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Streamflow Network Design

The question of where to site streamgages and how long to maintain them at these sites is a central one for hydrologic data collection agencies throughout the world. Many approaches have been used to design and maintain data collection networks. In the past, network design approaches at the U.S. Geological (USGS) and elsewhere have relied largely on statistical methods, most commonly based on the standard error in estimating regional discharge at ungaged sites. Although statistical procedures offer numerical precision for network design supporting regional hydrologic estimation, these approaches do not support the many other goals and uses of site-specific streamflow data. In contrast, coverage models are based on articulating a goal, defining a measure of success ("metric") or procedure that identifies locations supporting that goal, and applying this procedure using geographic information system (GIS) analysis to yield a set of potential sites (e.g., for gages). One advantage of this approach is that it yields discrete yes or no answers about site locations for each goal considered.

This chapter considers and contrasts these approaches to network design and maintenance. The proposed National Streamflow Information Program (NSIP) gage network is considered in this broader context, including comparisons with state-level hydrologic networks, and the evaluation of other reviews of the NSIP. The chapter concludes with a vision of the NSIP as a national information program with the broad goal of providing streamflow information with confidence limits at any arbitrary point in the landscape.

STATISTICAL MODELS

The most common network design methods have been based on statistics. During the 1970s and 1980s, the USGS developed and applied statistical regression techniques to locate gages (Moss, 1982; Stedinger and Tasker, 1985; Tasker, 1986). More recently, other investigators have used entropy methods and other statistical concepts to quantify relative information content (Bueso et al., 1998; Lee, 1998; Mogheir and Singh, 2002; Perez-Abreu and Rodriguez, 1996). These studies invoked the strong assumption that streamflow observations (and therefore climate and land use) are stationary. For the narrow, well-defined problems of hydrologic regionalization and the estimation of specific flow quantiles (such as the 100-year flood) at ungaged sites, the information content of additional streamflow observations can be quantified by the decreasing standard error of the estimate.

Network Design

Considerable research has been done on the design of monitoring networks in the earth sciences. Perhaps most common are networks designed to use observations at discrete points in space and time to estimate the characteristics of a continuous field or flux (Bastin et al., 1984; Bras and Rodriguez-Iturbe, 1976; Pardo-Igúzquiza, 1998; Rodriguez-Iturbe and Megia, 1974; Sampson and Guttorp, 1992). If the spatial and temporal structure of the variable of interest (e.g., precipitation, evaporation) is well known, its value at any arbitrary location within the network can be estimated using this approach (Boer et al., 2002; Zidek et al., 2000). Geophysical networks can similarly be designed to estimate the position and magnitude of seismic events (Havskov et al., 1992) or to optimize the sensitivity and probability with which movements of the earth's crust can be detected. In contrast to these networks, streamgages are located only on the streams themselves, rather than throughout the entire catchment. Measurement nodes in the stream network provide estimates of fluxes or concentrations of particulate and dissolved constituents. Streamgage networks may be driven by the need for information at a specific location, such as concentrations or fluxes where a river enters a waterbody or crosses an in-ternational boundary, or a critical flood warning site. For these needs the gage site is fixed.

For other applications, the site at which streamflow information is needed is characterized only by the properties of the contributing upstream drainage area. For example, evaluation of hydrologic and ecological effects of land conversion from forest to agricultural use requires streamflow measurements from watersheds experiencing these land-use changes. Many different candidate sites can satisfy this type of information need, expanding the flexibility (and complexity) in designing a streamgage network. An important class of management problems requires streamflow data from gages that sample "representative" locations, to support regional modeling, estimation, and trend detection.

Information theory offers a formal approach to network design by quantifying the marginal contribution of each data collection node to the overall information provided by a network. This incremental value can be formally measured in probability terms by the "cross-entropy" of an event on the preexisting probabilities. Shannon (1948) showed that a "measure of how much 'choice' is involved in the selection of the event or of how uncertain we are of the outcome" (*H*) must have (which relates to its information content) would be proportional to -ln (p), where p is the prior probability of the event happening.

Shannon (1948) also extended the definition from single probabilities to discrete distributions and defined the expected information content of a prior distribution $\Sigma_i\, p_i$ as the entropy of a distribution:

$$H = - \Sigma_i\, p_i \;\ln p_i. \qquad (1)$$

It follows that a uniform distribution, in which each event is equally likely, has the highest entropy and the lowest information content. Conversely, a distribution that puts a weight of 1 on a single outcome and zero on the rest has an entropy of zero and the highest information content.

The concept of cross-entropy (*CE*) as a measure of incremental information gain was extended by Kullback and Liebler (1951) and defined as

$$\mathrm{CE} = - \Sigma_i\, p_i \;\ln (p_i/q_i); \qquad (2)$$

where q_i is the set of prior probabilities that are held by the decision maker.

The importance of this theory to streamflow information is that it follows from equation (2) that if the new signals (e.g., for stage or discharge) coming from a monitoring system (p_i) (e.g., a gage) are close to those expected from the prior probability (q_i) generated from past streamflow observations, then ln (p_i/q_i) tends to zero and very little information has been added to the system. The converse, of course, is also true. For more theory, see Cover and Thomas' (1991) *Elements of Information Theory*.

In the narrow context of hydrologic regionalization, quantifying incremental information in this way can support the formulation of a formal network design problem to maximize the trade-off between network information content and network cost. In contrast, the breadth of both the national NSIP goals and the hydroclimatic variation spanned by the NSIP network is not meaningfully reduced to a simple set of statistical measures. Thus, the most appropriate role for 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. Within this formality, distinct variations of this decision problem have been described and applied in network reduction, network expansion, and network refinement.

Network Reduction

Commonly, an existing network must be evaluated to determine which gages to discontinue when the network must be reduced (Boer et al. 2002; Oehlert 1996), for example, due to budget cuts. The USGS has abundant experience with this problem. "This network reduction" decision problem involves minimizing the information loss associated with discontinuing gages, subject to a constraint on the number of gages to be discontinued (a surrogate for the total cost reduction that must be achieved). In this case, records from each of the gages in the network provide observational data that can be used to quantify the information loss associated with eliminating each gage based on testable assumptions of regional homogeneity and stationarity. Monte Carlo experiments can be used to rigorously quantify this information loss over specific statistical measures, such as the change in the standard error of regionalized estimates of discharge quantiles (e.g., the 100-year flood).

Network Expansion

The complementary decision problem involves maximizing the information increase associated with adding gages to an existing network. Though similar, the network expansion problem requires an estimate of the information content to be gained from previously ungaged candidate sites. As in the case of network reduction, the accuracy of this estimate depends on understanding how the value of the variable of interest changes as a function of its position in the stream network, location in the landscape, topographical position, and other watershed attributes. The accuracy of this estimate (which determines the performance of the enhanced network) is based on assumptions of regional homogeneity and stationarity (i.e., invariance of the underlying random processes with respect to time) within the network (Haas, 1992). Unlike the case of network reduction, for network expansion this assumption is less easily tested, since observations are obviously not yet available at new gage locations.

Network Refinement

A third variation of the network design problem involves adding new gages to a network when neither the candidate locations nor the number of gages to be added has been decided a priori. Such is commonly the case in designing a network of groundwater monitoring wells where the location of the wells (e.g., relative to the estimated position of a contaminant plume) and the number of wells to be added are both decision variables. This problem similarly requires an indirect estimate of the information contributed by each new well derived from an underlying structural model of the currently unobserved system. For the NSIP network design, candidate gage locations are effectively unlimited.

The most general problem with respect to deciding to remove or add new NSIP gages combines all three decision problems in which an existing monitoring network is to be improved through the combination of adding gages, discontinuing gages, and locating new gages. All of these approaches require continuous, well-defined information metrics that can be expressed as a function of the number and/or location of gages. In well-defined networks with limited objectives, statistical approaches for network design can be used to evaluate incremental decisions to add or eliminate individual gages within a local gage network serving narrow, well-defined goals, such as estimating flows at ungaged sites. An example of such an application is given in the following section.

Example of a Statistical Network Design: Texas

Statistical approaches to design regional streamgage networks are exemplified by a recent study to assess the state streamgage network (Slade et al., 2001) conducted by the Texas District of the USGS and the Texas Water Development Board. The goals for the Texas streamgage network were the following:

- *Regionalization*—estimate flows or flow characteristics at ungaged sites in 11 hydrologic regions of Texas

- *Major flow*—obtain flow rates and volumes in large streams
- *Outflow from the state*—account for streamflow leaving the state
- *Streamflow conditions assessment*—assess current conditions with regard to long-term data and define temporal trends in flow

As shown in Figure 4-1, in 1996, Texas had 329 streamflow of which 312 stations were continuous flow recorders and 17 were peak flow stations. The number of continuous flow recorders reached a maximum of about 420 gages in 1972 and declined thereafter. The NSIP goal for Texas is 416 gages, a number that was actually exceeded for about five years in the 1970s. The downward trend in streamgages for Texas during the 1980s and 1990s is not representative of the national picture, where the number of active streamgages has remained fairly stable over the last two decades (Figure 2-9) despite some erosion in recent years. The growth in the number of gages through the 1950s and 1960s in Texas was due in part to the extensive surface water development—including reservoir construction—carried out at that time.

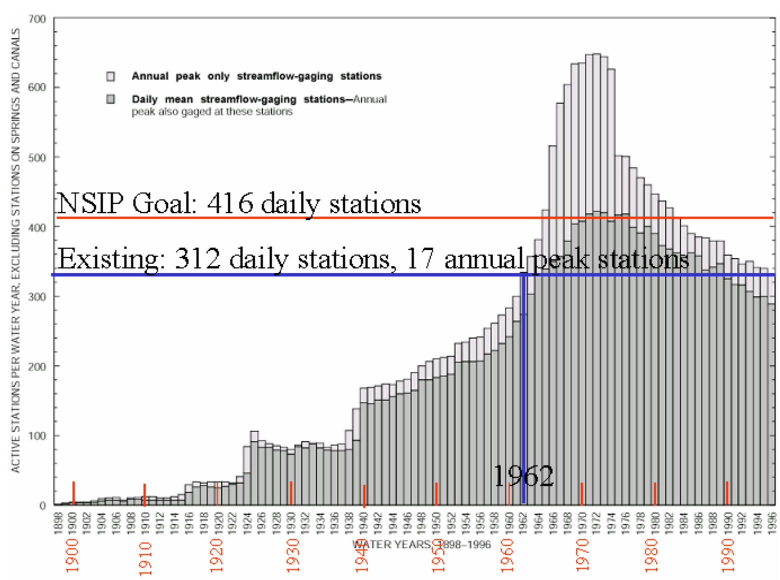

FIGURE 4-1 Trends in streamflow measurement in Texas. SOURCE: Underlying graph from Slade et al. (2001).

Slade et al. (2001) developed a regional optimization model for each of 11 hydrologic regions in Texas (Figure 4-2) using generalized least-squares regression to separate error due to the regression model from error due to a finite sample size. This model estimated mean annual flow and 25-year peak flow using basin characteristics as explanatory variables in multivariate regression equations for each region. Three planning horizons were considered (5 year, 10 year, and 25 year), and active and discontinued stations in natural (i.e., relatively undisturbed) watersheds were considered. In each region, the analysis began with all candidate stations included and then stepped backwards, eliminating the least informative station at each step.

A typical result is shown in Figure 4-3 for estimation of the peak 25-year flow in three hydrologic regions in East Texas. The sampling error was relatively insensitive to the number of stations in the estimation set until this number dropped below about 20 stations, at which point the sampling error started to increase significantly. This figure also shows that as the planning horizon (length of streamgage record) increases from 5 to 10 to 25 years, the sampling error decreases correspondingly. Slade et al. (2001) concluded that

- stations on the steepest part of the curve offered the most valuable regional hydrologic information relative to basin characteristics;
- sampling error increased to the west where the climate is more arid:
  - — sampling error for mean annual flow was 6.6 to 114.3%, and
  - — sampling error for 25-year peak flow was 9.9 to 28.5%;
- there was greater variability in error between regions than was introdcued by changing the number of stations within a region; and
- there was much less error in regression equations for the 25-year peak flow than for the mean annual flow in arid regions.

Besides the regional regression analysis, Slade et al. (2001) analyzed the correlation among paired stations upstream and downstream of one another on the same river (Figure 4-4). They found the expected strong correlations in flows for upstream and downstream stations on the same river, especially for the mean annual flow:

- 61 of 81 station pairs analyzed for mean annual flow had correlation coefficients > 0.9; and
- 43 of 129 station pairs analyzed for 25-year flow had correlation coefficients > 0.9.

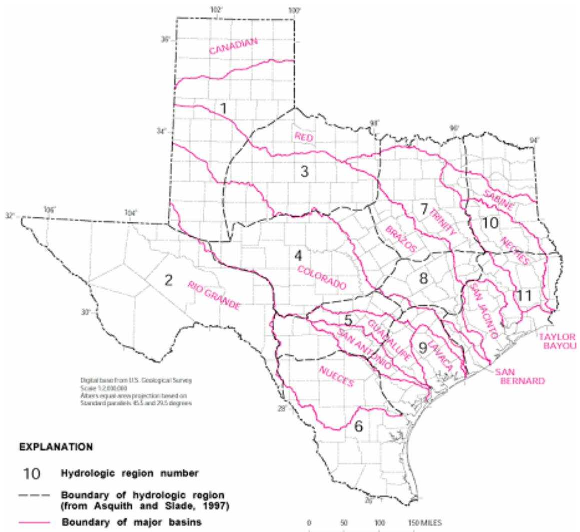

FIGURE 4-2 Hydrologic regions of Texas. SOURCE: Slade et al. (2001).

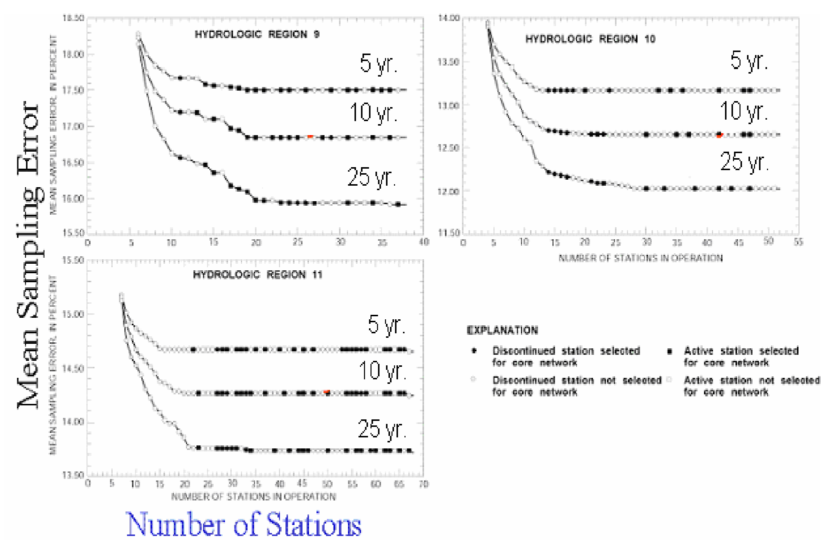

FIGURE 4-3 Sampling error for planning horizons of 5, 10, and 25 years for 25-year peak flow as a function of number of available stations in a hydrologic region. SOURCE: Slade et al. (2001).

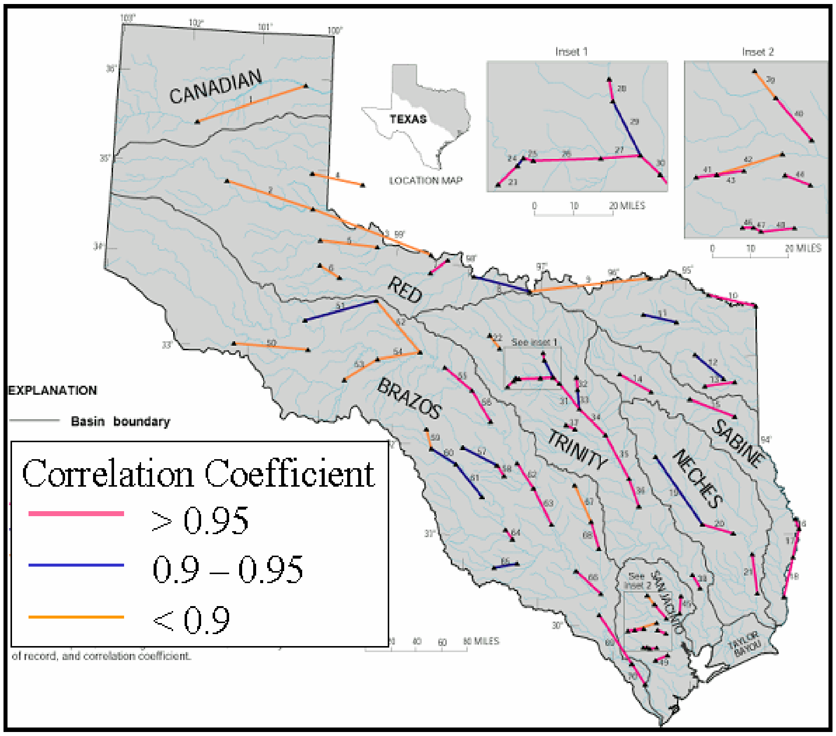

FIGURE 4-4 Correlations of mean annual flow among pairs of stations on the same river. SOURCE: Slade et al. (2001).

As a result, Slade et al. (2001) decided to select stations for a core network that were not highly correlated with other selected stations. The study concluded that Texas needs a core network of 263 stations for regional hydrology purposes on natural watersheds (not including many gages on rivers with large upstream diversions). This number can be contrasted with the NSIP network for Texas, which specifies 416 gage locations. The two numbers, however, are not directly comparable because the statistical study applies to gages in natural watersheds while the NSIP study applies to all watersheds.

This study illustrates both the strengths and the limitations of the statistical approach to network design. The method is rigorous and reproducible, and yields quantitative results about the degree of uncertainty of particular quantiles for a given gage network. The gage sites can thereby be arranged in an unambiguous rank ordering from highest to lowest information content. This helps identify the relative value of each gage for hydrologic regionalization. However, one important limitation of statistical methods is the decoupling of performance metrics used to evaluate network performance from the possibly unrelated purposes for which the gages were installed in the first place. That is, a gage may serve a critical purpose for water management or flood forecasting even if it is not one of the gages most useful for estimating regional hydrologic information at ungaged sites. Although statistical methods can quantify trade-offs between information and cost, such as those in Figure 4-3, these trade-offs (and the value of any particular gage network) change with different design objectives. For example, the "optimal" network to support regional estimation of mean annual discharge (Q_1) and the 25-year discharge (Q_{25}) may differ substantially from the "optimal" network supporting regionalized estimation of 7-day, 10-year low flow ($_7Q_{10}$). More generally, regionalized estimation of a specific set of discharge quantiles (Q_1, Q_{25}, $_7Q_{10}$) represents only a small subset of the data generated and information derived from a streamgage network.

Perhaps more significant to the design of a national network, statistical network design methods are most applicable to homogeneous hydrologic regions within which regionalized estimates may be derived. Statistical methods typically assume that the basin response, land use, and climate remain the same over time and may suggest configurations very different from networks designed to detect trends or interventions (Schumacher and Zidek, 1993).

Finally, from a management perspective, statistical methods always yield a "gray" answer rather than a black or white answer as to whether a gage is needed or not. Some gages have more information content, others have less, but it is difficult to know how much information content is enough to justify the existence of a gage.

Statistical methods for stream network design should be used to justify incremental decisions to add or eliminate individual gages within a local gage network serving narrow, well-defined goals (such as hydrologic regionalization). In contrast, the breadth of both the national goals and the hydroclimatic variation spanned by the NSIP network is not meaningfully reduced to a concise set of statistical measures. Thus, the most appropriate role of these methods for the NSIP is supporting the analysis of incremental refinements to local and regional hydrologic networks, within the broader context of NSIP network design.

COVERAGE MODELS

The design of a steamgage network has much in common with a rich family of facility location problems (Drezner, 1995; Drezner and Hamacher, 2002). These include the siting of facilities for fire protection (Schilling et al., 1980; Swersey, 1994), ambulances and hospitals (Branas et al., 2000), vehicle emission test stations (Swersey and Thakur, 1995), hazardous facilities (Kleindorfer and Kunreuther, 1994), oil-spill response centers (Alidi, 1993), and "hubs" (Campbell et al., 2002) for air passengers and cargo transport (Serra et al., 1992).

The concept of a coverage model is best explained by example. Rainfall varies continuously over space, but it can be directly measured only at discrete points (Figure 4-5). Recently, the National Weather Service located a series of weather radar (NEXRAD) sites to estimate this rainfall distribution. Figure 4-6 shows the distribution of NEXRAD radar stations in the 48 conterminous states; each radar provides "coverage" over a range of approximately 200 km, recognizing that the quality of radar coverage degrades with distance. Within an operational definition of "acceptable" coverage, there is a binary aspect to this model in that either an area is covered or it is not. By siting radars so that at least two and preferably three coverages overlap, the National Weather Service (NWS) can observe rainstorms from several angles and estimate the precipitation rate from radar.

Subregions Within Coverage Models

As consequence of defining a coverage model, sampling at discrete locations subdivides a spatial domain into subregions; each subregion is explicitly associated with its respective measurement point. This is typically the case for computing mean areal rainfall from point measurements at raingages, in which Thiessen polygons drawn around the raingage locations are used to estimate watershed average rainfall using an areally weighted average of the raingage values (Figure 4-7). When streamgages are located in a stream network, the watershed draining to that streamgage can analogously be delineated; a unique subarea associated with each gage defines the land area whose drainage flows past that gage before it reaches any other gage (Figure 4-8). This subwatershed is the coverage area associated with that streamgage. Any set of points on a stream network can be used to subdivide a watershed into subwatersheds. Figure 4-9 shows several subwatershed divisions of the Guadalupe basin in Texas for flooding, water quality, and water supply. The upper right panel in this diagram shows

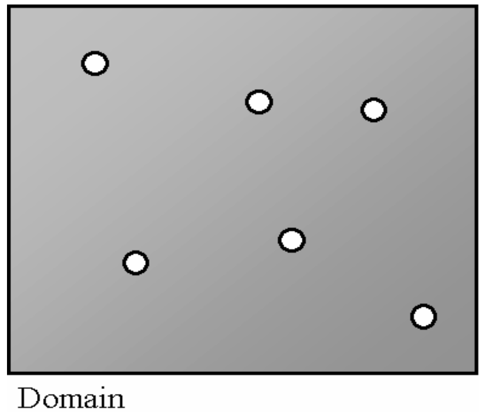

FIGURE 4-5 Coverage of a continuous spatial phenomenon by measurements at points.

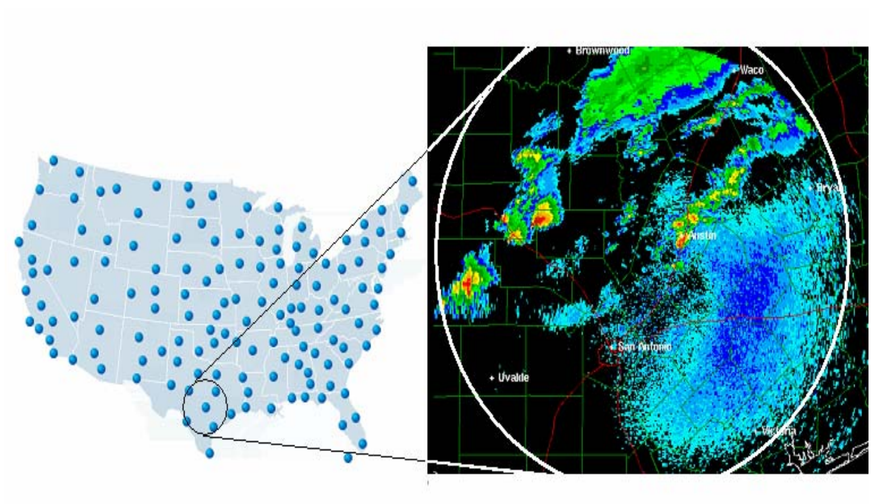

FIGURE 4-6 NEXRAD radar rainfall locations and coverage of radar station KEWX, Austin-San Antonio, Texas. SOURCE: *http://weather.noaa.gov/radar/national.html*.

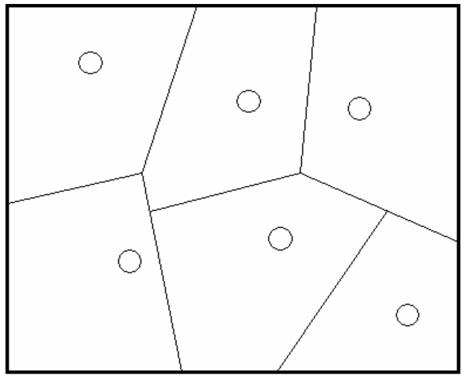

FIGURE 4-7 Spatial subdivision of a region using Thiessen polygons.

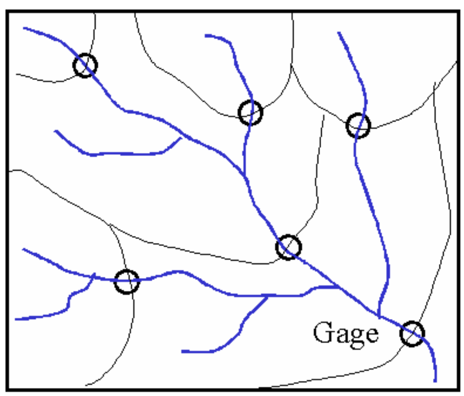

FIGURE 4-8 Spatial subdivision of a region using subwatersheds of streamgages.

the subdivision of the watershed using the NWS river forecast watersheds in which the watershed outlet is an NWS forecast point or data point. The lower right panel shows the subdivision used for the U.S. Environmental Protection Agency's (EPA's) Total Maximum Daily Load (TMDL) studies, where water quality management segments are defined on the principal reaches of the Guadalupe River, and the subwatersheds are the areas draining to these segments. The lower left panel shows the subwatersheds defined for water availability modeling in which the outlet of each subwatershed is a point at which the Texas Commission for Environmental Quality

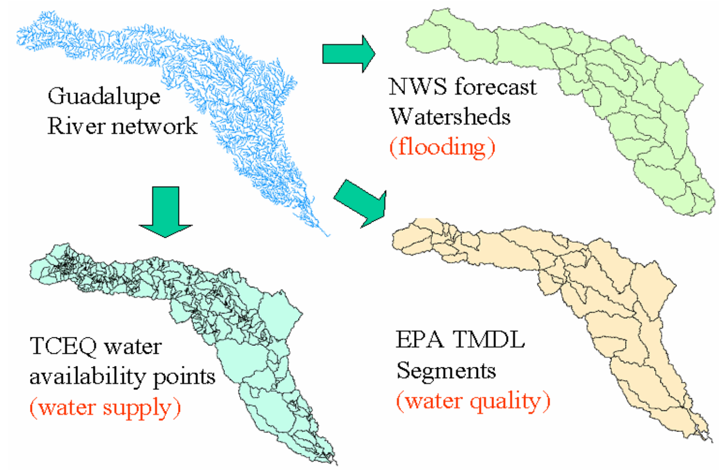

FIGURE 4-9 Subwatershed delineations in the Guadalupe Basin, Texas. SOURCE: Maidment (2002).

(TCEQ) has issued a permit for water withdrawal from the Guadalupe River or its tributaries. As part of estimating the reliability of water supply at these permit points, a long-term water resource simulation is done using monthly data over a period of 40-50 years, in which the "naturalized flow" is estimated for each USGS streamgage (this is the gaged flow adjusted for significant upstream diversions and return flows), and a corresponding naturalized flow is estimated at each diversion point using the ratio of the drainage area of the diversion point and the drainage area of the next downstream streamgage.

In contrast to network designs used to monitor continuous surfaces, fluxes, or fields (e.g., air quality, solar radiation, contaminated groundwater; see Figure 4-5), streamgage locations are confined to the stream network (Figure 4-8), suggesting analogues with facility location in transportation and communication networks. For example, facilities may be optimally sited in a transportation network to intercept traffic flows for vehicle safety inspections or to detect the transportation of hazardous substances (Berman et al., 1995; Gendreau et al., 2000; Hodgson et al., 1996; Mirchandani et al., 1995;). The flow interception location problem engenders subtle trade-offs between maximizing capture (e.g., by locating facilities at the 1995;). The flow interception location problem engenders subtle trade-offs between maximizing capture (e.g., by locating facilities at the "outlet" of directed networks through which all traffic must flow) and "protecting" the network (which favors siting more facilities in the "upstream" reaches of the network for early detection). These problems naturally relate to monitoring and quality management in water distribution networks for which Subramaniam (2001) formulated the location of chlorine booster stations in a water distribution network as a *location set covering problem* (Daskin, 1983).

Service Standards and Thresholds

Many problems with continuous, quantitative performance measures (such as police response time) can be transformed into discrete coverage problems by defining a "service standard." For example, a "threshold" concept of coverage is commonly used to rate residential fire insurance risks, in which a homeowner is considered covered if the home is within 1,000 feet of a fire hydrant or within five miles (or five minutes) of a firehouse. All such homeowners are considered covered and therefore implicitly rated as though they have "equivalent" fire protection, even though homes closer to the fire station clearly have incrementally faster response times. The public interest and public policy in efficiently providing full coverage for critical public services such as fire protection (Marianov and Revelle, 1991) or emergency warning (Current and O'Kelly, 1992) naturally extends to concepts of backup coverage, secondary coverage, and resilience (Haghani, 1996; Hogan and Revelle, 1986; Revelle et al., 1996) in network design.

Where clear accepted service standards can be defined (e.g., insurance standards defining acceptable standards for fire protection) the trade-off between level of coverage and number of facilities (a surrogate for cost) can be meaningfully analyzed. For critical services and national needs, complete, efficient (i.e., minimum number of gages) coverage is the compelling design goal.

An evocative example of the coverage concept to locate a network of facilities was offered by Revelle and Rosing (2000), who analyzed the fourth century deployment of Roman legions by the Emperor Constantine in order to defend (within a particularly defined "level of service") the eight provinces of the Roman empire using only four "field armies." The problem was to either minimize the number of armies required to cover all provinces or maximize the extent of defensive coverage when the number of field armies was inadequate to defend the empire. From the Roman perspective, there was a clear "national" interest in achieving complete coverage of the empire.

THE NSIP NETWORK AS A COVERAGE MODEL

In contrast to the long history of statistically based network design at the USGS, the NSIP network is essentially a coverage model. In its broadest outline, the program has identified a set of gages that satisfies national needs by *covering* "demands" defined by the five NSIP program goals. This long-term design for the national gage network does not attempt to integrate statistical evaluation of the marginal information gains or losses associated with incremental changes in the number and location of gaging stations.

This approach is reasonable. The NSIP network design problem has the complexity of other "strategic network design" (Owen and Daskin, 1998) problems, such as investment decisions to locate international manufacturing facilities that must incorporate future uncertainties and changing conditions. The long-term commitment of limited resources requires such networks to be robust against an uncertain future (Ghosh and McLafferty, 1982; Mulvey et al. 1995; Owen and Daskin, 1998). The design of the national streamgage network must similarly serve current and future national needs and therefore must similarly be designed to be robust against both natural and anthropogenic change. The design for a national gage network is therefore much more complex than the traditional network design problem that has historically been defined by the narrower problem of hydrologic regionalization. Pragmatically, traditional statistical methods based on marginal information value will continue to support incremental decisions and continual improvement in locating new streamgages as the NSIP plan is implemented. **Beyond local refinement, the coverage model based on five minimum national needs is an appropriate model to develop the long-term design of the national streamgage network.**

Some of the NSIP goals, such as gaging for treaty obligations and boundary crossings, are clearly binary coverage goals. For example, the flow of the Colorado River entering Mexico is either gaged or ungaged, and the goal is thereby either covered or not. Other goals, such as gaging river outflows, implicitly define coverage through a service standard (i.e., all basins of a certain size scale; see discussion of goal in Chapter 3).

By analogy to Figure 4-9, the choice of a set of streamgaging sites for each of the five NSIP goals has associated with it a subwatershed dataset that represents the spatial subdivision of the nation into sampling units, each unit having an NSIP gage at its outlet. For three of the NSIP goals (border or compact points, NWS forecast points, water quality points), the point location is chosen first and the subwatershed delineation is determined by these points. For the other two NSIP goals (river basin outflows and sentinel watersheds), the subwatershed dataset is chosen and then streamgaging points are selected at or near the outlets of these subwatersheds. For river basin outflows, the subwatershed dataset is the six-digit USGS hydrologic accounting unit (Figure 3-5), while the sentinel watershed dataset is created by the union of ecoregion boundaries (Figure 3-6) with hydrologic accounting unit boundaries.

Thus, it can be seen that there is a close association between a set of gages chosen to meet an NSIP goal and a subwatershed dataset drawn from these gage points as watershed outlets. The NSIP gage network resulting from the five NSIP goals results in a subwatershed dataset for the nation. In effect, this NSIP subwatershed dataset subdivides the nation into water resources sampling units, each measured by a gage at its outlet.

Since the NSIP base gage site locations for each of the five goals are defined separately for each goal, there does not presently exist a subwatershed dataset that results from all sites taken together. By creating national NSIP subwatershed dataset maps for each criterion using the proposed and active gage sites (approximately 70 percent of the total), 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. The Interstate Council on Water Policy (ICWP, 2002; see following section) suggested that uniformity of coverage, if desirable, could be achieved by locating as many NSIP gages as possible at or near the outlets of the USGS Hydrologic Unit Code (HUC) watersheds, which are part of the Watershed Boundary Dataset of the United States, presently under development. It would also be useful to define the geospatial (e.g., soil and land-use properties, stream network) and hydrologic (e.g., mean annual rainfall and evaporation) properties of these subwatersheds so as to support hydrologic studies of NSIP data with a consistently computed set of supporting watershed data.

The USGS should delineate the subwatershed dataset for the NSIP base gage network stations and define their geospatial and hydrologic properties.

RECOMMENDATIONS OF THE INTERSTATE COUNCIL ON WATER POLICY

The ICWP (2002) assessed the NSIP from the viewpoint of state, local, and tribal users of streamflow data. Because of the importance of the ICWP and its member organizations to state and national streamflow networks, its recommendations are summarized and evaluated.

ICWP Recommendations

In addition to the five NSIP goals, the ICWP considered nine additional goals for streamflow data, originally proposed by the Department of Interior's Advisory Committee on Water Information (ACWI). In doing so, the ICWP not only implicitly accept the validity of the coverage approach taken by the USGS for the program but extended it. These goals include providing (ICWP, 2002, p.1) the following:

- streamflow data for determination of base flood discharges and elevations for communities participating in the National Flood Insurance Program;
- streamflow data for all watersheds with impaired water quality, based on the EPA's TMDL list;
- streamflow data at river reaches with major National Pollution Discharge Elimination System (NPDES) permits;
- stage and discharge information for rivers used for canoeing, kayaking, or rafting;
- streamflow data for rivers draining parcels of federal land of >100 square miles;
- streamflow data for all major rivers with surface water diversions that exceed 25 percent of the river's mean annual flow;
- discharge data for the inflow and outflow of all reservoirs with >50,000 acre-feet of total storage;
- streamflow data for coastal rivers that support a migratory fish population; and
- stage or discharge information on rivers that support commercial navigation.

Like the NSIP network design, a metric was defined for each of these additional nine goals, and the number of gage sites needed to meet these goals was evaluated. The number of sites identified separately for each of the goals totaled more than 30,000, with the largest number of sites supporting National Flood Insurance Program communities (7,297 sites) and Impaired Water Quality Reaches (9,123 sites). Allowing for coincident sites selected by two or more goals, there are 18,330 unique sites chosen according to the 14 goals (the 5 original NSIP goals and the 9 additional goals listed above). It was apparent to the ICWP that not all these goals could be fulfilled by adding new streamgages. Consequently, it recommended the following adjustments to the "base federal network" to be supported by NSIP (ICWP, 2002):

1. Provide stage and discharge data at each National Weather Service and Natural Resource Conservation Service forecast or service location for the purposes of flow forecasting (flood, normal, and drought).
2. Monitor representative discharge at each major subbasin defined as a hydrologic cataloging unit (HUC-8 as opposed to the original HUC-6 basin proposal) for assessing status and trend of flow availability.
3. Provide river streamflow data for rivers governed by compacts between states, tribes, or nations or as dictated under Supreme Court decree (but not including waters crossing jurisdictional boundaries with no legal agreements).
4. Use the existing Hydrologic Benchmark (HBM) station network to monitor streamflow and act as sentinel watersheds to evaluate altered rainfall-runoff relations induced by changes in climate or weather.

The ICWP also recommended what it called "a new concept: defining a national network through watershed coverage." This would involve subdividing the landscape into HUC-8 and HUC-10/11 subwatersheds and siting gages funded by the Cooperative Water Program at or near the terminus of each HUC-8 subbasin and, within these subbasins, have gages placed as a function of the localized water management need for such information. For example, Kansas has 12 HUC-6 units, 80 HUC-8 subbasins, and 330 HUC-10/11 units, and presently has 166 NSIP gage locations identified. In the coverage model proposed by the ICWP, federal-state cooperative gages would be sited in such a manner as to augment the NSIP distribution and be representative of all HUC-8 and as many HUC-10/11 units as possible.

The ICWP concept of identifying gage locations by a coverage subwatershed model is consistent with the design of the national gage network proposed by the NSIP. Using subwatershed coverage to locate streamgages is an appropriate approach to designing a robust national network and is similarly endorsed by the committee.

Comments on the ICWP Recommendations

Providing additional feedback on the ICWP recommendations requires that one first make an important distinction between *data collection (*or, specifically*, streamgaging) points* and *information points*. The former are locations at which streamflow and(or) some other property is measured; the latter represent sites at which streamflow information is desired and generated from the available data. Advances in geospatial information technology in conjunction with the National Hydrography Dataset, the National Elevation Dataset, and modeling techniques have greatly improved our accuracy in spatially estimating streamflow (with confidence limits) for a dataset of information points on the stream network. Applications of this concept are further developed later in this chapter.

ICWP recommendation 1: "Provide stage and discharge data at each National Weather Service and Natural Resource Conservation Service forecast or service location for the purposes of flow forecasting (flood, normal and drought)."

The committee concurs with this recommendation to include the Natural Resource Conservation Service (i.e., not just NWS) forecast points as part of the NSIP flow forecasting goal information points.

ICWP recommendation 2: "Monitor representative discharge at each major sub-basin defined as a hydrologic cataloging unit (HUC-8 as opposed to the original HUC-6 basin proposal) for assessing status and trend of flow availability."

The six-digit HUC is an appropriate scale to characterize flows of the nation's major rivers and evaluate national river outflows from the continental United States. There are many uses and a clear national need for streamflow information from the smaller, eight-digit and ten-digit HUCs as well. Encouraging cooperators to support gages at the outlets of HUC-8 and HUC-10 watersheds is a desirable goal. Pragmatically it is unclear that the national needs for streamflow information from eight- and ten-digit HUCs can be reliably satisfied opportunistically, within the Cooperative Water Program. The USGS should therefore consider a stratified random sampling design to gage and characterize smaller watersheds. This design should support and be closely coordinated with methods development to provide consistent estimates of streamflow information for all eight- and ten-digit HUCs.

The provision of streamflow information at boundaries of standardized watersheds is desirable, and the HUC-8 dataset, and the emerging HUC-10 and HUC-12 datasets from the Watershed Boundary Dataset, should be considered *information points* if not specifically gaging sites. The USGS should develop a coverage-based method to provide streamflow information *with quantitative confidence limits* for these information points using an appropriate combination of measurement technologies, data assimilation, and synthesis techniques.

ICWP recommendation 3: "Provide river streamflow data for rivers governed by compacts between states, tribes or nations or as dictated under Supreme Court decree (but not including waters crossing jurisdictional boundaries with no legal agreements)."

In its report on the USGS National Water-Use Information Program (NRC, 2002), this committee documented the status of legal permitting for water use in all 50 states. Rules and legal procedures differ significantly from state to state, and conflicts have arisen among several states over shared waters crossing state boundaries. As the intensity of water use increases in the future, more conflicts of this kind may be expected. In that event, long-term streamflow records from the USGS as an independent, trusted source of information will be required. Further, even if no legal conflict between states develops, state water availability planning requires the capacity to separate water arising from within the state from that flowing into the state.

The committee does not concur with the ICWP recommendation to eliminate from the NSIP program gage sites on jurisdictional boundaries with no legal agreements.

ICWP Recommendation 4: "Use the existing Hydrologic Benchmark station network to monitor streamflow and act as sentinel watersheds to evaluate altered rainfall-runoff relations induced by changes in climate or weather."

The HBM network is a set of 73 gage locations in pristine environments intended to monitor flows in undisturbed watersheds. The sentinel watershed goal of the NSIP generates 874 gage site locations representative of the nation's ecological and hydrologic regimes. This broad distribution of representative sites is valuable and represents much more than relatively pristine catchments with minimal human influence. Although sentinel watershed gages are chosen to be relatively unaffected by flow regulation and diversions, they are specifically selected to characterize the ever-changing status of the nation's water resources in response to changes in climate, land use, and water use in 800 watersheds that typify major ecoregions and river basins.

The current sentinel watershed goal sites should be retained rather than just using the Hydrologic Benchmark sites.

Concerning the additional nine goals identified by the ACWI and examined by the ICWP, and the total of 18,330 gage sites thus located, all of the ACWI-identified goals have merit. In particular, the goals of supporting

Impaired Water Quality Reaches for TMDL studies (9,123 sites) and National Flood Insurance Program communities (7,297 sites) have national significance, directly supporting federal water quality and flood mitigation programs. Gaging all sites required to meet these goals would be well beyond the capacity of a national network, even under the most optimistic assumptions about future funding. However, having a streamgage at each information point is not the only way to provide streamflow information. Further, streamgages are but one of many different data collection technologies that can be used to support the generation of streamflow information.

The additional sites identified to serve ICWP goals represent significant valuable information needs and should be considered information points. The USGS should develop a coverage-based method to provide streamflow information *with quantitative confidence limits* for these information points using an appropriate combination of measurement technologies, data assimilation, and synthesis techniques.

NETWORK DESIGN GOALS: CONTRASTING NSIP WITH STATE-DESIGNED STREAMFLOW NETWORKS

During the 1980s the USGS sponsored several state-level studies assessing the adequacy of the state's streamgage networks (e.g., Fontaine et al., 1984; Medina, 1987). The prototype for these studies was the USGS network in Maine, where "the stream gaging activity is no longer considered a network of observation points, but rather an information system in which data are provided by both observation and synthesis" (Fontaine et al., 1984). A typical set of goals from these studies is listed below:

- *Regional hydrology*—relating basin characteristics to streamflow under natural conditions
- *Hydrologic systems*—water accounting including diversions and return flows
- *Legal obligations*—treaties, compacts, and decrees
- *Planning and design*—dams, levees, and water supply
- *Project operation*—reservoir releases and hydropower
- *Hydrologic forecasts*—floods and flow volumes

- *Water quality monitoring*—National Stream Quality Accounting Network
- *Research*—gages for specific studies
- *Other*—recreation (e.g., canoeists, fishermen)

This list of goals is more extensive than the goals adopted by the NSIP, but a side-by-side comparison of the two lists in Table 4-1 indicates that they have a good deal of commonality. The goals from the above list that are omitted in the NSIP are planning and design of facilities, project operation, research, and other purposes such as recreation and canoeing.

In considering goals such as the operation of facilities or research on a particular watershed, a disproportionate share of information value may go to a limited set of well-identified stakeholders. Similarly, recreational users of streamflow information are important locally, but streamgages designed to serve these needs may be difficult to justify at the national level. These disparities make local partners strong candidates for cooperative funding and other innovative arrangements to support the gage network. Consequently, the USGS has responded to uncertainty and variability in streamgage funding with vigorous and creative development of cooperative funding arrangements to avoid eliminating gaging stations. Indeed, one of the concerns that prompted establishment of the NSIP was the unreliability of funding from agencies operating water facilities. Nevertheless, in considering *national* needs supported by the NSIP network, valuable local and regional goals such as specific watershed research or operational needs should not play an overriding role in national network design.

Another area that is often mentioned as a candidate for the NSIP is urban hydrology. Land-use change associated with population growth is a broadly national issue, and this committee endorses Goal 4 of the NSIP (using sentinel watersheds to regionalize streamflow characteristics and assess trends in streamflow due to factors such as changes in climate, land use, and water use); see Chapter 3. However, many of the more specific goals for streamflow measurement in urban areas are not appropriate for a national program or are not appropriate for a USGS program.

For example, measurement of flow and water quality from large sewer pipes whose discharge is regulated by EPA may be most appropriately performed by that agency or a state regulatory agency. Short-term measurement of flows at street and highway crossings to generate design data for culverts might be done more appropriately by federal, state, or local highway administrations. Also, regulatory authority over stormwater and erosion issues is a local, not a federal, matter. Thus, streamgaging in urban areas is often driven by regulatory reasons, by transportation interests, or

TABLE 4-1 Comparison of NSIP Network Design Goals with Those of Earlier State Network Design Studies

1980s Network Design Goals	NSIP Network Design Goals
Regional hydrology	Sentinel watersheds
Hydrologic systems	River basin outflows
Legal obligations	Borders and compacts
Planning and design	No
Project operation	No
Hydrologic forecasts	NWS flow forecasts
Water quality monitoring	Water quality
Research	No
Other (recreation, canoeing)	No

simply by the desire of a city administration to manage its streams and watersheds. It is unclear that there is a major federal interest in many of these activities and, where there is a federal interest, that the USGS is the best agency to assume the responsibility.

Another area of streamflow measurement that is of concern, especially from the viewpoint of river science, is to gage very small, first- or second-order headwater streams. These small streams are critical components of river networks. Although gaging such small streams is part of the USGS research program, as at the Luquillo Experimental Forest in Puerto Rico (*http://pr.water.usgs.gov/public/webb/*), it is not undertaken generally around the nation and gaging small watersheds is not an explicit part of the NSIP. If a GIS (geographic information system) based metric for gaging small streams were to be developed similar to the other five goals in NSIP, it would require a high-resolution digital representation of the stream network of the nation. At present, the best representation of the digital stream network of the nation is the National Hydrography Dataset (NHD) at the relatively coarse scale of 1:100,000. For some states, 1:24,000-scale NHD data have been or are being prepared. The definition of what constitutes first- and second-order streams changes with the scale of the map representation, with the higher-resolution 1:24,000 data yielding a larger number of smaller first-order streams than the 1:100,000-scale data.

Thus, the digital basis for systematically defining first- and second-order streams across the nation is improving but is not yet in place. However, the USGS should revisit the issue of gaging first- and second-order streams in the future as part of its review process, as the degree of detail of the geospatial coverage of the nation's streams continues to improve. This might be done through random subsampling of small watersheds with the cooperation of other agencies and the private sector (e.g., transportation).

In addition to Maine, other statewide analyses have been done in recent years and have taken a variety of approaches. These include studies of the Wisconsin (Team for Evaluating the Wisconsin Water-Monitoring Network, 1998), Delaware (Doheny, 1998), Maryland (Cleaves and Doheny, 2000), Illinois (Knapp and Markus, 2003), and Texas (Slade et al., 2001) networks. The Wisconsin study uses Geographic Management Units established by the Wisconsin Department of Natural Resources as its basic watershed coverage for streamgage planning. The Delaware study cites a list of goals similar to those given above for streamgaging in Maine. The Maryland program attempts to cover various water management goals while maintaining long-term gages and a broad range of geographic areas and watershed sizes. Illinois has focused on understanding the many needs of users with an exhaustive survey of both the public and the private sector. It acknowledges the impossibility of anticipating many of the future data needs of the program and therefore supports maintaining a base network that is "representative of the streams of Illinois, such that these long-term data are available to meet a broad range of potential needs" (Knapp and Markus, 2003). The Texas study is discussed in detail earlier in this chapter as an example of statistical network design.

NSIP NETWORK DESIGN: FROM DATA TO INFORMATION

As noted earlier in this chapter, there is a sharp distinction between sets of gaging points (i.e., sites at which streamflow is measured) and sets of information points (i.e., sites at which streamflow information is generated). These sets are not mutually exclusive. This distinction mirrors Fontaine et al.'s (1984) description of the Maine streamgage program as an information program supported by both observation and synthesis. As a national *information* program, the NSIP is the primary federal program to satisfy the nation's current and future needs for streamflow information, supported by both observation and synthesis. The broad long-term goals of the NSIP should be building the capacity to provide streamflow information (with rigorous, quantitative confidence limits) at any arbitrary information point in the nation.

The NSIP should be integrated, managed, and evaluated as a national information program, strategically focused on the long-term goal of providing streamflow information with confidence limits at any arbitrary point in the landscape. The design and continuous refinement of the NSIP gage network should be driven by and consistent with this broad overarching goal.

Quality and Value of Information

Emphasizing both information and confidence limits acknowledges that streamflow information is generated through a suite of measurement technologies and synthesis methods that jointly determine the quality of information. Here information *quality* and information *value* must be distinguished; the value of information can be determined only in the context of applications and decision making supported by that information (Cleveland and Yeh, 1990; Wagner, 1999). For example, real-time streamflow information can be a critical component in flash flood warning and response, yet the marginal value of gage information cannot be quantified independently from the warning, dissemination, and emergency response plans that collectively determine the effectiveness of any flash flood warning system (Drabek, 1999; Gruntfest and Handmer, 2001; Handmer et al., 1999).

For this reason the value of streamflow information is inherently coupled to its many and growing uses, as national demands for streamflow information change. The evolving needs for streamflow information are illustrated in the prioritization of FY 2003 streamflow information needs within the Cooperative Water (Coop) Program (*http://water.usgs.gov/coop/priorities.-html*). The general category of hydrologic hazards has been a core focus of the USGS for many years. However, the recent dramatic fires in the western United States have highlighted the need for improved understanding of the effects of "large-scale forest fires," which is now explicitly identified among the Coop priorities. While suggesting the potential capacity for the Coop program to respond to emerging needs, if funding is available, this also highlights the need for a robust capacity for adaptation within the NSIP data collection program.

If cooperative funding is available, opportunistic data collection directed to watersheds experiencing large-scale forest fires will provide a wealth of information ranging from understanding sediment storage, disturbance ecology, and the biogeochemical cycles in fire-disturbed ecosystems, to practical management information on changes in flood risks and sedimentation. However, the value of these data would be greatly increased if baseline data collection had been initiated prior to these extreme events. Data collection to establish baseline conditions in anticipation of future, uncertain needs may be particularly difficult to support through the Cooperative Water Program. Of course any decision to collect such baseline data must anticipate its future use. Strategic anticipation of future needs is more appropriately incorporated into core federally funded NSIP data collection efforts.

Consider for example, the Hydroclimatic Data Network (HCDN) consisting of USGS streamgages with relatively long records on watersheds that are minimally affected by regulation and diversions (Slack and Landwehr, 1992). This unique network has proven especially useful in evaluating hydrologic trends and testing climate change hypotheses (Lins, 1997; Lins and Slack, 1999; McCabe and Wolock, 2002; Vogel et al., 1999). Though highly valued today, the HCDN is a "discovered" network that exists today only as the cumulative result of a series of independent gaging decisions made over the last century. When decisions were made to support these gage stations, their future use in the analysis of climate change was unimagined. Moreover, although the marginal value of adding additional gages with long records in "natural" watersheds could be estimated, it is too late to add these gages today—regardless of their value.

The current discovered value of the HCDN gages illustrates the importance of considering the nation's future needs and future uses for streamflow information. The challenging decision to commit current gaging resources that will support the nation's future (and uncertain) needs for streamflow information does not lend itself to traditional cost-benefit analysis. Predicting future streamflow needs with certainty is obviously not possible. Although the particular needs that will emerge in the future cannot be confidently predicted, one can confidently predict that such needs will emerge.

Thus, as first noted in Chapter 3, the NSIP program should therefore be structured with the robust capacity to target data collection resources to likely future needs. For example, powerful trends in population growth (and accompanying water use) in the arid Southwest and near the coastal ocean portend future demands and the likely value of "current" baseline water information in these hydroclimatic regions. The NSIP should also support data collection for less certain future needs for expanded data collection, such as enhanced streamflow information in coastal zone streams discharging to estuaries or ephemeral streams in the Great Basin.

The USGS should create a mechanism to institutionalize adaptive management of the nation's likely future needs for streamflow information and provide a mechanism to support these likely emerging needs as part of the core federally funded gage network.

NSIP: An Enhanced National Information System

When viewed as an information program supported by observation and synthesis, the NSIP motivates a new paradigm for streamflow data collection and management. The current model emphasizes data collection and processing of stage height measurements that are synthesized, electronically archived, and most commonly reported as discharge values. Storage and dissemination of streamflow information are primarily oriented to tabular values of daily average discharge reported at the location of a streamgage. In contrast, the NSIP should support an "information base" that is both spatially and substantively far more expansive. Spatially, the goal of providing streamflow information at an arbitrary point in the landscape generalizes the concept of information points and requires close integration of data collection, data management, and methods development for information generation. Substantively, the national need for streamflow information extends far beyond discharge measurements and includes information about the geomorphic characteristics of the stream channel, the riparian corridor, the landscape, and their coupled biogeochemical and ecological systems. While maintaining continuity with historical and current gaging technologies, the application of the nation's streamflow information program to evolving societal needs such as river science (see Chapter 6) will demand new paradigms in data collection and data management, as well as a consistently rigorous approach to the generation, management, and dissemination of information.

Conceived in this way, the dynamic NSIP can be viewed as supporting a continuous streamflow "information cycle," represented conceptually in Figure 4-10. Built on the USGS's core expertise in streamflow measurement, NSIP *data collection* relies on the NSIP gage network, including a base network of federally funded gaging stations. However, data collection also integrates the full range of data collection technologies and procedures, including crest stage gages, intensive data collection during hydrologic extremes, remote sensing, and innovative technologies for non-contact water measurement. Moreover, NSIP data collection involves far more than discharge measurements and includes a broader suite of measurements within the channel (e.g., velocity fields, bed material load, channel geometry, stream biota) as well as measurements that characterize the form and function of the riparian corridor and floodplain.

This richer data collection stream requires a *data management* system with the capacity to handle very diverse data formats, ranging from remotely sensed digital imagery to four-dimensional velocity fields derived from acoustic Doppler current measurements over a river reach. Together, the

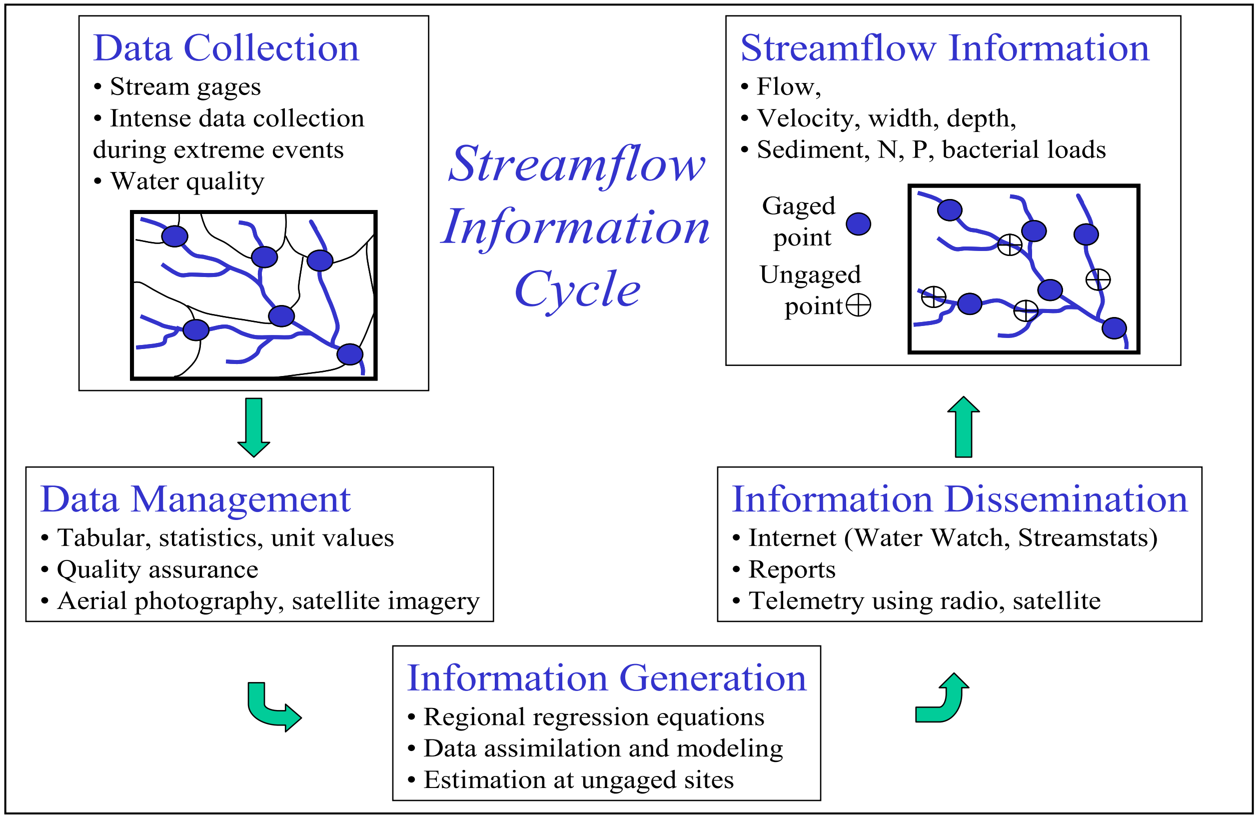

FIGURE 4-10 Streamflow information cycle: from data to information.

data collection and data management components of the NSIP support *information generation*, providing streamflow information, with quantitative confidence limits, at any information point in the landscape. NSIP information generation incorporates traditional hydrologic regionalization and statistical approaches for estimating discharge at ungaged sites, as well as methods development to incorporate spatially referenced information (e.g., land use, land cover, topography, water control structures) and indirect information such as paleoflood deposits and historical high-water marks.

Like the expanded scope of the data collection and data management components of the NSIP, *information dissemination* should expand the USGS's exceptional commitment to the Internet and extend to other emerging information technologies and models for information dissemination. For example, the current USGS technology for information dissemination is a user "pull" moder, in which users can access, select, and download streamflow information. Alternate models allow users to specify data needs that may be accumulated passively from a larger data stream using "push" technologies, that is, data is transferred as the data stream is generated without requiring user action. Push technologies have been successfully developed and economically deployed using satellite, radio, and the Internet by, for example, the NWS to support the Emergency Managers Weather Information Network.

Together these NSIP components provide the framework to support the nation's expanding need for *streamflow information*. The streamflow information cycle is then "closed" by continuous feedback and the recurring systematic evaluation of current and emerging information needs. Generating streamflow information with quantitative confidence limits helps both in its interpretation as well as in linking the quality of the information to its value for individual users and the nation.

It is recognized that in the past, watershed information has been neither the traditional nor the primary goal of the USGS streamgaging program. However, the NSIP will establish the observational and data infrastructure for the nation's streamflow information needs in years to come. The USGS should therefore anticipate the needs for streamflow information to address emerging science questions ranging from the source, flowpaths, and dominant mechanisms of overland flow to the role of hyporheic processes in the fate and transport of nutrients and contaminants. As the nation's streamflow information program, the NSIP can anticipate and lay the foundation for the continued development of integrated "river science" programs within the USGS and at other institutions (see Chapter 6).

SUMMARY

The USGS has been exceptionally successful as the nation's source for unbiased, science-based water resources information, despite great uncertainty and variability in funding for basic, core data collection and continuous operation of the national streamgage network. The USGS's responsibility to meet current and future national needs requires a strategic network design (Owen and Daskin, 1998) structured to be robust against inevitable changes and uncertainty. The network should be oriented toward the overarching goal of providing streamflow information with confidence limits at an arbitrary information point in the landscape. Tactically, both limited funding and changing needs will require the USGS to continually reevaluate, refine, and adjust the national gage network. Success can only be judged iteratively and will require continual refinement of the network.

Many approaches have been used to design and maintain data collection networks. Statistical procedures offer numerical precision for network design and quantitative estimates of uncertainty. However, they are most effective in local to regional, homogeneous regions, and they do not support the many other goals and uses of site-specific streamflow data. In contrast, coverage models that articulate a goal, define a metric that identifies locations supporting that goal, and apply this procedure to yield a set of potential sites for gages, have many advantages for a national network.

Each of the NSIP components contributes to both the quality and the value of streamflow information. This streamflow information cycle should, of course, represent an ongoing process of evaluation and improvement. Overall, the proposed design of the NSIP streamgage network represents a sound and well-reasoned foundation to support this continuous process.

The use of a coverage model to design the national gage network to meet the five NSIP goals represents a sound approach to designing a robust data collection network for the NSIP. Where possible, statistical methods that quantify the marginal information gains or losses from incremental changes in local and regional gage networks should be integrated into the implementation of the NSIP plan, including the continual refinement and reevaluation of hydrologic data collection. The NSIP program should include an explicit mechanism to direct gaging resources to support emerging issues of national significance.

The NSIP's current model emphasizes data collection and processing of stage measurements that are synthesized, electronically archived, and most commonly reported as discharge values. However, the NSIP should support an "information base" that is both spatially and substantively far more expansive. Its goal should be providing streamflow information at any arbitrary point in the landscape, and this information should include information about the geomorphic characteristics of the stream channel, the riparian corridor, the landscape, and their coupled biogeochemical and ecological systems whenever feasible. **The program should support a continuous streamflow "information cycle" of data collection, data management, information generation, and information dissemination.**

This richer data collection stream requires a data management system with the capacity to handle very diverse data formats, ranging from remotely sensed digital imagery to four-dimensional velocity fields.

Generating streamflow information with quantitative confidence limits is important in linking the quality of NSIP streamflow information to its value both individual users and the nation.