Executive Summary

The measurement of streamflow is part of the documentation of the history of the nation. Knowledge of the flow of water in the nation's streams and rivers plays a vital role in flood protection, water supply, pollution control, and environmental management. In 1998, at the request of Congress, the U.S. Geological Survey (USGS) prepared a report entitled *A New Evaluation of the USGS Streamgaging Network* (USGS, 1998), stating that the network's ability to meet long-standing federal goals had declined because of an absolute loss of streamgages, a disproportionate loss of streamgages with a long period of record, and the declining ability of the USGS to continue operating high-priority streamgages when partners discontinue funding. That report also stated that new resource management issues and data delivery capabilities have increased the demand for streamflow information and that new technologies and methodologies have to be developed to improve the reliability of streamflow information and decrease its cost. Most importantly, this report proposed creation of the National Streamflow Information Program (NSIP).

As part of NSIP's design, the USGS established five goals to satisfy minimum national streamflow information needs (Box ES-1), and conducted an analysis to locate gage sites that meet these goals; these sites constitute NSIP's "base streamgage network." About 70 percent of the sites selected are already gaged. The USGS intends to support these gages entirely with federal funds and, in future years, to increase the percentage of these sites that are gaged. In addition to enhanced streamgaging, the USGS envisages four other components of NSIP Box ES-1). The USGS asked the National Research Council to review this proposed program (Box ES-2).

BOX ES-1
Goals and Components of the
National Streamflow Information Program

The five components of NSIP are the following:

1. An enhanced nationwide base streamgage network that would be 100 percent federally funded
2. Intense data collection during floods and droughts, and additional analysis of these data
3. Periodic regional and national assessments of streamflow characteristics
4. Enhanced information delivery
5. Methods development and research

The first of these components, the base streamgage network, is designed to meet the following goals:

1. Meet legal and treaty obligations on interstate and international waters
2. Support flow forecasting
3. Measure river basin outflows for calculating regional water balances over the nation
4. Monitor sentinel watersheds for long-term trends in natural flows
5. Measure flow for water quality needs

FEDERAL SUPPORT FOR A BASE STREAMGAGE NETWORK

Independent of the USGS's long experience in providing consistent, quality-assured streamflow data, a national streamflow information program merits federal support because streamflow information supports national interests (e.g., interstate water supply disputes) in addition to local or private interests. In fact, streamflow information has many of the properties of a public good, because everyone benefits, whether they pay or not, and benefits to additional "users" come at no additional cost. The public also values efficiency and equality of access, both of which are characteristics of this federally provided information.

The national economy is inseparably bound to the adequacy of water supplies. By mass, consumptive use of water is the single largest material flow in the U.S. economy by a factor of more than 20. The national interest in economic information on commodity flows has long been recognized and supported with federal funding. Unfortunately, much of the funding for the network comes from cost-sharing partnerships between the USGS, other federal agencies, and

BOX ES-2
Statement of Task for the
Committee on Review of the
USGS National Streamflow Information Program

The nation requires streamflow information for a variety of purposes to address local, regional, and national water-management issues. The USGS has developed a conceptual plan, the National Streamflow Information Program (NSIP), as a new approach to the acquisition and delivery of streamflow information. NSIP as proposed by the USGS includes a set of minimum national streamflow information needs that should be met by the network and design characteristics of the program.

Streamflow information also supports analysis of river science, including interaction of hydrology, geomorphology and ecology. For example, changes in land use, climate change, reservoir construction, and other factors, cause changes in streamflow through time.

Therefore, the committee will evaluate the program with respect to:

- The minimum national streamflow information needs that should be met by the network, including those related to interstate and international waters, flow forecasts, river basin outflows, sentinel watersheds, and water quality.
- The components of the NSIP plan that are reasonable, appropriate, and sufficient, including an enhanced nationwide streamgaging network with a larger share of national funding, intensive data collection during major floods and droughts, periodic regional and national assessments of streamflow characteristics, enhanced streamflow information delivery to customers, and methods development and research.
- The ways a National Streamflow Information Program should support the data and information needs of the various fields of river science, in addition to meeting its operational objectives.

state and local water resource agencies. Reliance on these agencies to support the nation's needs for streamflow information has caused troubling instability and declines in the network.

Federal support of a base streamgaging network is recommended to ensure the long-term viability of this network for national needs and is justified because many national interests are served by providing streamflow information, which has many properties of a "public good."

NSIP COMPONENT 1: THE BASE GAGE NETWORK

Program Goals

In addition to the five goals for the NSIP base gage network recommended by the USGS (Box ES-1), many others could be formulated. Indeed, the Streamgaging Task Force of the Department of Interior's Advisory Committee on Water Information discussed nine additional possible goals relating to National Flood Insurance Program communities, National Pollution Discharge Elimination System (NPDES) permits, canoeists and rafters, federal lands, reservoirs, migratory fish, navigation, and others (ICWP, 2002). However, the goals selected by the USGS are important nationally and were chosen well. The committee does not concur with the recommendation of the Interstate Council on Water Policy (ICWP) to delete the NSIP sites measuring flows at many state border sites.

Goal 2, originally conceived as supporting only National Weather Service (NWS) forecast points, should be broadened to also supporting Natural Resource Conservation Service (NRCS) forecast sites. USGS streamgages are clearly indispensable in the NWS's streamflow predictions, and this goal already dictates more than 60 percent of the sites selected for NSIP gages. However, the NRCS also forecasts flows—for water supply, drought management and response, hydroelectric and thermal power production, irrigation, and navigation in western states. These forecast sites should be added to the NSIP base gage network. A greater degree of collaboration between the USGS, NWS, and NRCS in planning and locating future gage sites and forecast points would be beneficial, especially in arid and semiarid states with growing populations, where intermittent or "flashy" streamflow creates forecasting challenges.

The five NSIP goals reflect areas of compelling national interest in streamflow information and are an appropriate foundation for the National Streamflow Information Program. The set of minimum national streamflow information needs that underlie these goals are reasonable and appropriate. The national distribution of NSIP base gage sites is also reasonable.

Streamgage Network Design Methods

The question of where to sample (gage) streamflow to estimate streamflow at any point of interest is a central one for hydrologic data collection agencies worldwide. One traditional approach relies on statistical methods,

including correlation of flows at pairs of gages, regression analyses to estimate flow characteristics, entropy analysis, and other approaches. Statistical methods can be effective for assessing the information content of existing streamgage records for limited goals. However, the nation's need for streamflow information is extraordinarily diverse and dynamic, and is not readily reduced to a small number of information metrics. Further, these methods assume hydrologic homogeneity throughout the study area—a poor assumption for a national network.

The approach the USGS has taken with NSIP is to generate a "coverage" model in which a goal or set of goals is established (Box ES-1) and a set of gage sites is selected using a performance metric to evaluate national coverage for each of these goals. The coverage model treats gage network design as a facility location problem—an approach that has not been widely used in the design of streamgage networks. However, coverage models are used in many other fields, such as locating fire stations so that each household is within five minutes of a fire station. The addition or omission of a particular goal corresponds to the addition or omission of a specific set of gage site locations. The coverage method provides "yes or no" answers about where gage sites should be located, regardless of whether gaging has been done there previously.

It is conceptually appealing to think of streamgage network design by assigning a "value" to individual gages and then optimizing the value or utility of the entire network. However, the list of factors that could be used to value information for individual gages is long and diverse and incorporates inherently noncommensurate uses (e.g., real-time reservoir operation and scientific evaluation of regional water balances). The value of information cannot be quantified independently from the decision-making process in which that information will be used. Moreover, weighting and combining estimated information value (e.g., property loss versus loss of life) inherently engenders local and regional (not just national) preferences and values.

Within the larger context of coverage, methods such as statistical modeling based on hydrologic regionalization and estimating the value of individual gages can be useful. They can guide incremental decisions to add or eliminate individual gages within a local or regional network serving narrow, well-defined goals by, for example, ranking gages in order of their marginal regional information content. In contrast, the breadth of both the national goals and the hydroclimatic variation spanned by the NSIP network cannot meaningfully be reduced to a concise set of valuation measures. Therefore, the most appropriate role of these methods for NSIP is supporting the analysis of incremental refinements to local and regional hydrologic networks within the broader context of the NSIP network design.

The method of designing the NSIP base gage network by establishing national goals and then using geographic information system (GIS) based methods to select sites to provide national coverage of these goals is reasonable. This is an effective use of geospatial information and analysis, and provides an innovative new method for streamgage network design. Statistical methods should only be used to justify incremental decisions to add or eliminate individual gages within a local gage network serving narrow, well-defined goals.

NSIP COMPONENT 2: INTENSE DATA COLLECTION DURING FLOODS AND DROUGHTS

The opportunistic collection of hydrologic, climatologic, geomorphic, and biological data during extreme events is a high-return, cost-effective activity, well suited to both the mission and the expertise of USGS. The value of this information is high, especially when the protocols are integrated with continuous improvement in techniques. Such protocols and measurement techniques have to address the unique challenges in monitoring flow extremes, which are usually outside the range of direct measurements used to establish flow rating curves and are often poorly measured by conventional techniques. The USGS's outstanding studies of the 1993 Mississippi River provide compelling models for integrated interdisciplinary study of extreme events, integrating expertise in water resources, channel and floodplain morphology, sediment transport, hyporheic processes, and ecosystem response.

Such data collection and analysis is a strength of the USGS and should be continued.

NSIP COMPONENT 3: PERIODIC REGIONAL AND NATIONAL ASSESSMENTSOF STREAMFLOW CHARACTERISTICS

The essential role of water in the U.S. economy, along with growing demands and policy conflicts, creates a vital national interest in consistent, objective, regional and national assessments of the nation's water resources. The information content of the whole streamflow network is more than the sum of the parts. Regional and national assessment is an integrating lens that can bring a sharpened focus to data collection and information generation within NSIP. However, the national interest is not well served

by the current paradigm in which interpretive studies are supported mainly by cooperators. Assessment raises significant political and scientific challenges, including evaluating risks to and reliability of the nation's water resources; accounting for irrigation return flows, in-stream uses, and surface water-groundwater interactions; integrating economic and social dimensions of water use; projecting hydroclimatic variability; and addressing a host of issues at the intersection of natural, engineered, and human systems.

Such studies are fundamental to NSIP and should be continued.

NSIP COMPONENT 4: ENHANCED INFORMATION DELIVERY

The revolution in information technology is changing old paradigms regarding the access, storage, and generation of information—including streamflow information. The steady increase in data telemetry and near-real-time data delivery on the Internet has vastly expanded the awareness and utility of national streamgaging data. The USGS is committed to reengineering its data delivery paradigms, despite the variability in funding for core programs. Users are unequivocally enthusiastic about the new modes of information delivery. Notwithstanding these successes, even richer opportunities exist to enhance the content, value, and national benefits gained from streamflow information.

Streamflow information that most users see consists of tabular discharge measurements derived from "unit values," that is, stage measurements at points in space and time, for example, each 15 minutes. Presently, the USGS displays these unit values on the Internet as part of its real-time streamflow information system, but limits the publication of historical streamflow data to daily values. Significant information content is lost in this process, particularly for studies of floods on small watersheds, where the whole flood may come and go within a few hours. Publication of unit value data for the historical streamflow records would be a significant information delivery enhancement.

Streamflow data can support a far richer interpretation if combined with geospatial information, as indeed the USGS has done in designing the NSIP base gage network. Streamgaging points can be associated with information about the stream network (e.g., network topology codified in the National Hydrography Dataset) and its associated subbasin, the geomorphic and hydraulic features of the stream channel, floodplain characteristics, and other landscape attributes.

Since a streamgaging site has a subwatershed just upstream of it, whose drainage passes through that gage site before reaching any other site, the selection of a set of gage site locations can be associated with a map or dataset of subwatersheds draining to those sites. The effect of associating a dataset of subwatersheds with a set of selected gage sites is to more intimately connect the land and water systems of the nation. This is important because it provides a mechanism for using geospatial information to generalize measured streamflow to ungaged locations where information is needed, such as at the boundaries of Total Maximum Daily Load (TMDL) segments for water quality management or at the upstream ends of reaches for Federal Emergency Management Agency floodplain map delineation. In this manner, streamflow measurement and associated geospatial interpolation of flows can support streamflow information estimates at any location on the stream network of the nation. At present, through its Streamstats program, the USGS is developing the technology to support estimating streamflow statistics at any location on the stream network. This approach also might usefully be applied to geospatial interpolation of flow records to ungaged locations where streamflow information is desired.

Supporting this rich interpretation requires an enhanced data delivery system capable of handling a diverse data mixture including tabular data, geospatial data (GIS layers), remotely sensed images, and multidimensional data fields such as stream velocities. An enhanced data delivery system should also explore emerging modes of data delivery, such as direct satellite delivery and radio-frequency "push" technology, to transmit streaming information (e.g., for the NWS). Users could then tailor this information to their needs (e.g., streamflow characteristics at ungaged points, estimating channel characteristics for Hydrologic Engineering Center (HEC) modeling, flood inundation simulations).

Enhanced data delivery is an important and highly valued component of NSIP. The USGS should provide access to a broader range of geospatially linked data (unit values, channel cross sections, remotely sensed images, velocity fields, stream network position, and landscape attributes) to enable richer data interpretation than is presently done.

NSIP COMPONENT 5: METHODS DEVELOPMENT AND RESEARCH

The USGS is investigating new methods for measurement of streamflow and water quality. These include the use of radar for surface water

velocity and water depth measurement, and the deployment of acoustic Doppler profilers for measurement of the cross-sectional distribution of velocity. The intent is to create the "gaging station of the future" wherein the measurements of flow, cross-sectional bed profile, and velocity are accomplished and recorded continuously. Another goal is the rapid reconnaissance of flow at ungaged locations during floods.

Water quality parameters such as conductivity, temperature, pH, dissolved oxygen, turbidity, and total chlorophyll are being sensed continuously and connected by regression equations to provide estimates of nutrients, bacteria, and other constituents of concern continuously through time. This effort places water quality measurement in the same mode as streamflow measurement and is a very significant enhancement over spot sampling of water quality constituents at periodic intervals. For example, for TMDL studies, this approach may illuminate under what flow conditions and at what times the water quality standards supporting reasonable water use are not being met and, thus, provide guidance for closer attainment of these standards.

Advances in techniques for remote sensing and analysis of information are accelerating. Besides the techniques just mentioned, video image analysis and new forms of LIDAR (light detection and ranging) show promise of providing significant improvements in streamflow and streambed measurement.

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

In addition to evaluating the goals and components of the NSIP, several broader issues related to the program were examined. These included the overall role of the NSIP as an information program, the integration of the principles of adaptive management into such a program, and the potential for the NSIP to contribute to the USGS's future work in "river science" (i.e., integrated research involving all of the major disciplines at the USGS).

NSIP AS AN INFORMATION NETWORK

The historical specialization of the streamgage program has fostered a cultural separation of data collection and data use. Conceived and struc-

tured as a national information program, the NSIP embodies the broader vision required to meet the nation's needs in the twenty-first century. It is important to highlight the difference between the need for data from data collection points where streamflow or some other property is measured, and the need for information, with corresponding information points for which streamflow information is desired and generated from available data. The locations identified as sites for NSIP gages represent a well-defined set of locations where streamflow information would clearly support the five goals. However, locating a permanent streamflow gaging station at every point is not necessarily the best way to meet the information needs. In many applications the need for information may be satisfied with intermittent or remotely sensed measurements or with regionalized analytical approaches that do not require direct measurement. The benefit of such approaches will be realized as expanding populations identify new locations at which streamflow information is needed. This goal is valued by the public and is an appropriate task within the scope of the NSIP.

The ultimate goal of the NSIP should be to develop the ability to generate streamflow information (with quantitative confidence limits) at any location, gaged or ungaged, on the stream network.

ADAPTIVE MANAGEMENT

Although the five goals (Box ES-1) reflect compelling areas of national interest, the USGS's role as the nation's source of unbiased streamflow information creates unique streamflow information demands. In contrast to an individual user whose streamflow information needs are driven by well-defined operational needs (e.g., hydropower production, flood warning), the USGS has the added responsibility to develop streamflow information to satisfy the future needs of the nation. For example, the Hydro-Climatic Data Network, which allows national analysis of the trends in streamflow (the integrator of climate, topography, geology, and land use), is a "discovered" streamgage network, serendipitously maintained within the national network through the cumulative effect of unrelated decisions to maintain gaging at these sites. When gaging was initiated at many of the sites with 50- to 100-year records, detection of trends in climate change was an unimagined use of streamgage data.

The USGS's role requires forethought to provide the basic data collection and information that the nation will need decades from now. These needs, which may be most valuable to future users of streamflow information, typically have the least support from cooperators who currently sup-

port much of the network. The application across the nation of a single set of rules for locating gages may not adequately ensure streamflow information coverage in all situations. For example, the committee's analysis shows that NSIP sites are sparsely located in Nevada, to some extent because many of Nevada's streams are ephemeral. It may occur that in the future, streamflow information from ephemeral streams has greater value than is presently perceived, as more people move west to states such as Nevada.

The principle of adaptive management should be incorporated explicitly into the NSIP program to periodically reevaluate the network to ensure that it meets anticipated future needs for streamflow information.

NSIP SUPPORT FOR RIVER SCIENCE

An understanding of the integrated hydrologic, geomorphic, and biological processes in rivers—here termed "river science"—is a prerequisite for effectively managing rivers for navigation, water supply, power generation, or ecological functions. As an example, the closure of Glen Canyon dam on the Colorado River in 1963 changed the magnitude, timing, and temperature of streamflow and reduced sediment inputs into the Grand Canyon segment of the Colorado River. This has impacted the number and sizes of sandbars that are used by river runners and form the habitat for native fish. The 1996 controlled flood released from Glen Canyon dam was an experimental effort to rebuild sandbars and evaluate the potential for controlled flooding as a management tool. The effectiveness of such management has to rest on the scientific understanding gleaned from river science. With the recent addition of the biological resources discipline to the water resources, geologic, and geographic disciplines, the NSIP can be an important contributor to river science at the USGS.

River science is intimately concerned with flow regime, sediment transport, and channel morphology and integrates information on streamflow, water quality, sediment load, and biota from headwaters to mouth. This requires the characterization of river systems continuously in space, not just at gaging stations, and would benefit greatly from a more comprehensive NSIP data delivery system, focusing on streambed, sediment, and velocity distributions, as well as the discharge itself. Data of relevance to river science should also be rescued from historical files and made available on the Internet; these include crest stage data, slope-area data from flood studies, gaging station channel geometry, and bed sediment characteristics.

The USGS should identify watersheds for which good hydrologic information is available and land-use changes are documented. These sites should be prime sites where hydrograph information is retrieved and stored to better understand how changes in land use affect hydrologic characteristics. These issues are also being examined at experimental watersheds operated by other federal agencies, such at the U.S. Forest Service and the Agricultural Research Service. Close coordination with the efforts of these agencies and the academic communities that work at these sites is desirable.

With the addition of channel morphology data, sentinel (and other) watersheds can provide not only hydrologic reference points for the nation but stream morphology reference points as well. The representativeness of sentinel watersheds for characterizing the hydrologic and geomorphic diversity of the nation in support of river science should be explicitly evaluated.