase in $153 million per year in generation revenues (Hamlet et al., 2002). Streamflow data are critical for water management, allowing flow-based quantification of the dollar value of alternative uses of stream water (recreation versus municipal use versus power generation versus agriculture) (e.g., Bosch, 1991; Douglas and Taylor, 1998; Hansen and Hallam, 1991; Leones et al., 1997). Similarly, streamflow information enables the agricultural community to make economically sound decisions.

## Reducing Impacts of Flooding

Flood disasters have a devastating impact on human lives and property. The National Flood Insurance Program operated by the FEMA has the mission of mitigating flood losses through insurance payments for flood damage. As shown in Figure 2-8, the number of flood insurance policies has increased steadily through the years; the number of damage losses paid out fluctuates significantly from year to year, averaging about 40,000 losses paid out per year in recent years; and the dollar value of these losses also varies significantly from year to year, averaging about $1 billion per year in recent years.

Generally speaking, streamflow data, including data uncertainty, are necessary for rational economic decision making for flood warning (Krzysztofowicz, 1999). The USGS has the federal responsibility in the United States for streamflow measurement, and the National Weather Service (NWS) has the responsibility for streamflow forecasting. Thus, the USGS is responsible for records of historical flows, and the NWS for forecasting future flows. These two responsibilities intersect in the present, where the National Weather Service uses real-time and historical streamflow information from the USGS in its flood forecasting operations. Although the number of gages in the national streamgage network has diminished slightly in recent years to less than 7,000, Figure 2-9 shows that the proportion of gages with satellite telemetry to transmit data in real time is increasing steadily, to currently more than 6,000 gages. Streamflow information in real time is critical to flood mitigation and forecasting efforts. It is very difficult to quantify the lives or property saved by a single gage used in a flood forecasting system. Without a doubt, gages are extremely valuable, but their value is encapsulated in the operation and accuracy of the entire forecast system, the forecast delivery mechanisms, and the flood forecast response.

Besides flood forecasting, streamflow information is also used in creating FEMA floodplain maps and, thus, in protecting property from flooding through flood ordinances. Most river reaches for which flood maps are constructed do not have streamgages on them, and flood peak estimates are defined by rainfall-runoff modeling. Streamflow information is used to calibrate the rainfall-runoff model at gaged sites in the flood study region and, thus to create confidence that the flood peak estimates defined for ungaged reaches are reasonable.

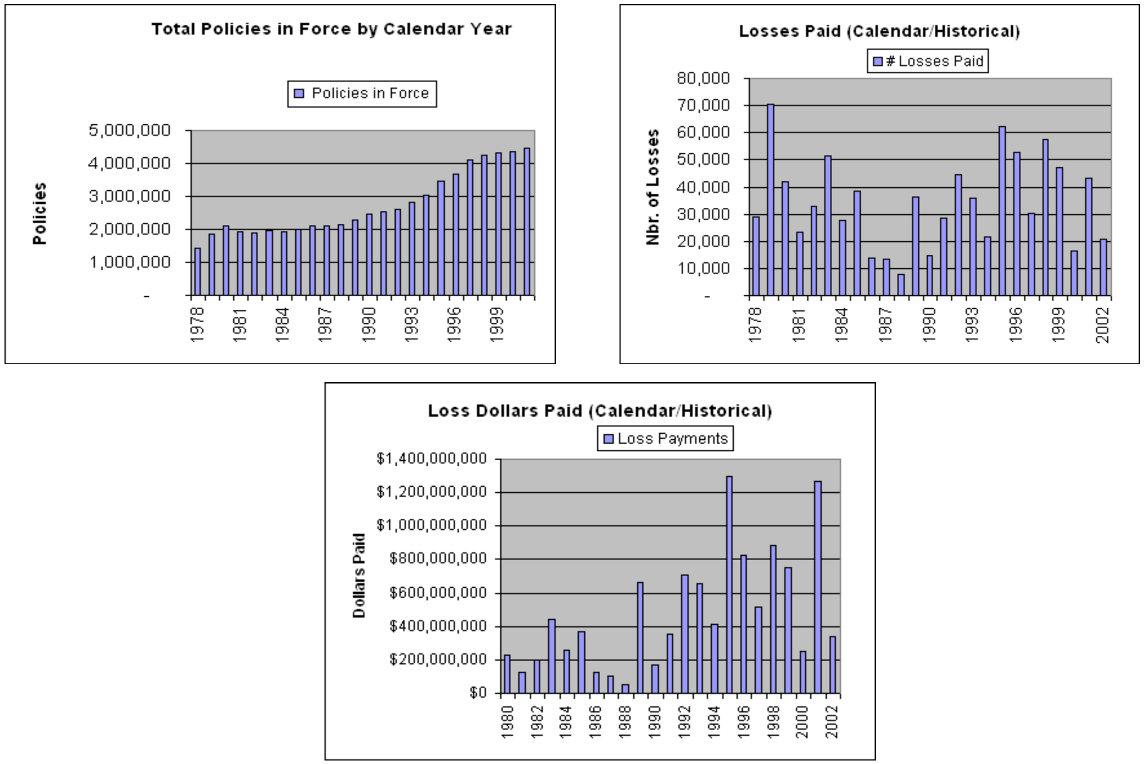


FIGURE 2-8 Trends through time in the National Flood Insurance Program. SOURCE: FEMA (2003; *http://www.fema.gov/nfip*).

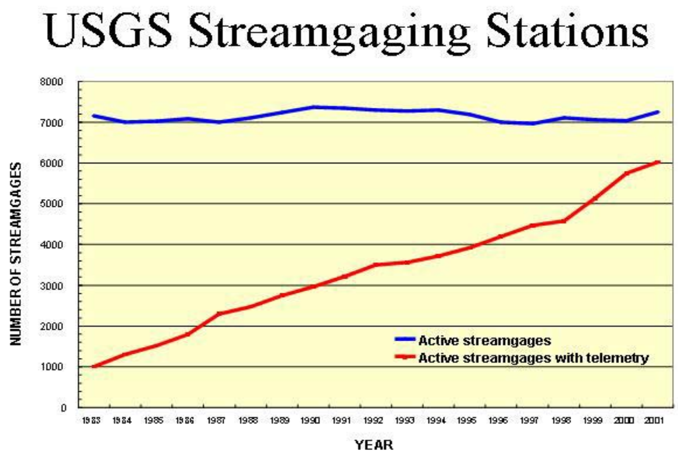


FIGURE 2-9 The total number of USGS gaging stations has changed only slightly since about 1990, but almost 90 percent of gages now have real-time data delivery, generally using satellite telemetry. SOURCE: J. Michael Norris, USGS, written communication, September 2003.

### Reducing Impacts of Droughts

Periodic droughts dominate the water supply strategies in the arid western states. For many years the only offsetting action for droughts was thought to be the construction of increased dam capacity. Water supply management during recent droughts in the western United States has strengthened the realization that more precise streamflow forecasts and predictions can partially substitute for increased structural supplies. By making better use of existing storage capacity and allowing more precise regulation of minimum streamflows to meet environmental standards, better information can substitute for structures at a substantial saving. Essentially, the management of water supplies under drought conditions requires stochastic, dynamic decision making. That is, it can be demonstrated that given a supply safety standard defined as the probability of a certain level of shortfall, the greater the variance of future stream inflows to a dam, the larger the "safety stock" must be to ensure a given supply probability. The same logic applies to meeting environmental goals that are often defined in terms of minimum streamflow levels to protect endangered species. Better monitoring of the watershed streamflow enables more precise real-time prediction of the run-off as a first indicator of the severity of a drought. In addition, past monitoring information can lead to improved predictions of changes in streamflow needs during periodic droughts.

Recent droughts in the western United States have shown that both water supply and environmental water requirements can be managed more precisely with improved predictions and forecasts. Improved forecasts of water demand enable managers to enter into contracts for water transfers that are conditional on streamflow conditions. Such contracts enable water demand to be more flexible and to adjust to fluctuations in supply while maintaining supply reliability. However, these contingent transfer contracts depend on reliable forecasts of water demands under different streamflow conditions and on the ability to accurately monitor real-time streamflow conditions during droughts.

## Reducing Pollutant Loads to Waterbodies

Water quality is also intimately linked to stream discharge and velocity, and discharge estimates are critical to accurate contaminant load estimates and pollutant reduction plans. Aside from the obvious fact that loadings are calculated as discharge times concentration, the sediment transport capacity of a river is highly dependent on velocity. In addition to sediment pollution itself, many inorganic and organic species (e.g., phosphate, heavy metals, pesticides, PCBs [polychlorinated biphenyls]) are attached to suspended clays, iron oxyhydroxides, and organic matter. As an example, USGS estimated the load of nitrogen to the Gulf of Mexico (Goolsby and Battaglin, 2000), an issue that bears on hypoxia and the loss of fisheries in the Gulf. Estimates of loads using nutrient inputs to the land (e.g., fertilizer use) were greatly improved by factoring in the stream discharge. This approach also suggested where nutrient management could most effectively be targeted (i.e., Illinois, Iowa, northern Indiana) to reduce loads to the Gulf.

Many recent environmental regulations have been promulgated as restrictions on the TMDL for a body of water or section of a stream. Total Maximum Daily Loads were established in the 1972 Clean Water Act. The TMDL is a measure of the assimilation or dilution capacity of the waterbody for a particular pollutant. Most causes of quality impairment fall into five categories: sediment and siltation, pathogens, metals, nutrients, and organic enrichment. From 1996 to 1999 there were only 300-500 TMDLs approved nationally, but approvals in recent years have ranged from 1,100 to 2,500.

TMDLs cannot be set accurately without reliable information on the characteristics of the flow in the waterbody. Clearly, the assimilative capacity of a waterbody is related to the average flow and its variability. Historical streamflow monitoring data are required to establish TMDL levels for different flow regimes and to determine when the streamflow is at the specified stages for different TMDL levels. Often, a single level or threshold is established due to a lack of detailed streamflow monitoring data. Prudence requires that single threshold TMDLs be set at levels that do not compromise the quality of the water at low-flow levels; however, these TMDL levels may have an unnecessarily high cost at other flow levels. Therefore, there is a direct inverse relationship between the precision of streamflow information and the efficiency and social cost of TMDL regulations.

## RATIONALE FOR FEDERAL SUPPORT

The rationale for the National Streamflow Information Program rests on both the value of streamflow ***information*** and the ***national*** need for this information. Streamflow information, like most goods and services, can be provided through a variety of administrative and institutional mechanisms. Many public (e.g., flood control districts) and private (e.g., power generators) entities invest in streamflow information to satisfy their specific needs and applications. Private sector streamgaging is a common value-added service offered in association with environmental assessments and site evaluations. The common provision of streamflow information by the private sector naturally requires us to consider the national interest in streamflow information: Who benefits from streamflow information? Who should bear the costs?

### Public Investment in National Streamflow Information

Streamflow information has many features of a product that is a "public good," serving the national or regional interest. Public goods are characterized by (1) the inability to exclude those who have not paid for the service, (e.g., radio broadcasts warning of floods) and (2) a zero marginal cost of servicing additional individuals. Because of these two characteristics, they are rarely provided by private enterprise. A survey of the main characteristics of and literature on public goods can be found in Kolm (1988). In his survey, Kolm stresses that the exclusion and marginal cost characteristics noted above are rarely absolute or "pure." In reality, the degree of exclusion and marginal cost extend from the pure public good, such as defense, to private goods. The defining factor is the cost of exclusion and provision. Information, in the form of streamflow data, has a low but measurable marginal cost of provision even with methods such as web page data download sites. It is clear that modern data access methods have significantly lowered the marginal cost of provision and, thus, made streamflow data and analysis more clearly a public good. In addition, Internet links and data programs have raised the cost of exclusion, further reinforcing this trend.

The optimal level of provision of streamflow data requires that public recipients reveal the benefits that they receive and that they be taxed in proportion to them. Clearly this process requires a series of "revelation mechanisms" in which a public center receives information from consumers of a public good by providing incentives for its clients to reveal information on the value of the goods; this is necessary to set efficient production levels for the information. One such mechanism is to persuade clients to establish a cost-sharing agreement for location-specific services such as flood warning systems.

In the case of streamflow information, technology can either expand or restrict access to that information. It may not, however, be possible to provide streamflow information to everyone because the cost could not be recovered by those producing the data (such as cooperating non-federal agencies).

## Equity Versus Efficiency

Public goods (e.g., the prevention of communicable diseases, the provision of sanitary water supplies) often serve societal values and preferences that motivate their production and supply based on considerations of equity, as well as economic efficiency. Market inefficiencies and market failure associated with public goods may result in distributional impacts that are not acceptable to society. The normative aspects of distributional outcomes reflect value judgments and competing interests that society resolves through the political process rather than market-driven outcomes.

The value of streamflow information may be realized and quantified in, for example, improved infrastructure design (e.g., cost-effectively sizing culverts and bridges). However, the value of this information at the time of design will be very sensitive to the period of record for which information is available. Consequently many of the future benefits and beneficiaries of streamflow information are not fully reflected in current market demand. Current individual pricing and consumption decisions in the competitive market fail to capture the future benefits of current period investment. This further motivates public investment to correct intertemporal market failure.

## SUMMARY

The USGS has a history of streamgaging that spans well over a century. Streamflow information supports innumerable planning, management, and scientific activities over a broad range of spatial and temporal scales. These include optimizing hydropower and water supply; reducing impacts of flooding; reducing impacts of droughts; reducing pollutant loads to water bodies; and providing for national defense, food and fiber production, recreation, and wildlife habitat and diversity, including Endangered Species Act requirements. For many specialized applications, the value of streamflow information is enhanced by the density of the streamflow network—that is, the whole is greater than the sum of its parts. In many applications, the direct value of streamflow can be monetized. However, streamflow information displays many of the attributes of the broad class of public goods that are not allocated efficiently through price signals between producers and consumers in competitive markets. This strongly motivates public investment to fully meet the nation's current and emerging needs for streamflow information.