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Contributions of NSIP to River Science

Rivers do more than simply convey the water, sediment, and dissolved components from the watersheds they drain. Streams and rivers have distinctive channel characteristics that are the product of the flow regime's capacity to transport the sediment supplied to the channel. The interaction between water, sediment, and in some instances, large woody debris creates many aquatic and subsurface habitats for the diversity of riverine life, from microorganisms to insects to fish to riparian trees. Groundwater delivered to streams and surface water in the stream can be biogeochemically transformed in subsurface hyporheic zones beneath and around the streams. An understanding of the functioning of the integrated hydrological, geomorphic, and biological processes in rivers is a fundamental goal of river science, and it requires information on streamflow, water quality, and sediment load. This understanding is complicated because of the substantial imprint of human activities on river systems, activities that can greatly modify geochemical, physical, and biological processes. These processes are sensitive to land-use change and climate change; therefore, one key way that in which the National Streamflow Information Program (NSIP) can support river science is by providing information on how human activities influence key processes that alter a river system relative to some minimally disturbed "reference" conditions (such as might be provided by the sentinel watershed element of NSIP; see Chapter 3).

Streams and rivers also provide numerous goods and services to society, such as water supply, recreation, hydropower generation, food production, and aesthetic values. Demands for these goods and services are increasing as population grows and as concerns about recurrent drought and climate change increase (Postel et al., 1996; Vörösmarty et al., 2000). At the same time, societal interest in maintaining the ecological sustainability of these flowing water ecosystems is growing, leading to potential conflicts between perceived human and ecosystem needs for fresh water (Baron et al., 2002; Naiman et al., 2002). Potentially conflicting demands can be expected to increase into the future due to pressures of population growth and climate change, which will only intensify society's need for better scientific information and understanding required to manage the nation's freshwater resources (Poff et al., 2003).

As an example, the closure of Glen Canyon Dam in 1963 changed the magnitude, timing, and temperature of streamflow and reduced sediment inputs into the Grand Canyon segment of the Colorado River. This has impacted the number and sizes of sandbars which are used by river runners and form the habitat for native fish. An experimental flood was released from Glen Canyon Dam in 1996 in an effort to rebuild sandbars and evaluate the potential for controlled flooding as a management tool (Webb et al., 1999). Scientific understanding of the interaction of geomorphologic, hydrologic, and biologic processes within rivers is needed to support this kind of management. The U.S. Geological Survey (USGS) has a critical role to play, through streamgaging and more comprehensive river process studies, in water resources prediction and in support of river management in the coming decades.

The committee was asked to address the following statement of task: How does the National Streamflow Information Program support river science, and can it support an integrated river science program in addition to its operational objectives? In that context, the purpose of this chapter is to briefly review opportunities in river science provided by the existence of the NSIP and to identify some additional requirements for streamflow information and dissemination to support river science.

RIVER SCIENCE OPPORTUNITIES CREATED BY THE NSIP

The term *river science* as used in this report is a largely interdisciplinary field that includes surface and groundwater hydrology, fluvial geomorphology, and various subdisciplines of biology (e.g., biogeochemistry, riparian ecology, aquatic ecology). The USGS is in a unique position to play a very important, leading role in guiding the development of a river science that can support society's broader concerns about river sustainability and management. The growing need for scientific information on rivers affords the opportunity for the USGS to define and explain how the development of a river science program represents a desirable societal investment. The USGS has already demonstrated its role in providing high-quality scientific information in a number of high-profile river management contexts including, for example, the Missouri River (Auble and Scott, 1998) and the Glen Canyon controlled flood on the Colorado River discussed above.

The opportunities for involvement of the USGS in river science, however, are significantly greater than its current role. The primary service provided by the USGS in enhancing river science would be to collect and provide the information needed to advance scientific understanding of the natural biophysical processes that define river systems and to build scientific capacity to predict how human alterations affect these processes for streams and rivers across the nation. Secondarily, the USGS should be in a position to provide unbiased scientific expertise in river science as requested by the public in the management of rivers.

Figure 6-1 illustrates a simplified view of the core USGS disciplines that contribute information and data fundamental to river science. This view of river science is inherently interdisciplinary and envisions integrated interaction among component disciplines, as well as interactions with related disciplines (e.g., hydroclimatology, geology). Most scientific studies on rivers conducted to answer federal or state questions require that data be acquired in addition to those normally collected at streamgage sites. However, the USGS's NSIP currently provides, and will continue to provide, the basic infrastructure for these studies.

Streamflow Information Needs for Geomorphic Studies

The USGS has been a leader in the development of scientific fields that are anchors of its river science program. One of the strongest examples of this is the field of fluvial geomorphology, which has developed with strong support of USGS streamflow information and strong scientific leadership from within the USGS. For example, the term "hydraulic geometry" refers to the changes in hydraulic variables (width, depth, velocity) that increase to accommodate increases in discharge either at a gaged site or at successive locations in the downstream direction. The seminal paper on hydraulic geometry is Leopold and Maddock (1953). This research was made possible by the existence of streamflow and channel morphology measurements at USGS gaging stations.

Information on the hydraulic geometry of rivers has been published in various regions of the world. Surprisingly, the USGS and other groups have not published hydraulic geometry relationships (either at a station) or downstream for hydroclimatic regions of the United States. A consequence

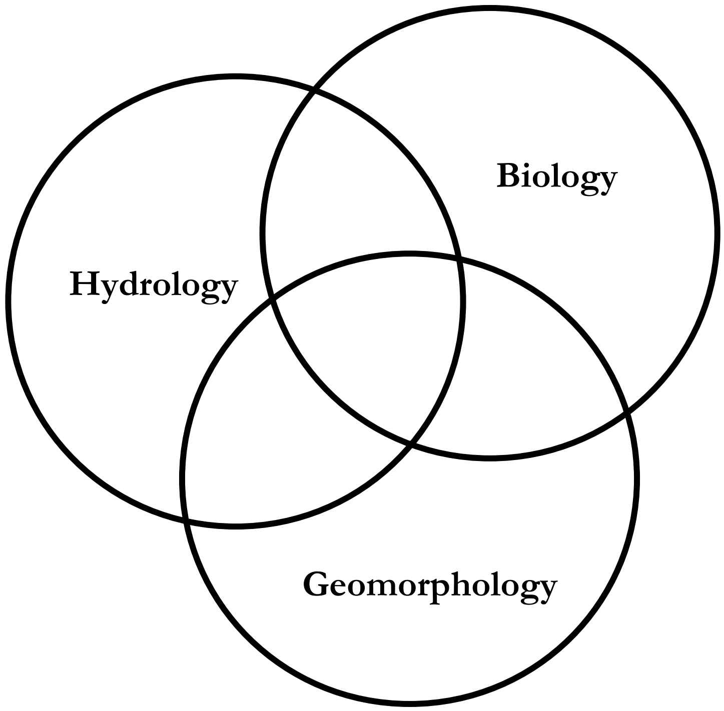

FIGURE 6-1 Venn diagram illustrating primary disciplines contributing to river science, an interdisciplinary endeavor represented by overlap among the disciplines.

of this is that many research projects that require channel hydraulic geometry use either "average" hydraulic geometry relationships, which are often the data from Leopold and Maddock (1953), or stream classification schemes (e.g., Rosgen, 1994), which are most appropriately applied in situations lacking high-quality data.

The USGS has begun to publish data from the individual streamgagings made at each active gage site (*http://waterdata.usgs.gov/nwis/sw*), which are essential for the evaluation of hydraulic geometry relationships. A limitation of this data source is that USGS gaging stations are chosen to have particular channel characteristics, such as the existence of a control section that will ensure a unique rating curve. The channel characteristics of streamgage locations may thus not be representative of randomly selected locations at any point along the entire length of a stream or river.

Geomorphic studies also require information that is sometimes, but not always, collected at streamgaging stations. These data include stream gradient, bed grain sizes, suspended sediment transport, and bedload transport. Stream gradient and bed grain sizes are essential for evaluation of bed mobility or sediment transport capability of a stream. Stream gradient is required to estimate local or reach-averaged stream power and shear stress. Further, flow resistance of a river can be calculated if stream velocity, hydraulic radius, and stream gradient are known. Flow resistance is a parameter that is used in all hydraulic models, including flood routing and flood inundation. USGS streamflow data provide an important data set that can be used to evaluate flow resistance, provided stream gradient is known.

Grain size information is also essential geomorphic information that is required both for geomorphic studies of channel morphology, sediment transport, and channel changes and for many ecological studies as well. Grain size information can be used to evaluate the mobility of bed sediment in rivers. At each USGS gage site and other reaches, the mobility of bed sediment could be evaluated if grain size distributions and the stream gradient data were measured in addition to the existing streamflow data.

Sediment transport data are expensive and difficult to collect, but because sediment load is an independent variable in stream systems and is highly variable spatially, these data must be collected from a range of watersheds. The USGS has a collection of suspended sediment data on streams that can be used to develop suspended sediment rating curves and loads. New technologies also hold promise for enhancement of data collection programs. For example, acoustic Doppler current meter data provide information on the variation of velocity with depth. These data can be used to evaluate roughness heights, local shear stress values, mixing lengths, and cross-channel shear stress distributions. These data provide a real opportunity to significantly enhance the hydraulics and sediment transport program at the USGS.

Streamflow Information Needs for Biological Studies

The hydraulic characteristics of river channels serve as determinants of many ecological processes and patterns in streams, through both direct effects on organisms and indirect effects mediated by factors such as sediment and wood transport and storage ("habitat"). Temporal variation in streamflow creates dynamic hydraulic variation that can reconfigure channel morphology and habitat for aquatic organisms and thus influence many ecological processes, both within the channel and on adjacent floodplains that experience inundation.

In the past decade or so, the general importance of hydrologically generated "disturbance" has become widely recognized in river ecology (e.g., Junk et al., 1989; Poff et al., 1997; Resh et al., 1988). Streams and rivers are naturally dynamic systems, due to frequent fluctuations in flow conditions. The occurrence of extreme events (floods, droughts) in particular is ecologically significant in that they typically "reset" ecosystems by creating sets of conditions that benefit early successional species and thus maintain high diversity. In other words, flow variation helps establish a "habitat template" that regulates many ecological process rates and influences the distributions and abundances of species (Poff and Ward, 1990; Schlosser, 1987; Townsend, 1989; Townsend and Hildrew, 1994). Several good reviews of this topic are available (Bunn and Arthington, 2002; Gasith and Resh, 1999; Poff et al. 1997). Indeed, there is now great interest in using long-term hydrologic data from USGS streamgages to characterize hydrologic disturbance regimes both within individual streams and among streams in a comparative fashion that allows for classification of regime types and enhanced ability to predict ecological responses to human alterations.

The USGS gage network has been instrumental in the progress of "hydroecology" in the last decade. For example, regional flow regime classifications have been constructed based on hydrological variables that are explicitly relevant to ecological processes in streams and rivers. These hydroecological classifications emphasize the patterning of flow variability at multiple time scales, described in terms of frequency, magnitude, duration, timing, and rate of change of flow events with ecological relevance (Olden and Poff, 2003). Computer software tools are now available and widely used to assist in codifying this approach (Richter et al., 1996). Several hydroecological classifications have been developed around the world for unregulated streams in the United States (Poff, 1996; Poff and Ward, 1989), Australia (Hughes and James, 1989), and New Zealand (Clausen and Biggs, 2000). An example of a U.S. classification based on more than 800 streamgages is shown in Figure 6-2.

Streamflow information from USGS gages is also critical for many site-specific hydroecological investigations. For example, Friedman and Auble (1999) used long-term streamflow records and dendrochronology to quantify the survival patterns for box elder stress along a gradient of flood inundation and shear stress in a section of the Black Canyon of the Gunnison National Park. They combined empirically derived relations between flow and tree mortality with a hydraulic model of the Gunnison River bottomland to generate Figure 6-3, a mortality response surface expressed in terms of key streamflow variables. Such a model provides park managers a tool for determining how upstream reservoir operations might be manipulated

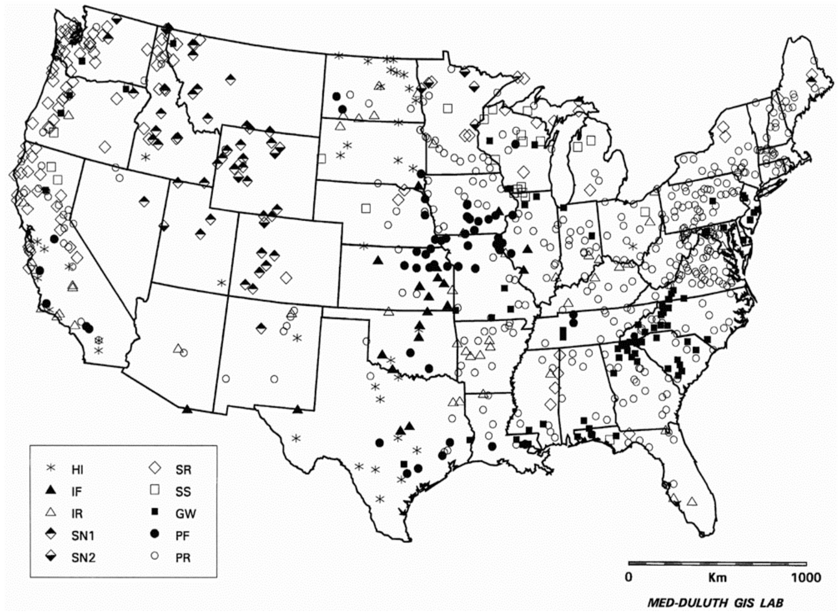

FIGURE 6-2 Ecohydrologic classification of 816 unregulated streams in the United States based on long-term daily streamflow data from USGS gaging stations. NOTE: Abbreviations refer to 10 streamflow "types" identified from cluster analysis based on 11 hydrologic variables: HI = harsh intermittent; IF = intermittent flashy; IR = intermittent runoff; SN1 = snowmelt 1; SN2 = snowmelt 2; SR = snow + rain; SS = superstable groundwater; GW = groundwater; PF = perennial flashy; PR = perennial runoff. SOURCE: Poff (1996).

to control the growth of box elder in the national park. As another example, innumerable studies are conducted by state and federal agencies throughout the United States to evaluate minimum instream flows for fish using techniques of quantifying time series of hydraulic habitat conditions, and these almost always require the availability of high-quality flow data (IFC, 2002).

Ecological studies, therefore, require information on the amount, flow rate, and timing of streamflow that regulates many of the ecological functions of the stream. Although many of the data collected at NSIP gages are appropriate for ecological studies, there is often insufficient information available for small streams. Geomorphic data are also required for many ecological studies, and therefore the data needs described above are also re-

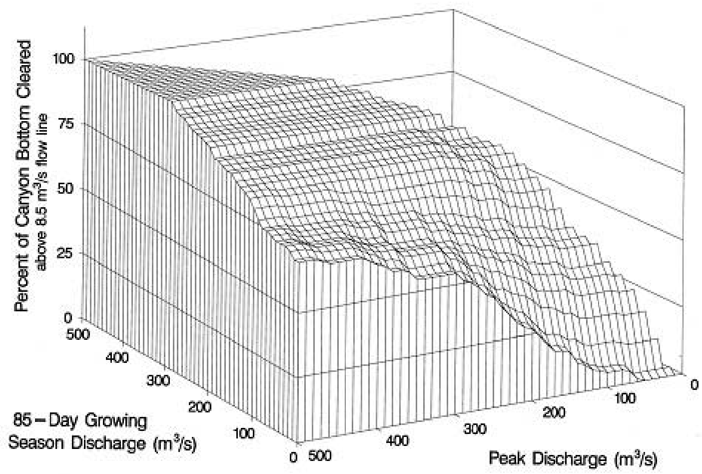

FIGURE 6-3 Mortality response surface for box elder trees as a function of flood magnitude and seasonal inundation. SOURCE: Friedman and Auble (1999).

quired for many ecological studies, amplifying the need for the dissemination of data that are currently not readily available. Ecological studies also require information at ungaged locations, indicating the need for development of streamflow estimation and geomorphic estimation procedures.

Streamflow Information Needs for Surface Water-Groundwater Interaction Studies

The hyporheic zone is the subsurface interface between stream water and the groundwater interacting with it (Figure 6-4). Groundwater can discharge to streams and maintain base flow and in turn, be recharged by streams (Figure 6-5). Groundwater flow patterns also can be influenced by stream gradient and geomorphology, and anthropogenic influences such as local pumping and water use.

The three-dimensional extent of the hyporheic zone and its hydrodynamics are related to overall streamflow dynamics (e.g., Battin, 1999; Jones and Mulholland, 2000), and within the hyporheic zones, focused groundwater discharge through macropores or other highly permeable zone can lead to unique biological habitats. The hyporheic zone is important both in

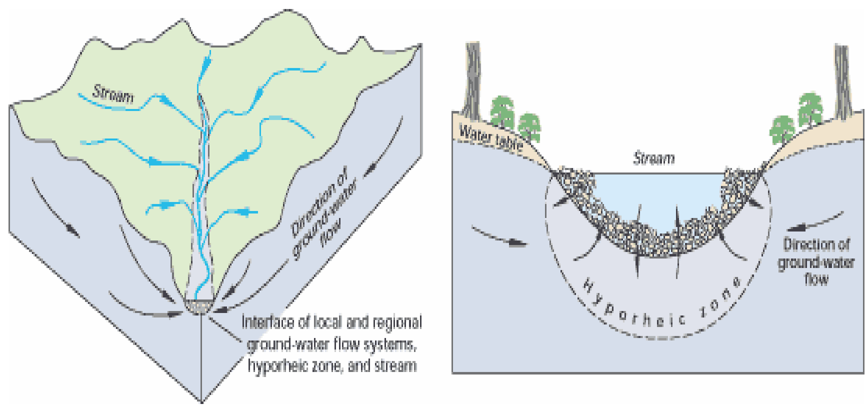

FIGURE 6-4 The hyporheic zone. Note the "envelope" of water under the stream that is active with respect to water fluxes and mixing and geochemical processes. SOURCE: Winter et al. (1998; *http://water.usgs.gov/pubs/circ/circ1139/htdocs/natural_processes _of_ground.htm*).

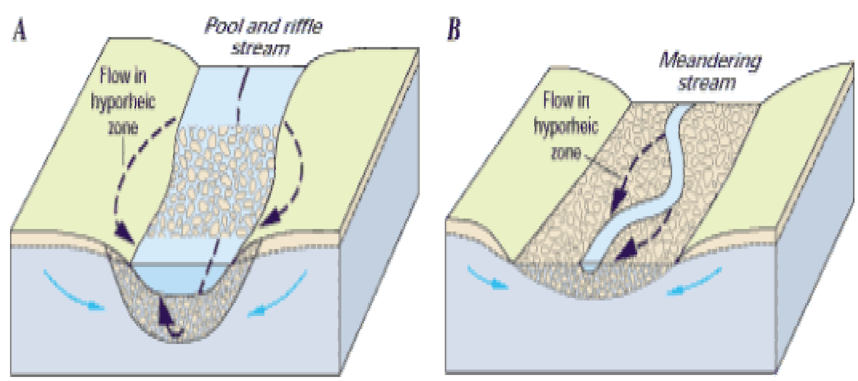

FIGURE 6-5 Water cycling between the groundwater system and streams (a) where pools and riffles create abrupt changes in the slope of the streambed and (b) at stream meanders. SOURCE: Winter et al. (1998; *http://-water.usgs.gov/pubs/circ/circ1139/htdocs/natural_processes_of_ground.htm*).

terms of biogeochemical transformations (e.g., Cirmo and McDonald, 1997; Grimm and Fisher, 1984; Harvey and Fuller, 1998; Hill et al., 1998; Hinkle et al., 2001; Triska et al., 1993) and as habitat for a wide variety of organisms (e.g., Hendricks, 1993). Fish and other biota are often highly sensitive to temperature and stream water quality at stream margins, which are partly controlled by the proportions of groundwater entering and leaving the stream.

Spatial and temporal gradients in dissolved oxygen, dissolved organic matter, and solutes can be profound in the hyporheic zone, which is where most nutrients and, logically, anthropogenic contamination to streams is processed (e.g., Harvey and Fuller, 1998; Jones and Mulholland, 2000; Nagorski and Moore, 1999; Schindler and Krabbenhoft, 1998; Winter et al., 1998). Geochemical changes in the hyporheic zone are coupled to microbiological processes (e.g., Hendricks, 1993).

The hyporheic zone controls not only transverse geochemical processes at the surface water-groundwater interface, but sometimes even longitudinal geochemical processes downstream (e.g., Wörman et al., 2002). The hyporheic zone in many places is the fundamental driver for geochemical processing and even weathering in watersheds over a wide range of hydrogeologic settings.

The clear linkage between the hyporheic zone and biological diversity and habitat there has made the study of hyporheic processes one of the richest areas for multidisciplinary research. Indeed, the hyporheic zone is now considered a distinctive ecotone (e.g., Vervier et al., 1992) wherein new instrumentation is being developed to better describe subtle and transient changes in pore-water chemistry and hydraulics (e.g., Duff et al., 1998; Geist et al., 1998).

It stands to reason that part of the scope of the NSIP could be tied to monitoring hydraulic and other parameters related to interaction in the hyporheic zone. For example, inexpensive pressure transducers or thermistors could be installed adjacent to small headwater streams to monitor directional changes in groundwater flow relative to the stream and the extent to which periodic flooding affects the fundamental hydraulics associated with floodplains. The data output from these devices could be sampled remotely along with stream stage. At the very least, the NSIP could provide reconnaissance data to help biological and hydrologic scientists determine where best to focus more detailed studies designed to determine the fate and transport of nutrients and anthropogenic contamination to streams.

Interdisciplinary research in hydrology, geomorphology, biology, and groundwater-surface water interaction is also being done at experimental watersheds operated by other federal agencies, such at the U.S. Forest Service and the Agricultural Research Service. Close coordination with the efforts of these agencies and the academic communities that work at these sites is, of course, desirable.

INFORMATION NEEDS FOR RIVER SCIENCE

There are two overarching information needs for river science. First, information must be generated that will promote an integrated, process-based understanding of hydrologic-geomorphic-biological linkages. A good example is channel geometry and bed material composition. These are critical information needs to evaluate the hydraulic characteristics of a river reach or even a whole network. They allow models of sediment and hydrologic routing to be used. 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.

Second, models should be developed that allow point information to be distributed spatially, both within the gaged watershed and into ungaged watersheds. Such interpolations will allow process-based models to be extended spatially. Equally as importantly, they will also allow biophysical comparisons between watersheds to be drawn that support classifications for research and management. Essentially, they provide a foundation for establishing the degree to which biophysical and geochemical processes have been altered by human activities and thus what kinds of management and regulatory actions might be required.

Both of these needs can be met only if there is an extensive streamflow gaging network that has representative coverage of the range of climatic and watershed characteristics across the United States. This section reviews the streamflow information available at NSIP gages and its suitability for the needs of the river science community as described above.

Streamflow Information Issues for River Science at NSIP Gages

As described earlier in this report, the streamflow information that is collected at gaging stations provides a wealth of information that can be used to evaluate the frequency and magnitude of floods that shape the channel and riparian vegetation. Flow duration information is also available for active streamgages and is used for geomorphic and ecological studies. Some problems with using these data for river science purposes are reviewed here:

• **Nonstationarity.** Hydrologic time series are the primary source of information used to construct water budgets at any particular spatial scale. Projections of future water yield or demand for human and ecological needs are based on these time series. These hydrological time series are usually assumed to be stationary, as in the Hydroclimatic Data Network. The robustness of this assumption has to be rigorously evaluated given the change in climate across the United States during the twentieth century. When the streamgage network was first established, it was thought that streamgages could have a limited lifetime to establish the characteristics of the flood frequency regime. Land-use change also influences hydrologic flux and therefore represents another source of non-stationarity in long-term hydrologic records. Even in watersheds minimally influenced by humans, vegetative cover can change naturally in response to climatic variations. For example, the precipitation regime can control the extent of vegetative cover in a watershed and the probability of fire that can eliminate established vegetation. Comprehensive integrated analyses of hydrologic-climatic-landscape linkages are needed to assess nonstationarity introduced by climate variations or land cover evolution. Such analyses provide information about the streamflow variability that is essential for analyzing ecosystem and geomorphic processes critical to river science.

• **Estimation of extreme events.** The USGS gaging network performs well in monitoring and reporting moderate- to high-flow conditions on the nation's streams and rivers. By comparison, low-flow measurements can be relatively poor because gages are better suited to measuring fully developed flow in open channels. Stream-flow technicians have to put significant effort into collecting stream discharge information at low flows to maintain a sufficient quality of data. Nonetheless, there is a great need for better low-flow estimation by many user groups of streamflow data, such as aquatic ecologists (Nilsson et al., 2003) and drought forecasters. There is also a need to collect information at sites other than gaging stations to develop low-flow estimation procedures.

• **Unit discharges.** In the current NWIS water information dissemination program, instantaneous discharges that provide essential hydrographic and peak flow information for streams are stored for 30 days after an event occurs. These data are essential for evaluation of channel stability, water and sediment routing, and so forth. **These data should be archived electronically in a retrievable form.** This is not as great an effort as it may seem. Daily mean discharge data are compiled by using the rating curve to convert each recorded stage value (e.g., each 15 minutes) to a corresponding discharge value. The resulting discharge values (the "unit values") are then averaged over a day to give the published value of daily mean discharge. The quality control process of checking that the recorded stage values are valid and that the rating curve is appropriate is already being carried out at the level of unit values so no further quality assurance would be needed if these values were published rather than simply the daily mean discharge values.

• **Crest stage data.** Crest stage data have been collected by the USGS in both past and present times. These data should be electronically archived and disseminated with other streamflow information. For some ephemeral streams, even in large watersheds, these may be the only data available. Further, as information technology continues to expand, historical records of extreme events will become increasingly important to researchers.

In addition to collecting and reporting streamflow data, the USGS typically collects non-flow information at NSIP gages, but much of this is not disseminated, which stymies advances in River Science. Collected but unreported information includes data on channel cross sections collected at gaging stations, bed particle size information, and flood survey data.

Importance of the Non-base NSIP Network for River Science

In previous parts of this document, we evaluate the core, or base, NSIP network. It should be emphasized, however, that the non-base network is also essential to evaluate regional channel geometry relationships, downstream changes in surface water-groundwater interactions, and other river science relationships.

For example, Andrews et al. (2004) used 38 non-NSIP gages in California to examine the influence of the El Niño-Southern Oscillation (ENSO) phase on flooding in coastal streams. They created a normalized El Niño flood magnitude for various recurrence intervals as the ratio of twice the El Niño flood divided by the sum of the El Niño and non-El Niño floods. The relative magnitude of El Niño floods with a five-year recurrence interval decreases with latitude (Figure 6-6), which explains 84 percent of the variation in relative flood magnitude between El Niño and non-El Niño phases in California coastal streams. This analysis further showed that depending on local orographic effects, ENSO floods can be significantly smaller than expected solely from latitudinal position, as seen for floods in Soquel and Corralitos Creeks, which lie in a rain shadow.

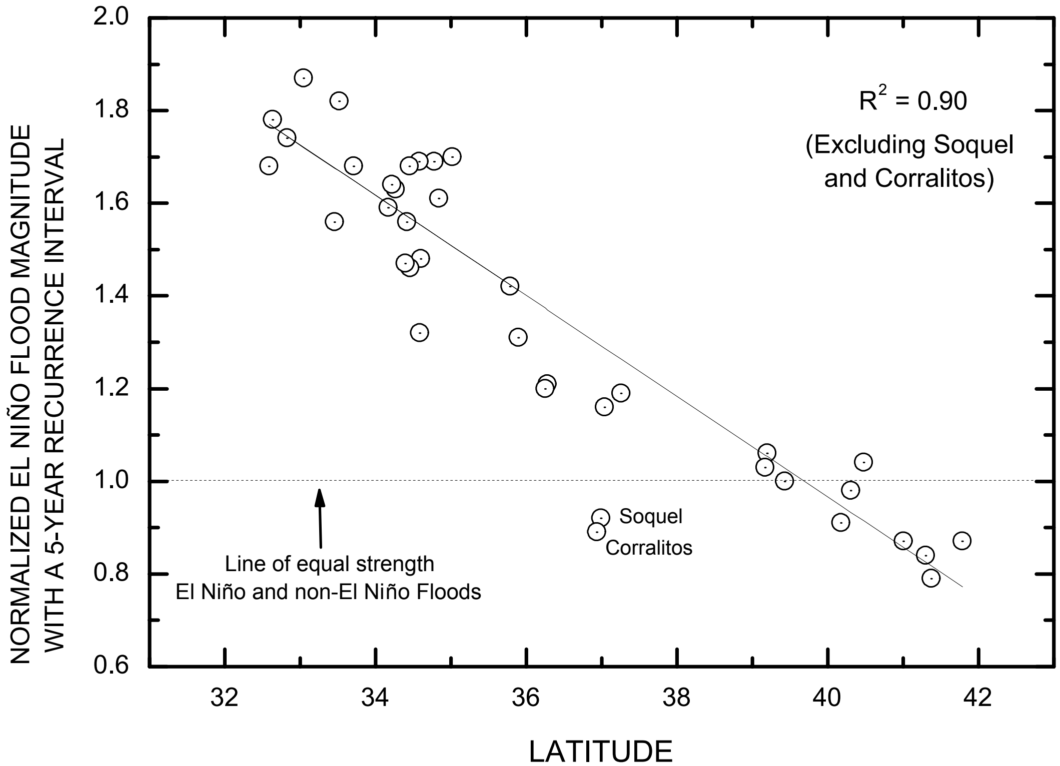

FIGURE 6-6 Relationship between normalized El Niño flood magnitude and latitude for 38 California coastal streams. SOURCE: Andrews et al. (in press).

SUMMARY

The NSIP data management system should be developed or designed with the capacity to integrate nontraditional or emerging data types, such as satellite imagery, velocity profiles from ADCM's, particle size information, channel mapping, etc. Developing and new technologies will require the capacity to store, manipulate, and disseminate more than simply "tabular records."

Data of relevance to river science that have not been archived electronically should be rescued, if necessary, by digitizing from paper records and made available on the Internet. Valuable information is contained in crest stage data, slope-area data from flood studies, and gaging station channel geometry and bed sediment characteristics.

The USGS should to continue to work on explicitly linking surface water to groundwater. This should be done in the context both of gages (estimating groundwater inputs) and of modeling.

The USGS should identify watersheds for which good hydrological information is available and land-use changes are documented. These sites should be prime sites at which hydrographic information is retrieved and stored to better understand how changes in land use affect hydrological characteristics. This will improve both planning and knowledge of the ecological and geomorphic consequences of land-use changes.

With the addition of channel morphology data, sentinel watersheds (Goal 4 of the NSIP) can provide not only hydrological reference points for the nation but stream morphology reference points as well. The representativeness of sentinel watersheds for characterizing the hydrologic and geomorphic diversity of the nation in support of river science should be explicitly evaluated.

Finally, this chapter raises as many questions as it answers. For example, which kinds of integrative river science questions should be investigated at the USGS and which are more appropriate for the broader scientific community? Within the USGS, how can monitoring efforts involving flow, sediment, chemistry, and biota be integrated? Also, what temporal and spatial scales should the USGS focus on? These are just three of a substantial set of issues that the USGS will have to resolve in order to design a truly effective program in the multidisciplinary science of rivers.