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Summary and Conclusions

The National Streamflow Information Program (NSIP) has been formulated by the U.S. Geological Survey (USGS) to create a stable, federally funded *base network* of streamgages and to enhance the information derived from this network with 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 USGS has proposed that the base network of streamgages meet five minimum federal streamflow information goals, namely, (1) interstate and international agreements, (2) flow forecasts, (3) river basin outflows, (4) long-term monitoring using benchmark (sentinel) watersheds, and (5) water quality. This report examines the goals and method by which the base gage network sites were selected, the rationale for the supporting elements of the NSIP, and the role of streamflow information in advancing river science.

The USGS is the nation's unquestioned leader in the conduct of streamgaging, and its national repository of streamflow information has in recent years been made much more accessible to the public through an exemplary program of information publication on the Internet. Overall, the committee concludes that the National Streamflow Information Program is a sound, well-conceived program that meets the nation's needs for streamflow measurement, interpretation, and information delivery.

The nation needs streamflow information to address water management issues related to irrigation, flood warning, public water supply, waterpower generation, water conservation, industrial water supply, chemical loading, recreation, and biological health of rivers. For more than a century, the USGS has met this task by developing and maintaining the national streamgaging program, and by publishing the resulting data. Also, USGS research has enhanced the understanding of river processes through the publication of thousands of documents on the state and behavior of the nation's waterways. This research rests on the foundation of a network of gages and a large body of water quality and river sediment data.

RATIONALE FOR FEDERAL SUPPORT OF A NATIONAL NETWORK

A strong federal role in the streamgaging network is important in view of the growing stress on water resources arising from population expansion and movement into water-short and flood-prone areas. In the words of one federal flood forecaster, "[USGS streamgages] are everything; without them we are dead in the water" (Gary McDevitt, National Weather Service [NWS] River Forecast Center, Chanhassen Minn., oral communication, 2002). Therefore, there should be national support for a base network of permanent gages. However, the USGS, in collaboration with the NWS, needs to communicate better that streamflow information creates public value, for example, by saving lives and preventing economic losses through flood forecasting.

A federal agency logically fills the role of providing streamflow information because such information supports national interests, not just 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 federally provided information. National interests are served by the provision of impartial, legally accepted information for arbitration of interstate water supply disputes. Streamflow information is also essential for state and local water supply management, and consequently many USGS gages are partly funded by local cooperators.

The streamgaging network, however, has had to contend with unstable and discontinuous funding support. Gages have been inactivated when cooperators cut budgets, and these incremental losses have eroded the network. Many inactivated gages had long records that are valuable for trend analysis and forecasting. It is practically impossible to quantify the cost of losing an individual gage. Its value even for one goal—for example, flood or drought forecasting—is embedded in the operation and accuracy of the entire forecast system, the forecast delivery mechanisms, and the forecast response. It is the integrity of the system as a whole that must be safeguarded.

Federal support of the base network would help provide stability and continuity to the network. Federal support of part of the network does not, however, imply the sufficiency of the overall network, which will always rely heavily on cooperators to help meet national goals for stream data.

THE BASE GAGE NETWORK

There are about 7,300 USGS-operated streamgages presently recording continuous stage and flow data. Not all of these would be federally funded base gages in the NSIP. Only 5,293 gage sites are listed under the five NSIP criteria, and since some sites serve more than one criterion, the actual number of sites presently identified as NSIP base gages is 4,424. Further, about 1,300 of these sites are not active: about 800 are inactive and 500 would be new. Of the remaining 3,100 or so currently active gages, the NSIP base gage network includes 2,800 gages that the USGS presently operates and 300 gages that other agencies operate and for which, under a fully funded NSIP, the USGS would assume the operational costs.

One concludes that the majority of the 7,300 USGS-operated streamgages will not form part of the base gage network. This does not mean that they are not fulfilling important purposes, but simply that those purposes may be primarily local in scale or otherwise not of highest national priority as defined by the five federal goals noted above. Regardless, all active USGS streamgages are considered to be part of the overall NSIP network.

In the following sections, each stated NSIP goal for the base gage network and the number of gage sites designated to meet that goal are examined in turn.

NSIP Goal 1: Meeting Legal and Treaty Obligations on Interstate and International Waters

The USGS designates 515 gage sites to provide streamflow information supporting legal compacts (185 gages) or to gage flow near where a stream crosses a state or international border if the upstream drainage area exceeds 500 square miles (330 gages). An examination of the NSIP base gage network was also conducted by the Interstate Council on Water Policy (ICWP, 2002). It concluded that there is not a compelling federal need for providing streamflow information at state and international borders with no legal compacts.

The committee does not concur with this view and believes that the USGS should proceed with the NSIP gage sites at their planned locations. Water-use permitting and data collection practices vary greatly from state to state. USGS streamflow data have been critical in cases of interstate disputes, especially during drought. As competition for water increases over time, further interstate conflict over water use will likely arise. Resolving such disputes will rest on a foundation of long-term streamflow information, and it will be too late once the conflict emerges to begin to collect such information.

NSIP Goal 2: Flow Forecasting

The USGS has designated 3,244 gage sites as part of the base network to support the flow forecasting mission of the National Weather Service. This number is 73 percent of the 4,424 NSIP base gage network sites, so it is clear that this goal dominates numerically among the five NSIP site selection goals. The USGS and the NWS have complementary roles with respect to streamflow information: the USGS does streamflow measurement and the NWS does flood forecasting. Thus, the USGS deals with past and present (real-time) streamflow information, and the NWS focuses on the near-term future. The NWS operates hydrologic models whose forecast points at watershed outlets are located wherever possible at USGS streamgage sites. As part of the flow forecasting goal, the USGS intends to provide streamgaging data at all NWS forecast points. The NWS hydrologic models also forecast flow "data points," which are the outlets of other watersheds used in the hydrologic model. Many of these points are also located at USGS gage sites so as to allow for forecast model calibration. Thus, USGS gage information is crucial to the NWS flood forecasting mission. With nationwide losses due to flooding averaging on the order of $1 billion per year in recent years, this goal is well justified as a criterion for NSIP gage selection.

The U.S. Department of Agriculture (USDA) National Resource Conservation Service (NRCS) also has a forecasting mission in the western states for estimating water supply over the coming months. This mission involves 576 forecast sites, of which 321 are already included in the NSIP base gage network. Since the NSIP mission is to support flow forecasting, as distinct from just flood forecasting, the NRCS forecast sites should also be included in the NSIP base gage network. This would add 255 new sites to the 3,244 sites presently attributed to the flow forecasting goal, an increase of 8 percent. A joint task force of the three agencies is needed to prioritize the addition of gages at the flow forecasting sites.

NSIP Goal 3: Measuring River Basin Outflows

The USGS designates 450 gages to measure discharge from major watersheds. Streamgaging sites are designated near the outflow of each of the nation's 352 Hydrologic Accounting Units (six-digit hydrologic unit code basins). Adequate coverage will allow the USGS to calculate regional water balances over the nation. Federally supported, long-term gages provide the continuity needed to calculate present and forecast future river basin outflows. River basin outflows over different time scales are the integrated response of the entire hydrologic system within the basins. Knowing how outflows are affected by changes in climate and landcover will lead to better forecasting and contribute to a better understanding of regional differences in hydrologic systems. Stream basins are inherently "nested," with large basins encompassing smaller ones. Knowing how and why outflows change per unit area from small-size to large-size basins will lead to better extrapolation of extreme floods and low flows. Overall, the breadth of ongoing and potential applications of a sound understanding of the hydrologic response of basins throughout the country justifies the inclusion of this goal as a selection criterion for the NSIP.

NSIP Goal 4: Monitoring Sentinel Watersheds

Sentinel watersheds are those watersheds chosen to represent the hydrologic diversity in the nation's landscape. The USGS designates 874 gage sites to meet this goal. The criteria for selecting sentinel watersheds are watershed size and representation of ecoregions. Watersheds with regulated (e.g., dammed) streams are avoided, and preference is given to watersheds that have been minimally influenced by human activities, thereby allowing tracking of long-term trends. Sentinel watersheds, which may also serve other roles, provide important information to meet long-term national needs for monitoring and science. In particular, long-term streamflow records in sentinel watersheds provide the benchmark data needed to assess hydrologic, ecologic, and water quality changes in similar, more numerous, watersheds with substantial anthropogenic landscape changes and thereby improve watershed management and planning. Given the interplay between hydrology and geomorphology, collecting channel morphological data in the sentinel watersheds would increase their scientific value—the sentinel watersheds could serve not only as hydrologic reference sites, but also as morphologic reference sites.

NSIP Goal 5: Measuring Flow for Water Quality

Water quality is closely tied to a stream's discharge, which dictates the concentration and flux of pollutants. High discharges may dilute pollutants; low discharges may concentrate them. On the other hand, pollutant loads (e.g., from agricultural or urban runoff) may increase under high-flow conditions. Proper interpretation of water quality data requires knowledge of stream discharge. The USGS designates 210 gage sites to provide streamflow information for a national network of water quality (concentration and loading) monitoring points. This streamflow information is matched to three national water quality networks: Hydrologic Benchmark (HBM) (63 stations), National Stream Water Quality Accounting Network (NASQAN) (40 stations), and National Water Quality Assessment Low-Intensity Phase (NAWQA-LIP) (107 stations).

The NSIP also supports other water-quality needs. For example, the Total Maximum Daily Load (TMDL) program of the Environmental Protection Agency (EPA) requires estimates of flow to determine chemical loads and transport. However, additional gaging to quantify the inflow to every one of the thousands of impaired water segments included in the TMDL program would be overwhelming in cost and manpower. There is a pressing need to be able to spatially interpolate streamflow time series from gaged locations to any point on the river network. Advances in geospatial information processing, used by the USGS in the NSIP site selection process, can be adapted for this purpose, as the USGS is doing in its Streamstats program for estimating streamflow statistics at ungaged locations. The USGS is well positioned in terms of expertise to do this research.

Distribution of Gage Site Locations

In general, the distribution of gages by state across the nation produced by the NSIP criteria appears reasonable when measured on metrics of number of gages per unit of land area and number of persons per gage. A possible exception is Nevada, where the committee's analysis of the NSIP base gage network found a surprisingly small number of gage sites (30) relative to neighboring states—Arizona (85), Utah (111), Idaho (95), and Oregon (136).

This anomaly arises in part because the NWS has only 10 forecast points in Nevada, compared to an average of 74 in the four neighboring states. It also arises because many of the border gages between Nevada and adjacent states are located in the adjacent state rather than in Nevada, and because Nevada has only a small number of ecological zones, so there are fewer sentinel watershed gages than would otherwise be the case. If NRCS forecast sites are added to the flow forecasting goal, this would add 17 sites in Nevada for a total of 47 NSIP sites, which is less anomalous.

Nevada is the nation's driest state, so the low number of NSIP sites may also arise because many of the state's streams are ephemeral. The hydrologic characteristics of ephemeral streams throughout much of the greater southwestern United States are sparsely measured, and the NSIP should incorporate a strategy to begin evaluating this large hydrologic landscape through the sentinel gage program. A single set of rules for siting NSIP base gage sites across the country may in some regions have to be adapted to allow for special hydrologic conditions not experienced everywhere.

Base Gage Network Design Methods

The five proposed NSIP goals in the design of a *national* streamflow information base network are sound. With the possible exception of Nevada, the geographic distribution of gages produced by these NSIP goals appears reasonable when states are compared using metrics such as number of gages per unit of land area or number of persons per gage.

The USGS has developed an innovative method for selecting sites for the NSIP base gage network using geospatial analysis of the national stream network, drainage areas, ecological zones, and gage sites where other functions are performed, such as forecasting floods or systematic collection of water quality data. Historically, gage networks have most often been analyzed statistically, so the move to a geospatial analysis of gage sites is a significant departure from past practice in this field, but one that is in harmony with the advancement of geospatial information availability and analysis capabilities. There is a duality between the selection of sites in a network, and the delineation of subwatersheds draining to those sites, that defines the *coverage* of the NSIP base gage network.

Coverage models have been used in other site selection processes, such as the locations of fire stations within a city, where each fire station is associated with its service area. An advantage of the coverage approach to streamgage network design is that it identifies where gages should be located, rather than being limited to consideration of where they are located now. By creating national NSIP subwatershed dataset maps for each criterion using the proposed and active gage sites, the USGS can assess the completeness of coverage. When new gages are to be installed from the

NSIP site set, consideration can be given to the impact of site choice on the NSIP subwatershed dataset.

Statistical methods for stream network design are useful for ranking gages in order of their regional information content, as illustrated in this report by review of a statistically based streamgage network analysis for Texas. Statistical rankings help to identify which inactive gage sites should be activated first when additional funds to support NSIP gages become available, with the goal of maximizing the value of streamflow information while minimizing cost.

A new research initiative to regionalize streamflow characteristics is recommended, with the goal of being able to estimate streamflow time series and stream channel characteristics at any location on a stream or river in the United States with a quantitative estimate of uncertainty. Regionalization methods will significantly increase streamflow information coverage of the nation.

OTHER NSIP COMPONENTS

Besides enhancing the base gage network, the NSIP has four other components dealing with intensive data collection during major floods and droughts, assessments of streamflow characteristics, streamflow information delivery to customers, and methods development and research. These appropriate activities continue the USGS tradition of striving to improve the coverage, access, and quality of streamflow information.

In general, the strong efforts that the USGS has made to transform the National Streamflow Information Program from a "streamgaging program" to an integrated effort in which *information* products of various kinds are available when and where the user wants them are commendable. Likewise, the USGS's ongoing development of new ways of employing advanced technology to improve measurement and information delivery deserve credit.

The spatial scale and risks of hydrologic extremes (e.g., floods and droughts) are research areas deserving of the attention that the USGS proposes in the NSIP. The hydrologic system organizes itself spatially and dynamically such that the most extreme events are organized over the largest spatial and temporal scales. This task recognizes that the regional information content of the network is greater than the sum of the information from individual stations.

The USGS should further refine its information delivery strategy. If the NSIP goal is saving life and property as well as promoting prosperity and well-being, delivery of information is at least as important as data analysis.

This would include on-line, value-added products such as flood simulations and water supply and water quality projections under various development scenarios.

The USGS should 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). These data are essential to document channel changes, evaluate stream hydrographs, calculate hydraulic parameters, examine climate change, and infer certain hydroecological relationships. An NSIP data management system must be developed to accommodate various types and formats of data that support river science. A system for publishing the unit value data will allow users to obtain historical streamflow data for intervals of less than one day.

Streamgages are nodes in the streamgaging network, so the accuracy of information provided by the network rests on the quality and type of information provided by the gages themselves. Gages are traditionally viewed as stationary points gathering data in a method similar to that of 150 years ago. The USGS is attempting to develop the "gaging station of the future." There are many research opportunities for advancement over current methods:

- Develop and use a portfolio of data collection tools in addition to the fixed, permanent stations. This would include phasing in new technologies such as acoustic Doppler current profilers to measure stream velocity and channel resistance; making the data widely available to foster research outside USGS on the relationships among channel morphology, velocity, and flow resistance in channels; and providing real-time information delivery at critical stations through satellite links.
- Provide real-time water quality estimates analogous to those for streamflow. This is a very valuable adjunct to traditional streamflow information and, to the extent that resources permit, this capability should be expanded to other gages. Gages in areas prone to flash flooding should be equipped with critical-stage alarms or web cameras to alert the public and resource managers of impending hazards.
- Measure streamflow at ungaged sites during high- and low-flow conditions using mobile units to respond to events as they occur. These additional data also will assist in regionalizing streamflow characteristics.

The NSIP program will lead to advancements in all of these areas, and if due care is taken to ensure comparability between traditional streamgaging data and those of new technologies, these areas of research should be pursued.

ADAPTIVE MANAGEMENT

Overall the five components of the NSIP plan are well conceived and form strongly complementary program elements. Active integrated management and coordination will result in an information program that will generate value to the nation far greater than the sum of its parts. Nevertheless, information needs and technologies evolve rapidly and dynamically, and will continue to do so. This requires continuous improvement and coordination to maximize the value of the national investment in streamflow information. No single solution will meet all of the nation's needs for streamflow information or remain the best choice in the face of changing demands. The combination of dynamically changing demands with future uncertainty strongly suggests the need to develop, integrate, and use formal adaptive management techniques as an integral part of the NSIP. Adaptive management not only identifies goals and program components (as does the NSIP plan), but also identifies expected outcomes that can be described with meaningful performance measures. These provide a benchmark against which management decisions may be consistently revisited and reevaluated relative to a more stable and clearly articulated set of goals and expected outcomes.

For example, one way to site gages is to identify point locations at which streamflow information would be useful—locating one continuous streamgage at each such point. The ICWP thereby identified the need for more than 18,000 gages. However, some of these information needs (e.g., for National Flood Insurance Program communities or Impaired Water Quality Reaches) can be satisfied (with some difference in the quality of information) with other techniques such as regionalization. The overarching goal for the NSIP should be to provide streamflow information (with quantitative confidence limits) at any arbitrary point on the landscape. The streamgage network must be sufficient to support this goal.

Adaptive management would identify the information need, determine the mode of information generation and delivery (e.g. gaging, spot measurements, indirect methods, hydrologic estimation) in order to achieve performance criteria, and later evaluate the expected and actual performance to determine whether modification is needed. It would help balance the multiple attributes of information—quality, reproducibility, resilience to extremes, and cost objective—and align resources to outcomes (not just activities). Implementation of adaptive management will generate performance information about the NSIP that will be essential to evaluate and incrementally improve the program in the future.

In addition, the USGS should consider how the public, the scientific community, and water management agencies will be included in the adaptive management of this national network. At present, much of the public input on prioritizing streamflow gaging comes in the form of having paying state and local customers through the Cooperative Water (Coop) Program. If the NSIP fully funds its base network independent of cost matching, other mechanisms for public consultation at various levels (e.g., an advisory board, surveys) will have to be found.

In summary, adaptive management and periodic systematic reevaluation should be an integral part of the program from its inception.

RIVER SCIENCE

The USGS has a long history of research on rivers. Pressing issues such as streamflow losses to groundwater pumping, nonpoint source pollution loads, and aquatic and riparian ecosystem degradation make a compelling case for developing river science. Streamflow information is a critical component supporting river science.

Streamflow information should be collected to promote an integrated, process-based understanding of hydrologic-geomorphic-biological linkages. Stream gradient, bed material size, and sediment transport should all be measured at more locations where discharge and stage are measured. Such data are needed for sediment and hydrologic routing models. The temporal and spatial characteristics of this material routing are of central importance to understanding many key ecological processes that influence ecosystem resilience and provide ecosystem goods and services.

Theoretical and empirical models are needed to estimate streamflow and channel characteristics *at any location* on the principal streams or rivers of the nation. Process-based models extend the value of streamflow data and support the generation of streamflow information throughout the watershed system.

To determine what data are most valuable, the USGS should engage the broader scientific community to seek input into what data it should be collecting for the development of river science. Since groundwater and surface water are two components of a fully integrated hydrologic system, appropriate data should be collected to understand aquifer-stream interactions.

In order to improve planning and assess the ecological and geomorphic consequences of land-use changes, the USGS should identify watersheds for which good hydrologic information is available and where land-use changes are documented. This information will improve understanding of how changes in land use affect hydrologic characteristics.