5
Streamflow Information

The National Streamflow Information Program (NSIP) is more than a streamgaging program. It is a comprehensive program designed to provide high quality and accessible streamflow information suitable for multiple uses (USGS, 1999). In addition to the nationwide system of federal interest streamgaging stations for measuring streamflow and related environmental variables, the NSIP has four other components:

1. a program for intensive data collection in response to major floods and droughts;
2. a program for periodic assessments and interpretation of streamflow data to better define their statistical characteristics and trends;
3. a system for real-time streamflow information delivery to customers that includes data processing, quality assurance, archiving, and access; and
4. a program of techniques development and research.

The purpose of this chapter is to summarize and assess the activities that the U.S. Geological Survey (USGS) has initiated to address these components. It should be noted that the full scope of the various subject areas covered in this chapter is extensive. The purpose of the chapter is not to survey all work done in these fields, but rather to summarize of the various studies and techniques that were presented by the USGS to the committee during the course of its study and to comment on the value of these activities.

INTENSE DATA COLLECTION DURING FLOODS AND DROUGHTS

As described in USGS (1999), "The NSIP approach to data collection for floods and droughts will be to supplement data from streamgaging stations with systematic field surveys. Every flood and drought is unique, but a standardized approach to field work and data collection will ensure that the important aspects of each event are documented. Data collected during these events will include information about precipitation duration/frequency, river stage and discharge, and opportunistic sampling of water quality variables to include suspended sediment, nutrients, specific conductance, alkalinity, bacteria, pesticides, and hydrocarbons. Changes in the geomorphology of river channels, such as river-bank erosion location and processes, and sedimentation volumes and distribution would be documented for high- as well as low-flow conditions."

Intense Monitoring During Floods

Streamflow conditions during floods are materially different from those during normal or low flows because the stream is no longer confined within its channel and may range widely over the floodplain (Figure 5-1). It is during floods that most of the annual sediment load is transported, and because many contaminants are adhered to sediments, floods are also a significant transporter of contaminants.

A possible prototype for the study and documentation of a major hydrologic event is demonstrated in U.S. Geological Survey Circular 1120, *Floods in the Upper Mississippi River Basin* (available on-line at *http://water.usgs.gov/pubs/circ/*). This circular series, with 12 chapters published between 1993 and 1998, provided a timely synopsis and assessment of the effects of the 1993 Midwest floods. After a wet spring, widespread flooding was caused by a persistent anomalous weather pattern in the summer, which produced excessive rainfall throughout a nine-state area (Wahl et al., 1995). Unusual aspects of the flood event that were identified included the large region affected by record flooding, especially during the summer season, and the long duration of the floods (Parrett et al., 1993). Relying heavily on data gathered at USGS streamgages, as well as special data collection efforts during and after the flooding, USGS Circular 1120 documented the magnitude and frequency of peak discharges and flood volumes (Eash, 1997; Moody, 1995; Parrett et al., 1993; Southard, 1995); the effects of reservoir storage on flood peaks (Perry, 1994); water quality characteristics of floods,

FIGURE 5-1 The Willamette River Flood, 1996. SOURCE: Bonneville Power Administration (http://www.bpa.gov/Power/pl/columbia/4-gal-2.htm).

such as chemical and sediment transport and deposition (Goolsby et al., 1993; Holmes, 1996; Schalk et al., 1998; Taylor et al., 1994); and the effects of inundation on groundwater quality (Kolpin and Thurman, 1995), as well as geomorphologic changes and stream-channel scour at bridges (Jacobson and Oberg, 1997). The series is noteworthy for more than its content; its publication so soon after the floods (the first five chapters were published within six months of the event) significantly enhanced its impact on the public and the scientific community.

An important contribution of documenting the 1993 Upper Mississippi floods was its impact on the scientific study of flood processes. In particular, some of the findings challenge conventional wisdom on the role of major floods in the transport of agricultural chemicals from the landscape (Goolsby et al., 1993). Although runoff during floods transports large amounts of nutrients, herbicides, and other agricultural chemicals to rivers, flood waters are thought to dilute the chemicals, resulting in lower chemical concentrations. However, a comparison of measurements showed that herbicide concentrations during the spring and summer of 1993 were similar to the maximum concentrations observed in the spring and summer of 1991 and 1992. Furthermore, water quality measurements showed that total chemical loads to the Gulf of Mexico during the spring and summer of 1993 were significantly larger than those in 1991 (80 percent larger for atrazine and 37 percent for nitrate nitrogen) and up to several times larger than in 1992 (235 percent larger for atrazine and 112 percent larger nitrate-nitrogen). Goolsby et al. (1993) concluded that the high loads of nitrates into the Gulf of Mexico could increase phytoplankton biomass, affecting the ecosystem along the Louisiana coast.

Data collection during major floods is challenging. Ironically, it sometimes happens that streamgaging stations are washed out during peak high-flow events when their records are most needed. Furthermore, the nature of floods means that direct access to streams for measurements may be difficult or hazardous. Remote sensing may offer innovative ways of gathering information on the extent of inundation over large areas or sediment concentration and loads during major floods. For example, it is possible to use satellite remote sensing on clear days to record the extent of inundation during regional flooding, and also to use radar measurement from aircraft during both night and day to sense the extent of surface water inundation. Since radar penetrates, clouds it is feasible to operate with this technique in adverse weather conditions. It may even be possible to routinely monitor regional floods from unmanned aerial vehicles similar to the drones employed during military campaigns.

Since the extent and depth of flood inundation are the critical factors causing flood damage, remotely sensed images of flood inundation from space, coupled with an accurate terrain surface model, would allow computation of the volume of water inundation. If a regularly sequenced set of such images were obtained, and corresponding volumes calculated, data for verifying two-dimensional models of flood inundation could be obtained, and perhaps new types of flood propagation models could be developed using finite volume methods. For example, Alsdorf et al. (2000) and Alsdorf (2003) used interferometric radar measurements of water-level changes on the Amazon floodplain to calculate volume changes, from which average discharge rates could be deduced. Smith and Alsdorf (1997) similarly used decorrelation of tandem European Remote Sensing Satellite (ERS) data to map flooding changes on the Ob River in Siberia, and Mertes et al. (1993) used Landsat images to estimate suspended sediment concentrations in the Amazon River.

Intense Monitoring During Droughts

Droughts offer the opportunity to quantify the low-flow characteristics of streams and rivers. This is typically done by establishing a network of secondary and tertiary streamgaging sites and conducting regular streamgaging surveys of them (Hardison and Moss, 1972; Riggs, 1972). A secondary site is one where a gage board has been installed and periodic measurement of stage is undertaken but no continuous recorder is installed. A tertiary site is one where no stage record is maintained, but rather the site is used solely for periodic streamflow measurement by current meters, acoustic Doppler current profilers, or perhaps in the future by noncontact land-based remote sensing approaches (see "Methods Development and Research"). Temperature (Constantz et al., 2001) and electrical resistance (Blasch et al., 2002) methods using small, inexpensive, waterproof sensors with integrated data storage also show promise for inference of streamflow timing in semiarid zones, especially in ephemeral channels with unstable beds.

Droughts can affect vast contiguous areas, leading to strong spatial correlation of low flows across a region. Because of this, periodic measurements of low flows can be used to extend information from streamgages to sites that are not continuously gaged. Potter (2001) examined the use of periodic measurements at ungaged sites to transform baseflow characteristics measured at the gage into estimates for the ungaged sites. He found that with as few as two periodic measurements per year, very good estimates of annual and long-term baseflow parameters (e.g., mean, median, lower decile) could be obtained. Such an approach during major droughts might be used to estimate baseflow parameters throughout the affected area, at scales much finer than those represented by the streamgage network. This information could help in understanding the geologic controls on the spatial variability of low flows during drought conditions. In addition, periodic measurements might also be made over many years at a few selected sites. This activity could provide valuable information on the interannual to interdecadal variations in baseflow response after an extreme drought.

The hydrodynamics of surface water-groundwater interaction can change dramatically during low flow when streams that normally receive groundwater discharge lose water if the adjacent water table drops below the stream surface water level. The transition from gaining to losing conditions can lead to significant biochemical processing of nutrients in the hyporheic zone. Similarly, during low flow, a streambed that was formerly covered by water is exposed, leading to discontinuous microhabitat zones for invertebrates and other fauna and flora, much like vernal pools and wetlands in the arid West. How these temporary microhabitats affect overall stream ecosystem health is not well understood. **Therefore, targeted intensive sampling of groundwater levels, geochemistry, and stream**

morphology is needed during low flows as part of the NSIP's intensive monitoring for floods and droughts to improve understanding of these and other processes.

As the USGS intensive monitoring activities for 1993 Upper Mississippi River floods illustrate, the integration of flow and ancillary information can make significant contributions to river science for flow extremes. **Opportunities to collect, compile, and integrate ancillary information during major droughts also should be pursued.** For example, there is potential for the USGS to integrate low-flow measurements with soil moisture data from the U.S. Department of Agriculture (USDA) Soil Climate Analysis Network profiles (*http://www.wcc.nrcs.usda.gov/scan/*), AMERIFLUX long-term CO_2 flux measurement sites (*http://public.ornl.gov/ameriflux/Participants/Sites/Map/index.cfm*), and other local or state data. Such integration might even lead to tools that would assist predictive efforts on the effect of regional drought intensity on low flow.

Planning for Intensive Data Collection

The findings and conclusions of Parrett et al. (1993) after the 1993 floods on the Upper Mississippi River basin illustrate the potential contribution of intensive data collection during extreme hydrologic events to scientific study and understanding of river processes. This potential could be realized most effectively if the plans for intensive measurements were formulated to test scientific hypotheses related to flood and droughts processes. Even though it is impossible to anticipate where and when major events will occur, extensive pre-planning to identify scientific questions (requiring specific types of sampling and gathering of ancillary information to answer) and unique sites for scientific inquiry (where opportunistic measurements could be interpreted in a broader context) could significantly increase the information produced for scientific investigations.

Another consideration in the planning of data collection activities during major floods and droughts is estimation of flows at ungaged locations. There are opportunities to improve estimates of streamflow characteristics, particularly low flows, through regional analysis. **Plans for intensive data collection during major flood and drought events should be designed both to test scientific hypotheses on river processes, and to support regional analysis and estimation of streamflow information at ungaged sites.**

REGIONAL AND NATIONAL STREAMFLOW ASSESSMENTS

One of the most oft-cited reasons for having a national stream network with long-term records is the need to make assessments of streamflow characteristics across a region or the nation. Each gage by itself has an information content that increases as the record lengthens, which enables increasingly precise specification of the characteristics of streamflow at that location, such as the 100-year flood magnitude. When data from a set of gages in a region are assembled, the total information content is more than the sum of the parts, because regional patterns and coherence appear that are not visible in individual records.

Regional Flow Assessment

The use of streamgage observations from multiple sites in regional flow assessment provides valuable information for water resources decision making (NRC, 1992). The USGS is a leader in developing regional approaches to define streamflow characteristics such as the mean flow, flood peaks, or other percentiles of the flow distribution. Today, USGS districts routinely analyze observations from the streamgage network to provide regional regression equations for making flow estimates at ungaged sites. As the example in Chapter 4 for Texas (Slade, 2001) illustrates, regional flow estimation objectives are a key consideration in streamgage network design. Regional flow assessment traditionally focuses on statistical analysis of streamgage data. However, there are significant opportunities for integrating ancillary information in the study of regional flow processes. For example, the use of climate and weather data resources, as well as geographical information, can be integrated with streamflow information to examine and account for the effects of changing climate, land use, and other variables on regional flow statistics and flood frequencies.

Regional flow assessment can also contribute to a better understanding of hydrologic processes. As an example, a recent analysis of peak discharge records by O'Connor and Costa (2003) has helped to identify the factors controlling the largest floods observed in the United States. After pooling flood records at all sites and accounting for the dependence of flood discharge on drainage area, O'Connor and Costa (2004) identified the largest floods that have occurred in the United States and mapped their location. Figure 5-2 shows the location of the top 1 percent of flood peaks in the United States. The top 1 percent were found by plotting flood peaks versus drainage area; a threshold discharge curve was then used to define the top

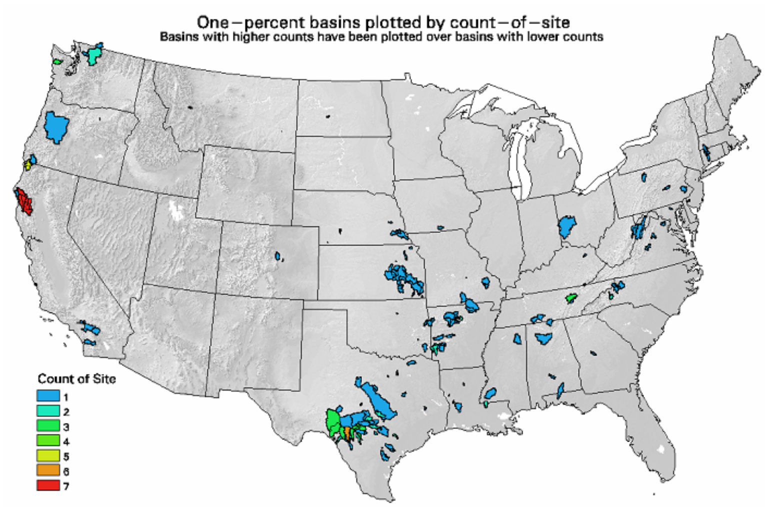

FIGURE 5-2 Drainage basins with the largest 1 percent of flood peaks recorded in the United States. SOURCE: J. Costa, USGS, written communication, March 2002.

events over the range of drainage areas. The results show that the location of the largest floods is not random throughout the United States. In fact, some basins had more than one flood among the top 1 percent. Some factors identified that make these areas prone to extreme flooding were the local topography, its interaction with atmospheric processes, and the proximity of the basin to atmospheric moisture sources. This and similar studies illustrate that regional hydrologic analysis of streamgage data has an important role in hydrologic science.

Long-Term Trends in Streamflow

One of the most important questions to be addressed in assessment of the streamflow network is, Are there long-term trends in streamflow? Such trends may be an indicator of the impact of climate change on water resources or the effects of human changes to the landscape. Using a subset of 395 streamgage records for the Hydroclimatic Data Network (HCDN), Lins and Slack (1999) examined trends in daily streamflow in the conterminous United States. The HCDN is a network constructed from existing USGS streamgages with watersheds that are relatively free of regulation, diversions, or land-use changes. Despite the popular perception that flood magnitudes are increasing, Lins and Slack (1999) found few significant trends in annual maximum flows across the United States. In contrast, significant and widespread trends were observed in lower flows, from the annual minimum to the median flow. These flows have increased across broad regions of the nation, except for the Pacific Northwest and the Southeast, where decreasing trends were observed.

In addition to the use of annual peak discharge (the annual series) (e.g., Lins and Slack, 1999), flood peaks as defined by the number of peaks above base (partial duration series) can also be valuable in flood frequency analysis and in the study of long-term trends in flooding. The two phenomena may be controlled by different processes. Traditionally, the USGS has reported both annual peak discharge and peaks above base. At present, however, these are not available on-line at the USGS web site, but they should be.

Questions regarding long-term trends in streamflow are relatively new and were probably not anticipated when USGS network streamgages were originally installed. However, with recent concerns over the potential effects of climate change on the water cycle, the availability of continuous long-term USGS streamgage records makes the study of trends possible. In addition to the study by Lins and Slack (1999), USGS streamgage records have been used to study long-term variability of monthly and annual flows throughout the United States (Chiew and McMahon, 1996; Lettenmaier et al., 1994; Lins and Michaels, 1994). These analyses have provided a valuable complement to investigations of the long-term variations in precipitation and precipitation extremes (Bradley, 1998; Karl and Knight, 1998; and Kunkel, 2003; among others). For instance, Karl and Knight (1998) observed significant, increasing trends in both precipitation and the proportion of total precipitation resulting from heavy precipitation events. The studies by Lins and Slack (1999) and others suggest that the hydrologic response to such changes has been an increase in low to moderate streamflows, but no discernible increase in flood magnitudes.

In addition to long-term trends, issues related to climatic variability and its impact on hydrology have emerged in recent decades. For instance, large-scale climate anomalies, such as the El Niño-Southern Oscillation and the Pacific Decadal Oscillation, are now known to affect streamflow variations over interannual to interdecadal time scales (e.g., Kahya and Dracup, 1993; Redmond and Koch, 1991; Sankarasubramanian and Lall, 2003). Increasingly, studies that integrate long-term streamflow and climate information are providing a hydroclimatic perspective on regional flow variations and extreme events. Examples of such investigations at the USGS include often-cited works on the impacts of large-scale climate forcing on snowmelt timing (Dettinger and Cayan, 1995) and the onset of spring (Cayan et al., 2001) in the western United States. Insights gained from hydroclimatological studies have also demonstrated the predictability of streamflow variations on a seasonal to interannual time scale, which may lead to better long-range streamflow forecasting (e.g., Hamlet and Lettenmaier, 1999). Additional studies of the linkages between streamflow, and climate and weather processes, are needed to advance scientific understanding of variations in the water cycle from local to global scales.

Overall, regional and national streamflow assessments are fundamental to NSIP and should be continued.

ENHANCED INFORMATION DELIVERY

The USGS is a leader in making its information and data easily accessible through the National Water Information System on the Internet (*http://waterdata.usgs.gov/nwis*), and these advances are especially compelling for real-time information.

Water Watch

The USGS Water Watch system (*http://water.usgs.gov/waterwatch/*) presents a map of streamflow conditions for the approximately 5000 streamgages whose data are acquired in real time (Figure 5-3). Each four hours, data are queried from the gages via the geostationary operational environmental satellites (GOES) system. For each gage and for each calendar day, the USGS has analyzed historical streamflow records to generate a percentage distribution of flow expected, and the actual flow is measured against these values to determine whether flow is above, below, or within normal flow conditions. A colored map of flow status is regenerated on the Internet every four hours with this information. Users can click on any station in this map and receive the "unit values," usually 15-minute streamflow and water-level data, for the past 30 days as a graph or as a data series. Given that it formerly took one to two years before daily mean streamflow data for gages were released, this real-time data delivery system is a great advance over past practices.

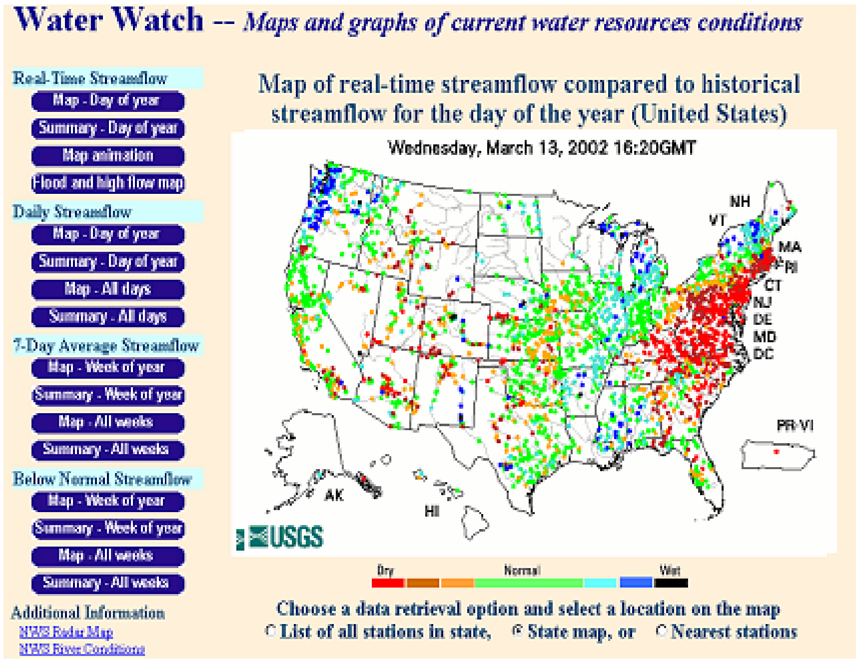

FIGURE 5-3 USGS Water Watch display for March 13, 2002, showing the regional drought in the Northeast. SOURCE: USGS (*http://water.usgs.gov/-waterwatch/*).

Real-Time Water Quality

The Kansas District of the USGS (*http://ks.water.usgs.gov*) has led the way in developing regression equations for real-time water quality display on the Internet (Christensen et al., 2000, 2002). In several streams in Kansas, the USGS measures, in real time, specific conductance, pH, water temperature, dissolved oxygen, turbidity, and total chlorophyll from sensors suspended in the water. Similar measurements are becoming routine at other water resources agencies, including publication of the observations on the Internet. However, the Kansas District work was innovative because it simultaneously collected periodic water samples and analyzed them for nutrients, bacteria, and other constituents of concern. Regression equations were then developed, and these equations were used to convert the real-time sensed variables into estimates with error bars of derived water quality variables.

This provided a continuous trace of water quality through time analogous to a streamflow hydrography. By combining estimated concentrations with flow, estimated constituent loads were also calculated, as illustrated in Figure 5-4 for fecal coliform bacteria. This is somewhat analogous to using a rating curve to convert measured water level into streamflow rate. Besides showing the estimated value, the resulting plots also show the range of uncertainty for these estimates. These data have a significant potential to inform Total Maximum Daily Load (TMDL) studies of water quality by quantifying the percentage of time that water quality standards are actually being met and the flow conditions under which they are not met. They also create an image of water quality and pollution loads varying through time with flow, which is not obtainable by viewing the results of periodic water quality sampling. By these means, water quality characterization at gage sites is placed on a continuous time basis as streamflow has been for many decades. The variability or extreme values of pollution concentration may in some cases be more critical for management than the mean concentration. For example, acidity loads to streams from abandoned underground coal mines may decrease stream pH to fish-killing levels only during low-flow conditions (Stoertz et al., 2001).

The provision of real-time water quality estimates analogous to those for streamflow is a very valuable adjunct to traditional streamflow information and, to the extent that resources permit, this capability should be expanded to other gages as quickly as possible.

Streamstats

In a pilot study initiated by the USGS Massachusetts District, a system called Streamstats has been developed to allow estimation of streamflow characteristics (mean, median, percentile values of the frequency distribution) at ungaged locations as a function of basin characteristics and regression equations (*http://ststdmamrl.er.usgs.gov/streamstats/*). When a user clicks on a desired location on the web-based map interface, Streamstats automatically determines the watershed draining to that location, applies the regression equations within the delineated watershed, and graphically displays the estimated streamflow values. This pilot study is being extended to several other states, and it is intended that Streamstats eventually will become a national system.

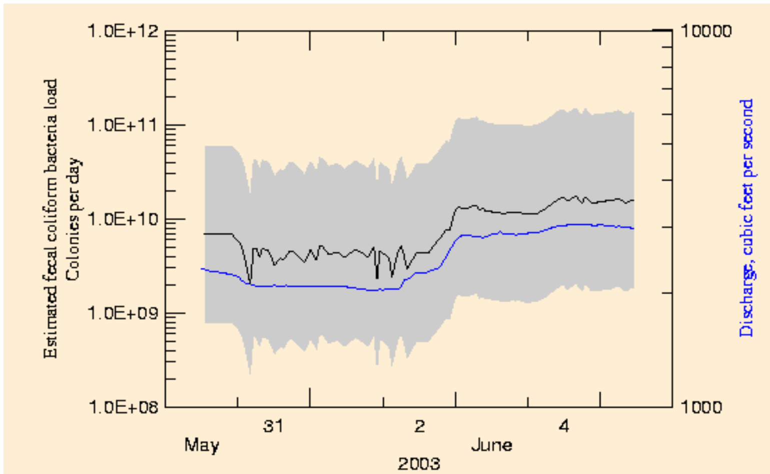

FIGURE 5-4 Estimated real-time fecal coliform bacteria load, with error bars shown, in the Kansas River at De Soto, Kansas. Discharge is shown for comparison. SOURCE: USGS (*http://ks.water.usgs.gov/Kansas/rtqw/index.shtml*).

Streamflow Information Products

Two traditional roles of the USGS have been the measurement and publication of historical daily mean streamflow data and streamflow statistics. Increasingly, provision of real-time data is occurring at streamgages through Water Watch. Also, a capacity is being developed to estimate streamflow statistics at ungaged sites with Streamstats. One can thus think about streamflow information in terms of location, such as at a streamgage or an ungaged site anywhere on the stream, and in terms on the time scale of the product, such as real-time data, daily summaries of historical observations, or statistical characteristics of the flow based on historical data. This conceptualization is illustrated in Figure 5-5, where the size of the filled circles illustrates the degree to which products are currently available at different locations. In a more complete system, shown by the open circles, a user would be able to estimate historical and real-time streamflow at ungaged locations in an analogous manner to stream statistics.

Another streamflow information product that would be useful in science and engineering applications is finer-resolution discharge observations. At present, real-time data are published as unit values, that is, for each interval within the day that the data were measured. However, only the daily

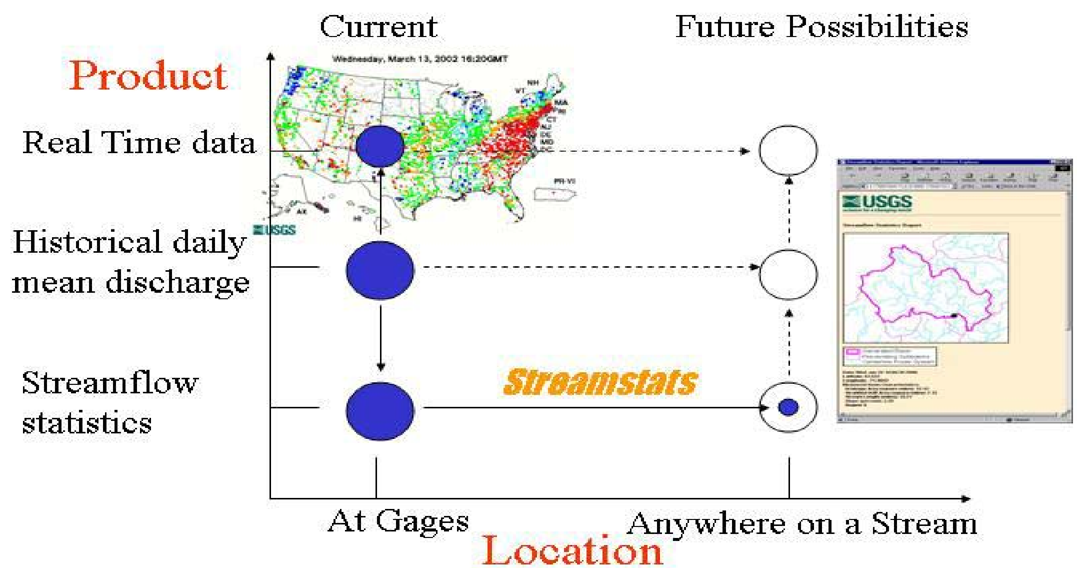

FIGURE 5-5 Streamflow information products and locations at which they are available. Filled circles represent the current capability, with the size of the circle representing the availability of data. Open circles represent future capabilities.

mean values are published as historical data in the National Water Information System (NWIS). **The USGS should develop a system for publishing the unit value data so that historical streamflow data can be obtained for intervals of less than one day.** These data would be of great value, for example in flood estimation studies on small basins where the duration of flood events is much less than one day.

Flood Inundation Simulation Using Two-Dimensional Flow Modeling

There is a significant public interest in real-time flood inundation mapping, especially if presented on the Internet or on television so that people can avoid flooded areas. Jones et al. (2002) have presented a pilot study of near-real-time flood simulation and Internet delivery of flood inundation maps in the Snoqualmie River, Washington. In this simulation, the input flows were generated by the National Weather Service River Forecast Center, and the inundation surface was generated by a flood model called TrimR2D that can reproduce backwater effects resulting in water in otherwise unflooded side channels draining into the main river. The resulting map was presented using an Internet map server. Other organizations are also working on real-time flood inundation mapping, including the Hydrologic Engineering Center (HEC) of the U.S. Army Corps of Engineers, which has created a Corps Water Management System that ingests real-time rainfall and streamflow information and computes flows, water surface elevations, and flood maps using HEC models embedded in the system.

Creating inundation maps over large stream networks requires having good measurements of the stream cross section along a river profile. Much of this information is stored in regression equations relating stream width and depth to drainage area and other variables. Currently available digital terrain data can be used to describe the inundation area in the floodplain. What is missing is sufficient detail about the geometry of the stream channel to support accurate flood inundation mapping. **The USGS should develop the capability to estimate stream channel characteristics at ungaged locations along significant rivers and streams.**

METHODS DEVELOPMENT AND RESEARCH

Methods development and research refers to advances in techniques for direct measurement of streamflow. For more than a hundred years, current meters have been the standard for making direct discharge measurements. Although a single discharge measurement can take an hour or more for large rivers, the technique is well documented (Buchanan and Somers, 1969) and accurate (Pelletier, 1988; Sauer and Meyer, 1992). In recent years, acoustic Doppler current profiler (ADCP) devices have been introduced for discharge measurements on larger rivers; all USGS districts have now been equipped with at least one of these devices. ADCP uses an immersed acoustic probe to measure velocity profiles from a floating platform on the water surface. Some advantages of using ADCPs are that measurements can be made much more rapidly than with current meters (i.e., minutes rather than an hour) and the device produces detailed information on velocity profiles, which is used directly for discharge estimation. A disadvantage of the ADCP is that it is unable to measure velocities near the water surface or the river's bed. This limitation restricts its use to relatively large rivers. There are other limitations of these conventional approaches that affect USGS streamgaging operations. For example, making measurements with current meters or ADCP requires contact with the flow. This can be hazardous to people or equipment, especially during a flood measurement.

Because of the limitations of existing measurement devices, the USGS has formed the HYDRO21 Committee to investigate and test new approaches to discharge measurement. The focus of the committee's work has been on remotely sensed, non-contact methods for gaging streams (Melcher et al., 1999). Unlike conventional techniques, current non-contact technologies are only capable of measuring surface velocities. Therefore, an assumption regarding the velocity profile, or complex hydraulic analysis, is needed to estimate discharge from surface velocity measurements. As with conventional approaches, discharge estimation also requires a measurement of the channel cross section. Promising techniques include Doppler radar and visible imagery techniques for surface velocity measurement and ground penetrating radar (GPR) and light detection and ranging (lidar) for channel bathymetry measurement.

Doppler radars send out electromagnetic pulses, which are reflected back to a sensor by periodic waves on the water's surface through a process known as Bragg scattering (Plant, 1990). The surface waves on a river are generated by wind, river turbulence, floating debris, and other processes. Both monostatic (an integrated transmitter and receiver) and bistatic (separate transmitter and receiver) sensors have been investigated. Since radars can only detect motion in the direction of the beam's path, the flow direction is assumed in order to estimate surface velocity vectors. Visible imagery techniques use digital images of the flow surface to detect surface motion. A cross-sectional technique, known as particle image velocimetry

(PIV; Adrian, 1984), is used to detect motion from image pairs. Although PIV is a standard technique for laboratory flow measurement, it has only recently been explored for measuring river flows (Creutin et al., 2003). Because it uses visible images, measurement can be made only in daylight, and there must been visible motion at the surface, from debris, eddies, or waves. GPR is used extensively to map the subsurface in geophysical applications. GPR measurement of channel bathymetry uses low frequency band wavelengths (60 to 300 MHz) to distinguish between air, water, and sediment boundaries. The radar must be suspended in close proximity to the water surface for measurement. Since a GPR signal is strongly attenuated in high sediment loads, measurements cannot be made when the turbidity is high. In contrast, lidar uses laser pulses to measure air-water-sediment boundaries. Lidar can make measurements from higher altitudes (a few hundred meters), but its resolution would average depths over relative large areas (a few square meters).

The HYDRO21 Committee has tested components of such non-contact devices in several "proof-of-concept" experiments. Spicer et al. (1997) used a GPR to measure cross sections of four streams near Mount Saint Helens, Washington. By suspending the GPR from a bridge or a cableway, they found that they could reliably create a plot of the streambed cross sections. Costa et al. (2000) combined GPR with Doppler radar to make a discharge measurement on the Skagit River, Washington. A suspended Mala Geoscience GPR measured water depths, and the University of Washington X-band Doppler radar measured surface velocities from the river's bank. Depth-averaged velocities were estimated by multiplying the surface velocity by 0.85 (assuming a parabolic velocity profile) and integrated with the cross-section information to estimate discharge. The resulting discharge estimate was remarkably similar to that based on current meter measurements (less than a 0.2 percent difference).

More recently, Melcher et al. (2002) made discharge measurements on the Cowlitz River at Castle Rock, Washington, from a helicopter using Doppler radar and GPR. The helicopter hovered 3-5 m above the water surface during the experiment, and measured surface waves induced in part by the propeller wash of the helicopter (see Figure 5-6). Depth-averaged velocities were estimated from surface velocities every 3 m across the river; the estimates were multiplied by the corresponding depths and summed across the river to obtain the discharge. The results for mean velocity and depth were within 2 percent of those obtained by a simultaneous sounding weight and current meter measurement, and the radar-estimated discharge was within 0.4 percent of the current meter discharge.

FIGURE 5-6 Helicopter experiments to measure discharge. SOURCE: John Costa, USGS, written communication, March 2002.

Other investigators have examined river discharge measurement using imagery techniques. For example, Bradley et al. (2002) used a video camera to visualize the flow seeded with tracers on Clear Creek, Iowa. Surface velocities were then estimated using particle image velocimetry (PIV) with 60 seconds of images. A hydraulic model based on kinematic principles (conservation of mass) was used to derive three-dimensional flow field for discharge estimation. The discharge estimated by this approach was within 1 percent of the current meter measurements.

The near-term goal of the HYDRO21 Committee's work has been to develop the "gaging station of the future" (Figure 5-7). For example, a future gaging station might consist of a permanently installed pulsed Doppler radar to measure velocity continuously, a GPR to make periodic measurements of channel bathymetry, and a satellite system to transmit data in real time. Still, the committee also envisions tailoring techniques to unique applications, such as those required to make intensive measurements at ungaged sites during floods and droughts. These other applications might use technologies such as video image analysis for discharge estimation or handheld radar guns for spot measurement of surface velocities, increased use of lidar for floodplain mapping or enhanced forms of lidar that can penetrate water for mapping stream bathymetry, and the remote sensing of water surfaces and areas of flow inundation using land-, aircraft-, or space-based sensors.

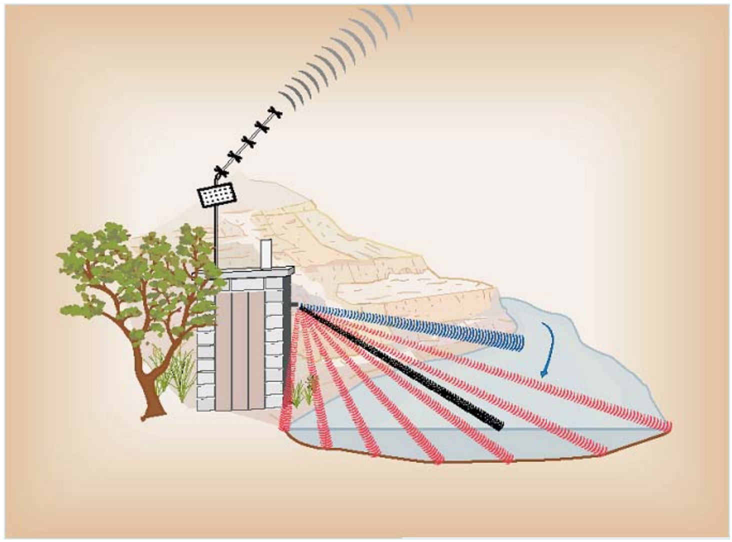

FIGURE 5-7 USGS streamgaging station of the future. SOURCE: U.S. Geological Survey (1999, p. 13).

In all of the technologies described above, a very careful evaluation of these techniques before and after they become operational is critical. The advantage of the relative lack of advancement in streamgaging technology in the last century is the consistency and comparability of data over this time. Even when a newer technique is proven superior over an older one, care must be taken to ensure that technique-based nonstationarities in the rich, long-term historical records of streamgage measurements are not created.

With due care in ensuring comparability between traditional streamgaging data and new technologies, the USGS is encouraged to continue aggressively pursuing these technologies for measurement of streamflow and related parameters with a view to accelerating the implementation of time- and labor-saving flow measurement techniques, and continuous water quality monitoring, as soon as practicable.

SUMMARY

In general, the four other components of the NSIP that complement the streamgaging network—intensive data collection during major floods and droughts, assessments of streamflow characteristics, streamflow information delivery to customers, and methods development and research—are well conceived and appropriate to the USGS. The spatial scale and risks of hydrologic extremes (e.g., floods and droughts) are areas deserving the attention that the USGS proposes in the NSIP. In particular, targeted intensive sampling of groundwater levels, geochemistry, and stream morphology are needed during low flows as part of NSIP's program of intensive monitoring for floods and droughts to improve our understanding of these and other processes. This information should be integrated with ancillary data such as soil moisture and CO_2 flux data as appropriate. Plans for intensive data collection during major floods and drought events should be designed both to test scientific hypotheses on river processes, and to support regional analysis and estimation of streamflow information at ungaged sites. The USGS should further refine its information delivery strategy to include on-line, value-added products, such as flood simulations and water supply and water quality projections under various development scenarios. The USGS should also disseminate more types of data, including historical data (requiring rescue of older paper format data), cross sections, velocity profiles, unit discharge values, and opportunistic data (e.g., crest stage data and slope-area data from flood studies). This is likely to require changes in the data management system to accommodate these various data types and formats.

Many research opportunities that should be pursued, including the following:

- Development and use of a portfolio of data collection tools in addition to the fixed, permanent stations, such as acoustic Doppler current profilers to measure stream velocity and channel resistance
- Real-time water quality estimates analogous to those for streamflow
- Measurement of streamflow at ungaged sites during high- and low-flow conditions using mobile units
- Spatial and temporal trends in streamflow, especially with respect to floods and droughts