Flood management benefits of USGS streamgaging program

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National Hydrologic Warning Council

Front cover

Kettle Creek gaging station above US Air Force Academy, Pikes Peak in background (photo courtesy of USGS)

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USGS gage station (photo courtesy of USGS)

Making wise decisions to manage floods and their impacts requires information derived from data on stream behavior—both current and past. For more than 100 years, the US Geological Survey (USGS) has collected, managed, and disseminated these data, measuring and reporting on the behavior of US streams. The USGS currently operates and maintains a nationwide streamgaging network of about 7,400 gages at an annual cost of $114 million (costs given are for 2004).

The data are used by a variety of public and private users, including government agencies, researchers, and recreational interests. The data are used in a variety of applications, including emergency management, flood forecasting and control, hydropower, and watershed management. Using the data in these applications yields direct and indirect, tangible and intangible benefits. The tangible benefits represent real monetary savings to the public.

At the same time, USGS activities to collect, manage, disseminate, and analyze the data incur a real cost. Data collection, transmission, and management equipment—some of which is highly specialized—must be purchased, operated, maintained, repaired, and replaced. Highly-skilled scientists, engineers, and technicians must be employed for these tasks and for the task of applying knowledge to convert the collected data into information that is useful to the broad user community.

From the perspective of national economic development, safety and social well-being, the logical question that arises then is this: Does the benefit derived from the streamgage network, in whatever form, exceed the cost of building and operating the network? Equally important, as proposals such as the National Streamflow Information Program (NSIP) are put forward to expand the system is this question: Does the incremental benefit of an expanded network equal or exceed the cost of the expansion?

Task

The questions posed are broad and difficult to answer, for the value of the gage network is not intrinsic. Instead it is a value that is accrued when the network is integrated with appropriate analyses and actions. Estimating that value is the task we have undertaken herein. Our goal is to find, or at least define a range for the value of streamflow data and the system that collects and disseminates them. While the uses of streamflow data are many, as noted by NHWC (2006), here we limit our consideration to flood-related uses.

Actions

To complete the task, we describe first the data needed to solve flood problems and how those data are used for decision-making. In particular, we consider use of streamflow data for decision making regarding:

- Mapping floodplains for land use management.
- Planning and designing flood management systems and facilities.
- Flood warning and reservoir operating.

In each of these categories, we present examples, identifying the benefit attributable to the use of streamflow data in context. For each of the decision-making uses identified above, we present examples with real cost savings due to the availability of streamflow data. When reasonable, we expand from the examples to a general assessment. While we do not argue that the benefit yielded is due only to the gages and the data available from them, we argue that without the gages, the benefit would be significantly less.

Findings

...each of the uses yields benefits that exceed much of the cost of the USGS streamgaging network...

The benefits attributable to collecting the streamflow data cannot be separated from the benefit of analyzing and using the data for better decision making—just as the success of our drive to the office this morning cannot be attributed solely to a bolt that holds in place the steering wheel on the car. In that case, and in the case of the gages, the absence will surely preclude success, even if we cannot claim that success is only due to the presence.

However, we can infer values, based upon the economic benefit due to wise flood management at both the local and national level. For example, we found that:

- For Folsom Dam, CA upgrade costs including increasing the height of the dam, expanding the outlet capacity and constructing an auxiliary spillway could have been avoided if a long record of flows was available. The potential savings is equivalent to $63 million annually.
- For Mecklenburg County, NC increased certainty in floodplain mapping for land use regulations could help prevent $330 million in potential damages. If that cost is spread over 50 years, with a discount rate of 6%, the benefit is approximately $20 million annually.

The cost savings for just these 2 cases represents a significant portion of the $114 million annual cost of operating the USGS streamgage network.

Extrapolating from the examples to a national scale, we found that:

- Accurate design of levee improvements, using a long record of flows, can save potentially $7 million/mile. If just 20 miles of levees are repaired nationally, the savings is equivalent to $140 million. This cost savings of the 10,000 or more miles of federal project levees in the US exceeds the cost of operating the streamgage network.

- FEMA suggests that approximately 64,000 flood maps need to be updated. FEMA values data in hydrologic analysis at $4,400 / map. Thus, the value of updating the flood maps is about $56 million annually when spread over the 5 years outlined in FEMA's original flood map modernization project.
- In an earlier report, NHWC estimated the value of flood forecasts and successful reservoir operation at over $1 billion annually. If 3 to 5% of this benefit is attributed to the streamgage network, the benefit nationally is $30-50 million annually.

A common thread amongst all these examples is the benefit of long, continuous records of streamflow data. For example, to fit properly a statistical model that might serve as the basis for floodplain development regulation, a minimum of 10 years of data is needed, and 30 years or more is preferred.

The total benefit of the network is unknown. From consideration of the examples here, the benefit clearly exceeds the estimated cost of operating and maintaining the network. Each of the uses that we consider herein yields benefits that exceed much of the cost, even when considered in individual cases. Nationwide, the benefits of reducing flood damages or of improving the efficiency of measures designed to prevent damage and loss of life greatly exceed the cost of collecting the data through NSIP.

Flooding in Des Moines, IA (photo courtesy of A. Booher/FEMA)

Users and uses of USGS data

In a companion report, *Benefits of USGS streamgaging program: Users and uses of USGS streamflow data* (NHWC 2006), the attributable benefits of the 7,400 NSIP streamgage stations are identified and described through presentation of information about users and uses. Findings from the companion report are as follows:

- Data from the network are valuable to public and private users in various applications, such as the following:
    1. Planning, designing, operating, and maintaining the nation's multipurpose water management systems.
    2. Issuing flood warnings to protect lives and reduce property damage.
    3. Designing highways and bridges.
    4. Mapping floodplains.
    5. Monitoring environmental conditions and protecting aquatic habitats.
    6. Protecting water quality and regulating pollutant discharges.
    7. Managing water rights and transboundary water issues.
    8. Education and research.
    9. Recreational uses.

Forecaster from Lower Colorado River Authority (photo courtesy of LCRA)

  Each of the 9 categories listed above has a range of data users, data uses, and beneficiaries of the data. Each category provides benefits—either direct or indirect, tangible or intangible.

- The value of streamflow records increase over time. Streamgages with a long period of record are particularly valuable as they form a baseline for information about future changes.
- Online access to USGS streamgage records dramatically shortens the process for obtaining historical streamflow data. In the future, both the number of users and the ways in which the data are being used will increase, and the information's value will increase accordingly.
- Streamgages serve multiple uses. The same gage may provide useful information for water diversions, water quality monitoring, or floodplain mapping. Often, users have a one-time need for data. These ad hoc uses are difficult to properly value, but produce additional benefits that can be quite large over the period of record.

In this report we focus on a subset of users: those related to flood management. We identify here more specific roles for the USGS streamgage data and we assess the tangible value of the data in that context.

What are the information needs for flood management in the US?

Is flooding a problem?

Despite 100 years of effort to manage floods and to manage the vulnerability of people and property, flooding and flood damage continue to be a problem in the US. For example, Figure 1 shows total annual flood damage for 1983-2002. The average throughout this 20-year period has remained more or less constant, at about $5 billion. This is, in part, a consequence of citizens moving to lands subject to flooding and infrastructure and industry traversing or developing in areas at risk of inundation. In fact, flooding now causes more deaths and damage than any other weather-related phenomena, and three-quarters of all federally declared disaster declarations are due, at least in part, to flooding.

Clearly flooding is a problem in the US.

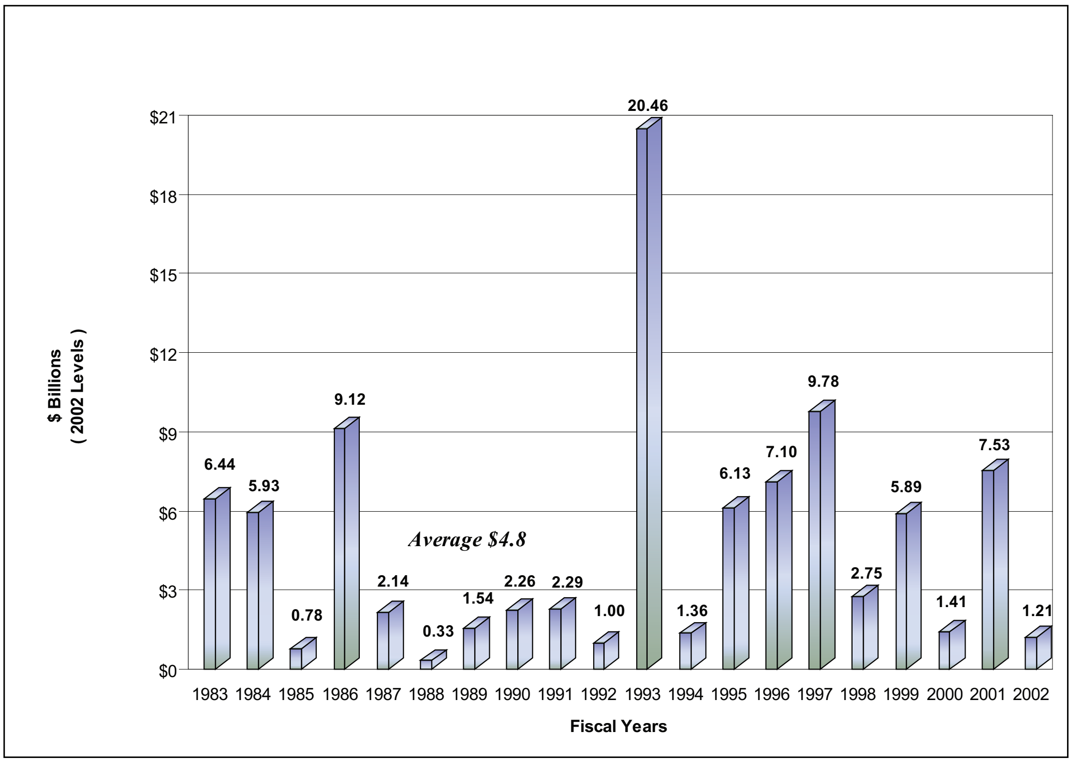


Figure 1. Flood damages in the United States, 1983-2002 (Pielke Jr. et al. 2002)

How is the flood problem solved?

In the US, there is a long history of working to reduce flood problems, at all levels of government. The federal government acts to reduce flood damages that have an adverse impact on the national economy, state agencies focus on intrastate flood problems, and city and county governments seek to reduce adverse impacts of floods within their jurisdictions. These agencies plan, design, construct, and operate facilities to meet these goals.

The facilities constructed and actions taken to do so can be categorized broadly as:

- *Construction and operation of structural (flood control) measures*. These are constructed facilities that control water in some manner. Detention ponds, for example, are constructed to store water upstream of vulnerable sites, releasing that water at a rate and at a time in which the adverse impact is minimized. Levees, on the other hand, are built to accept the water as it comes, but to keep it away from people and property by blocking the flow path, thus reducing the water level at the property.
- *Implementation of nonstructural measures*. These measures are actions taken, perhaps with some minor construction, to modify the susceptibility of property to damage. They reduce damage in the very near future and in the longer-term future. In the first case, for example, flood warning reduces flood damage in near real time by providing owners of property at imminent risk with timely information about the characteristics of that risk—how deep the water will be, when it will reach that depth, and so on. This advanced notice allows those owners to move or otherwise protect their property. Flood forecasting integrated with improved reservoir operation reduces flood damage in a similar manner, but by permitting operators to make better-informed decisions regarding storing or releasing water from a reservoir or the reservoirs of a system. Floodplain management also reduces damage, but by fostering wise use of property at risk. Floodplain land use ordinances—one tool of floodplain management—may effectively prohibit construction of residential housing in areas that have a 1 percent or greater chance of flooding in any year.

What information is needed to solve the flood problem?

Structural flood-control measure design needs

Major structural flood-damage reduction measures in the US are planned and designed to balance the cost of the protection provided by the measures with the risk-weighted damage incurred if the protection is not provided. For example, when decisions are taken by the US Army Corps of Engineers and local partners about raising Folsom Dam, upstream of Sacramento, California, planners will compare the cost of that raise with the cost of potential damage incurred by flooding in the region if the dam is not raised, weighing that flood cost by the long-term risk of the flooding. To do so, the planners require information about the magnitude of potential future hydrologic conditions—flows, volumes, water levels, and timing—and information about the risk or probability of those events. If an extreme event can occur, they must know the properties of that event. They must know also how likely that occurrence is. Is the risk 1 chance in 100 or 1 chance in 500? Greater investment is justified for the former case than for the latter, as the risk-weighted damage is greater. This information comes as a consequence of statistical analyses of streamflow information.

For smaller-scale flood management facilities, such as the stormwater drainage pipes and channels in our urban neighborhoods or the drainage facilities of highways, a decision about acceptable risk often is made first, then a cost-effective solution is sought. For example, culverts under roadways may be designed to carry safely flows that have a 1 in 50 chance of being exceeded. Such a decision is made considering implicitly the benefit and cost of larger and smaller levels of risk, including the indirect and intangible costs. A flow rate (or water level or volume) is determined for the selected risk, and the design of the least-costly, reliable solution proceeds.

Floodplain management needs

Similarly, decisions about floodplain management typically are made by defining first the acceptable level of risk, then identifying the floodplain area that would be inundated. Within this area, construction and development are controlled.

The common standard in the US is to constrain land use within the floodplain area that has a 1 percent chance of inundation to any depth. Information needed to identify this is a relationship of water level and frequency or probability, plus a corresponding geographic representation of the boundaries of the flooded area when the water reaches this level. The latter can be developed conveniently with geographic information system (GIS) tools and hydraulic analyses. The former require some form of statistical analyses, much like that required for structural design.

Flood warning, flood operations, and flood emergency responses needs

Hydrologic information needs for flood warning, flood operations, and flood emergency responses are slightly different than that required for design and floodplain management. While knowledge of the long-term risk is of interest, the time scale for decision making really focuses attention on conditions that are most likely to occur within the next few hours or days, rather than on the risk over the long term. For operation of flood control space in reservoirs along the Lower Colorado River of Texas, managers need information about likely inflows within the next few days; if high flows are expected, non-damaging releases now may be possible to empty storage space for future inflows. For example, for flood warning in the flood prone areas of Fort Collins, Colorado, emergency managers and others require information about how high the water will rise in the next few hours, so that they can act to move people and property out of the potentially inundated area.

Flood inundation map, Fort Collins, CO (photo courtesy of David Ford Consulting Engineers)

Where is that information found?

As with most natural phenomena, watershed and channel processes that lead to flooding are complex and not perfectly understood. This complexity precludes analysis of all contributing factors as a method of developing the required information. For example, a mathematical model cannot be created of all that happens in a watershed and used to predict flooding. Our understanding of the process is not sufficient, nor is our ability to measure or otherwise observe all the critical properties of the watershed. Consequently, empirical models are used: models that use information about past behavior to predict or forecast future behavior.

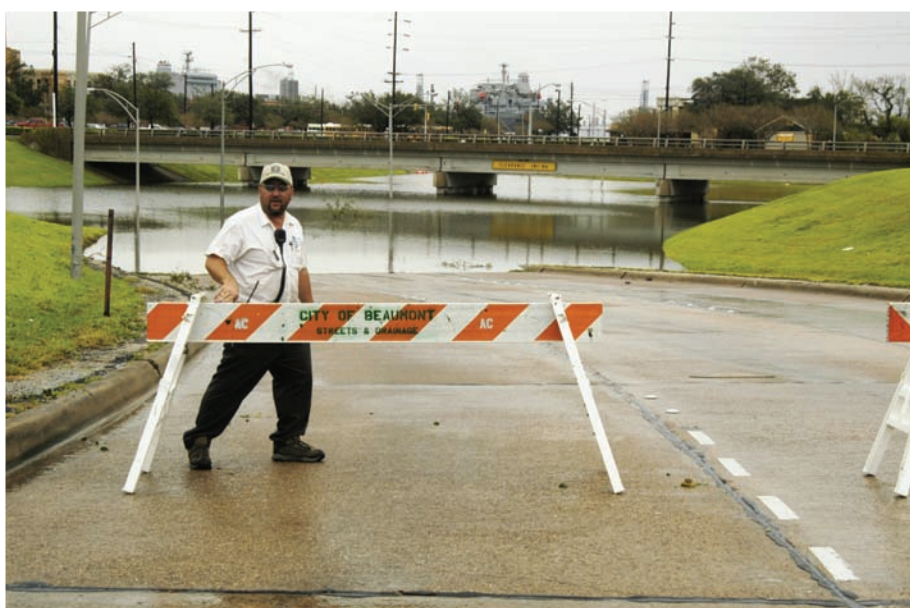
In flood management, these empirical procedures include:

- Statistical model fitting for design flow estimation.
- Empirical models for design flow estimation.
- Rainfall-runoff modeling.

Each of these is described in more detail in Appendix I.

A common thread amongst these procedures is that they all rely on historical streamflow data for development, calibration, and validation of the predictive tools. For this, as illustrated and described in Appendix I, longer, stable, consistent data sets are needed. For example, to fit properly a statistical model that might serve as the basis for floodplain development regulation, a minimum of 10 years of data is needed and 30 years or more is preferred.

Of course, engineers and hydrologists will make design, management, and operation decisions with less data. They do so almost every day. But they are less certain about the decisions as a consequence of the sparse data sets. In a nutshell, to estimate reliably the design flows of interest or to forecast well flood flows for emergency response a long, continuous streamflow data set is necessary.



Flooded underpass, Beaumont, TX (photo courtesy of L. Roll/FEMA)

How is the information need met?

Resolution of the problem requires information derived from streamflow data. To provide these data for flood-related uses and other purposes, the USGS operates and maintains a nationwide streamgaging network of about 7,400 gages at an annual cost of $114 million (costs given are for 2004). At these gages, water level is measured continuously, along with other weather and environmental states. Subsequent analyses provide peak flow, low flow, seasonal variations, hydrographs, volumes, impacts of development and facilities, and other valuable information.

> *...national investment in the streamgage network is appropriate, as the data and information provide a variety of national benefits...*

The network is supported by funding through the USGS's Cooperative Water Program, the USGS, NSIP, other federal water and environmental agencies, and approximately 800 state and local funding partners.

USGS activities to collect, to manage and disseminate, and to analyze the data collected incur a real cost. Data collection, transmission, and management equipment—some of which is highly specialized—must be purchased, operated, maintained, repaired, and replaced. Highly-skilled scientists, engineers, and technicians must be employed for these tasks and for the task of applying knowledge to convert the collected data into information that is useful to the broad user community. For example, expert statisticians and hydrologists are needed to complete the analyses to derive the often-used regional regression equations and modeling analyses.

Direct measurements by USGS hydrographers (photo courtesy of USGS)

Intuitively, national investment in the streamgage network seems appropriate, as the data and information provide a variety of national benefits. The companion report categorized these benefits as tangible or intangible, direct or indirect. A National Research Council (NRC) study in 2004 characterized streamflow information as a public good because (1) those who have not paid for the service (the majority of users) are not excluded from using it, and (2) the marginal cost of servicing additional individuals is zero (NRC 2004). For example, if individuals safely cross a stream during a flood, traveling on a roadway bridge that is properly sized to span the high water, no cost is incurred. Instead, the cost is borne as a component of the national investment in economic development and social well-being.

Other national-scale, competing investments also provide for national economic development and social well-being. Thus the logical question is this:

- Does the benefit derived from the streamgage network exceed the cost of building, operating, and maintaining this network, thereby justifying the investment?

Equally important, as proposals such as NSIP are put forward to expand the system:

- Does the incremental benefit of an expanded network equal or exceed the incremental cost of the expansion?

The questions posed are broad and difficult to answer, for the value of a single gage or the network itself is not separable. That is, outside of the context in which the data collected are transformed to information for decision-making, the gages and the data have no intrinsic value. Instead the benefit from the gages accrues when the network is integrated with appropriate analyses and actions. Similarly, the analysis that uses the data—be that for design, floodplain management, operation, or emergency response—has no separable value absent the gage network.

Accordingly, we consider in the remainder of this report the benefit of the data and the collection system, when integrated with appropriate evaluation and action. We limit our consideration to flood management here, noting that, in fact, the benefits extend to all uses identified in the companion NHWC report.

USGS field operations (photo courtesy of USGS)

What is the benefit of meeting the information need for floodplain mapping?

The National Flood Insurance Program and mapping

The NFIP, which is administered by the Federal Emergency Management Agency (FEMA), was introduced in 1968 as a way to assist families devastated by flooding and to promote safe development in floodplains. Currently, nearly 20,000 communities is the US participate in this program. These communities receive taxpayer-financed insurance subsidies on existing buildings, in exchange for which they must use their land and construct new building in ways that reduce the risk of flood damage (Hunter 2006). The program discourages communities from developing in areas subject to inundation with annual probability 0.01 or greater. This is commonly called the 100-year flood.

The area that would be inundated by the 100-year flood commonly is displayed in a map, as illustrated in Figure 2. The water surface is represented in the map by the shaded polygon adjacent to the stream channel; property within that polygon would be under the water if the event occurred. For example, land along Hitchcock Way in the figure will be inundated should the 100-year flood (or a larger flood) occur. Development within this area will require that new buildings be elevated to at least the 100-year level, often with more strict local ordinances.

Figure 2. Example regulatory floodplain map

Benefit from data

How the data are used

To create a map such as that shown in Figure 2, analysts commonly take the following steps:

1. Estimate the 100-year (p=0.01) discharge rate, using previously described methods.
2. With the 100-year flow from step 1 as input, compute, with a mathematical model of stream hydraulics, the water-surface elevation along the channel and in the adjacent floodplain if flow exceeds the channel capacity. This elevation, which is referred to as the base flood elevation (BFE), is the basis for regulation.
3. Combine the computed BFE with terrain data to develop the map. In general, land with elevation less than the BFE is shown within the regulatory floodplain, and land with elevation above is not. This step is accomplished conveniently with GIS tools. This step requires topographic data, which, in many cases, are collected, managed, and distributed by the USGS.

Error in the 100-year flow determination directly affects definition of the BFE, and this, in turn, affects delineation of land that is subject to regulation.

If the flow is underpredicted, the BFE also will be underpredicted. (This presumes that the hydraulics model and terrain data are without error.) If the BFE is underpredicted, the inundated area defined will be smaller than the area truly inundated by the regulatory flood. Property that is at risk will not be included in that case, and necessary restrictions on development will not be imposed. This will lead to increased property damage over the years and to increased risk for occupants of the structures.

Flooding in Mecklenburg County, NC (photo courtesy of Mecklenburg County)

Conversely, if the flow is overpredicted, the BFE also will be overpredicted, and the mapped inundation area will exceed the area that truly should be included. This, in turn, will lead to restrictions on development in areas that need not be restricted. Property there may decrease in value due to the limitations on construction. Development may shift elsewhere, or if construction does take place, it will be more costly as a consequence of the requirement that the structures be above the BFE.

Good quality data will reduce the likelihood of over- or underpredicting the regulatory flow, and hence the BFE and the inundated area. The improved accuracy, in turn, leads to economic benefit due to (1) reduced flood damage to property properly kept out of harm's way, and (2) maintained land values and reduced construction costs in areas truly at lower risk.

...streamflow estimates using data with short histories have large errors ...

Errors with short records

Thomas (2004) related errors in statistical estimates of 100-year streamflows to the record length of the streamgage, and in turn, related the streamflow errors to a corresponding error in flood depth. Thomas demonstrated that statistically computed streamflow estimates using gage data with short histories have large standard errors, but also noted that the uncertainties using regional regression equations and rainfall-runoff modeling are even higher—a finding that is consistent with information from the Corps of Engineers (shown in Table 5). Thomas found that for a location in the semiarid western part of the US with record of less than 30 years, standard errors for statistical estimates of the 100-year streamflow exceed 100%; the corresponding standard errors in flood depth exceed 34%. Thus, for a stream depth of 10 feet, the error in defining the BFE could exceed 3.4 feet. Thomas' analysis showed that standard errors for eastern streams, while lower, were still significant. For locations with 30 years of record or less, the standard error for the 100-year flow is 30%, and the corresponding error in depth would be about 12%.

Lacking any streamflow record at locations of interest, or lacking a sufficiently long record with which a statistical model can be fitted reliably, many floodplain mapping studies use regional regression or rainfall-runoff modeling to establish the regulatory flow. The implications for land use regulation are significant. Standard errors for regional regression equations in the USGS National Flood Frequency program (Ries 2005) are summarized in Table 1. Due to the short record upon which those are based (following Thomas' logic), about half of the regression equations will produce estimates of peak flows with errors in the 30 to 50% range. About 40% of the equations will produce errors of 50% or more for 100-year and 200-year peak flow estimates. Only about 1 in 8 equations will yield a 100-year flow estimate with a standard error of 30% or less.

This has a direct tangible economic "downside."

Table 1. Standard errors for regional regression equations

Standard error (% of flow) (1)	% of equations in error range for event shown			
	25-year (2)	50-year (3)	100-year (4)	200-year (5)
error>70%	10	11	13	10
50%<error<70%	22	24	26	31
30%<error<50%	50	50	48	50
error<30%	17	14	13	9
No. of equations in sample	*307*	*307*	*307*	*98*

Benefit of avoiding errors: Case study from Mecklenburg County

An example that illustrates the linkage between streamflow data, BFEs, and avoidable floodplain property damage comes from Mecklenburg County, North Carolina. That county, a leader in proactive floodplain management, funded a study in 2000 to determine the following:

...streamflow data yield accurate estimates of regulatory floods, avoiding $330 million in flood damages in North Carolina...

- Increase in BFE due to land use changes since a 1975 study.
- Potential property damage from higher flood peaks due to future development - when property in a watershed is fully developed according to the land use master plan (a condition referred to as build-out).

The Mecklenburg study found that the average BFEs, based on ultimate build-out of the County's 24 watersheds, were 4.3 feet higher than BFEs based on 1975 maps and land use. About half of the 4.3 feet increase was due to land use changes between 1975 and 1999, while half of the increase was projected from future development expected to occur between 1999 and build-out. The County's economic analysis found that more than $330 million in flood damages to structures and contents would be avoided if the County adopted effective floodplain management measures and regulated future development to account for that increase (ASFPM 2004).

Thomas' results of flow errors can be used to make the connection between streamgage data and these avoidable flood damages (Plasencia 2005). The Mecklenburg County study analyzed 17 watersheds and compared damages with the current building inventory to the damages that would occur in the future based on projected development. Of the $330 million in avoidable damages described above, 86% fell within 5 watersheds that have the highest projected growth. While the difference in BFEs in their studies was due to an increase in peak runoff from the effects of future development, differences of a similar magnitude would be expected from a hydrologic analysis that has errors consistent with those expected from analysis with 30 years of record.

The 100-year water surface profiles for the 5 streams in Mecklenburg County that comprise the bulk of potential flood damages show channel depths that range from 18—22 feet. From Thomas' estimates for eastern streams with 30 years of record, the 12% error in flood depth corresponds to uncertainty of 2.2—2.6 feet for BFEs for these streams. These depth differences are comparable to the increase in BFEs that the County's study predicted between 1999 and build-out. Therefore, it is inferred that the magnitude of potential economic benefit due to reducing hydrologic uncertainty is comparable to the $330 million in damage avoided with enhanced regulations in Mecklenburg County over the lifetime of the project.

It should be noted that Mecklenburg County has made a substantial investment in streamgaging. The County funds 55 streamgages in the County or in the vicinity, with operation and maintenance provided by the USGS. The County has concluded that the benefit from this investment offsets the cost, as the additional hydrologic records define better the baseline conditions to support wise floodplain management, avoiding future flood damages.

Benefit of avoiding errors on a national scale

On a national scale, many fast-growing communities are facing similarly complex floodplain management decisions, and wise decision making for those will require accurate floodplain mapping.

Table 2 shows the 10 fastest growing counties between 2000 and 2005 that have special flood hazard areas. If the counties that need to update their flood insurance rate maps (FIRM) have cost savings similar to Mecklenburg County, more accurate estimation of the BFE possible with lengthened data sets may well exceed the cost of operating the streamgages.

Table 2. Fastest growing counties[1] with special flood hazard areas (US Census Bureau 2006; FEMA 2006)

County (1)	Percent increase between 2000 and 2005 (2)	Current effective FIRM (3)
Flagler County, FL	53.3	07/15/92
Loudoun County, VA	50.7	07/05/01
Rockwell County, TX	46.1	09/17/80
Kendall County, IL	45.8	05/15/02
Forsyth County, GA	42.7	06/18/90
Douglas County, CO	41.9	09/30/05
Henry County, GA	40.6	05/16/06
Lincoln County, SD	38.2	10/01/86
Paulding County, GA	37.8	11/08/99
Lyon County, NV	37.7	11/20/98

[1] *Counties with 10,000 or more population in 2005.*

How does FEMA value hydrologic data?

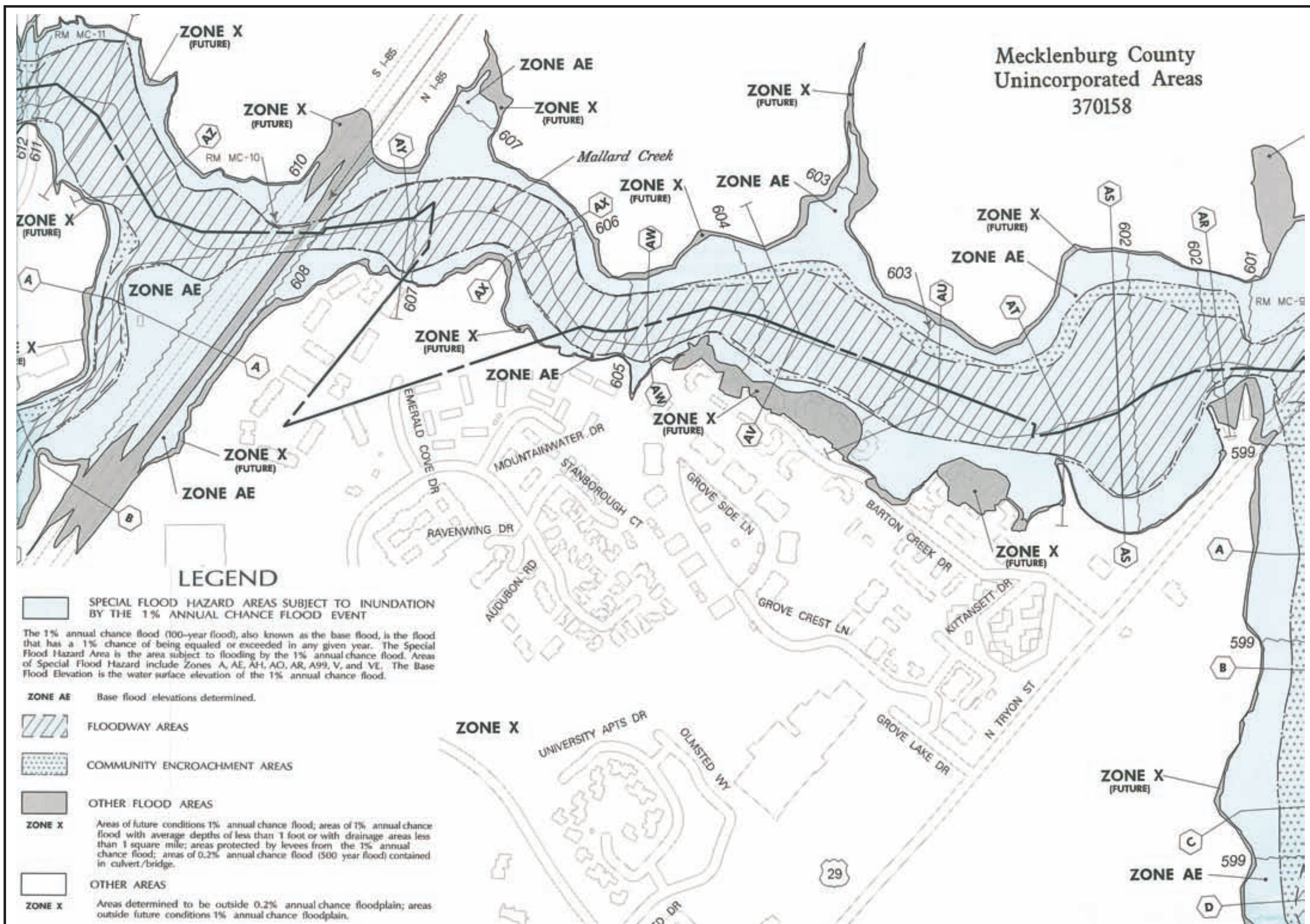
FEMA's *Blue Book* (2002) identifies monetary credits for technical contributions that cooperating partners make towards flood mapping. For detailed riverine hydrologic analysis, FEMA credits a cooperating agency $1,100 / stream mile to develop 100-year flow estimates with rainfall-runoff models, regional regression equation methods, or statistical analysis of annual flood peaks from gage data. (Note: This is not the total cost of delineating the floodplain. FEMA credits a cooperator $2,500 / mile and $1,400 / mile for computing the floodplain elevation and delineating the floodplain, respectively.)

As noted earlier, all three hydrologic analysis approaches have a foundation in streamflow data. We argue that without the data to develop or apply those approaches, we cannot estimate the flows and water levels for regulation. Without the regulatory water levels, we can produce no maps. Without the maps, we have no knowledge for wise floodplain land use regulation, and future damages will not be reduced to the extent possible.

To infer from this the benefit, it is assumed that the value of estimating the regulatory flows equals the cost that FEMA is willing to incur to do so.

A 2005 Government Accounting Office (GAO) report addressed the need to update flood maps. The GAO report cited FEMA statistics showing that nearly 70% of the nation's 92,000 flood maps or 64,000 maps are more than 10 years old and should be updated. In 2000, FEMA analysis of digital flood data for communities in the US showed an average of 4 miles / map panel. Using the FEMA credit for hydrologic analysis of $1,100 / mile, the cost of hydrologic analyses to estimate 100-year streamflows is $4,400 / map. Thus the value of hydrologic analyses to develop 100-year base flood discharge for the maps that are to be updated is about $280 million.

Since updating flood maps is a multiyear process, we think it reasonable to spread the estimated value over 5 years, the original duration for FEMA flood map modernization. Ignoring the time value of money in this short period, we estimate the cost as $56 million / year. This benefit alone represents approximately 50% of the $114 million annual cost (USGS 2006) of operating the streamgage network.



Example of updated Mecklenburg County FIRM

What is the benefit of meeting the information need for flood management project design?

Knowledge of flood volumes, peak flows and corresponding water levels, and the timing of the runoff from watersheds are basic requirements for planning, designing, and operating cost-effective flood management projects. These are projects with structures that keep damaging floodwaters away from property and people. The structures range from large dams upstream of major urban centers to small culverts beneath rural roadways.

Oroville Dam spillway (photo courtesy of California DWR)

How are these projects planned and designed?

Flood management projects commonly are planned and designed either to provide a selected level of protection from flood risk or to yield maximum economic return. In some special cases, the projects are designed to eliminate the risk to the extent practical.

Design for specified risk

With this strategy, an acceptable risk is identified as a matter of policy, and the facility is designed to provide that. For example, Table 3, from the Texas Department of Transportation (TxDOT) hydraulic design manual, shows that acceptable risk or level of protection varies for facilities designed and constructed by that agency. To plan and design a freeway culvert for TxDOT, for example, the project engineer determines the 50-year (p=0.02) discharge, and then sizes the culvert to pass safely that value. He or she will also estimate the 100-year flow and check performance of the facility with that.

Design for maximum benefit

Larger flood management facilities are designed in a similar manner, using risk measures. However, that information often is used in a slightly different way. Rather than considering a single event and designing to avoid its consequences, this design standard considers the full range of likely events and their consequences and seeks to strike a balance between risk, benefit, and cost.

For example, for design of a levee, the Corps of Engineers standard is to select from alternative designs the one that would maximize net benefit without having an adverse impact on the environment. Net benefit is the long-term benefit attributable to the chosen alternative, less the cost of planning, designing, constructing, and operating that alternative. This long-term benefit, in large part, is the economic value of inundation damage reduction due to the project.

Damage reduction in this case is not computed for a single flood event. Instead, it is computed as the statistical average for all likely flood events. Practically, that is accomplished by defining the complete flow or water level frequency relationship for the location(s) of interest, transforming that to a damage-frequency function using relationships between inundation depth and potential damage, then integrating the result. The procedure for this is well known and well described in Corps of Engineers documents (USACE 1996) and computer software (USACE 1998).

Table 3. Texas Department of Transportation design standards (modified from TxDOT 2004)

Functional classification and structure type (1)	2-year (2)	5-year (3)	Design 10-year (4)	25-year (5)	50-year (6)	Check 100-year flood (7)
Freeways (main lanes):						
• Culverts					X	X
• Bridges					X	X
Principal arterials:						
• Culverts			X	(X)	X	X
• Small bridges			X	(X)	X	X
• Major river crossings					(X)	X
Minor arterials and collectors (including frontage roads):						
• Culverts		X	(X)	X		X
• Small bridges			X	(X)	X	X
• Major river crossings				X	(X)	X
Local road and streets (off-system projects):						
• Culverts	X	X	X			X
• Small Bridges	X	X	X			X
Storm drain system on interstate and controlled access:						
• Inlets and drain pipe			X			X
• Inlets for depressed roadways[1]					X	X
Storm drain systems on other highways and frontage:						
• Inlets and drain pipe	X	(X)				X
• Inlets for depressed roadways[1]				(X)	X	X

[1] *A depressed roadway provides nowhere for water to drain even when the curb height is exceeded.*

[2] *Parentheses indicate desirable frequency.*

Design for negligible risk

Related to design for a specified risk is design for the case in which risk should be at or approaching zero. This is the standard for planning, designing, and constructing flood management structures for which failure would cause significant loss of life and extensive property damage. Such standards are used, for example, for design of the spillway on a large dam.

In that case, rainfall-runoff models are used, with inputs derived through climate studies that seek to define the probable maximum precipitation (PMP) for a watershed. This is defined by the World Meteorological Organization (1983) as a "…quantity of precipitation that is close to the physical upper limit for a given duration over a particular basin." Chow *et al* (1988) suggest that this PMP can have exceedence probability from 0.001 to 0.000000002.

What information is needed for this planning and designing?

Methods

...the benefit for planning and designing flood projects is attributable to costs avoided through good design based on adequately long records...

Planners and designers commonly acquire information needed for flood project design via statistical model fitting, empirical models for design flow estimation, or rainfall-runoff modeling. Designs for specified risk or designs for maximum benefits can be developed with any of these methods. PMP design, on the other hand, commonly relies on rainfall-runoff modeling, as the events of interest clearly exceed those experienced.

Role of streamflow data

The role of streamflow data in design for specified risk has been described earlier: It provides the foundation for developing design flows. If a streamgage with adequate records is located at or near the site of a proposed structural measure, then a statistical model can be fitted to the data. In the absence of that, regression equations can be developed with data from similar sites. If the information needs cannot otherwise be met, a rainfall-runoff model can be created. In that case, streamflow data provide the basis for calibrating and verifying the model.

Streamflow data play a critical role in estimating the PMP runoff too. For PMP runoff analyses, the rainfall-runoff-routing model that will be used must be calibrated, which is accomplished best by configuring a model with estimates of parameters computing and comparing with historical observations, then adjusting iteratively to reach a good representation of the response of the watershed, channel, or reservoir system.

Benefit from data

The benefit of streamflow data for planning and designing flood projects is attributtable to costs avoided through good design based on adequately long records. This is illustrated here with two examples from California.

Flood storage in Folsom Reservoir

Folsom Dam and Reservoir, was constructed in the 1950s on the American River in California, east of Sacramento. This multipurpose reservoir was sized using hydrologic records collected from about 1905 until 1940.

Folsom Dam (photo courtesy of USBR)

Examination of the longer record available now shows that the 5 largest flood events on the American River have occurred since 1950. Recent flood studies with the longer record indicate that the original flood reservation space, which was thought to provide protection against at least the p=0.004 flood, is, in fact, too small to provide that level of protection to the Sacramento metropolitan region.

To remedy this, the Corps of Engineers, US Bureau of Reclamation (USBR), and local governments have proposed measures that will enhance the protection, including increasing the height of the dam, expanding its outlet capacity, and constructing an auxiliary spillway. Estimated project costs to retrofit Folsom Dam are on the order of $1 billion. To accommodate greater flood control releases, substantial levee improvements have been completed, and more are planned. The total authorized cost of these levee improvements exceeds $20 million.

As the design for Folsom Dam was optimized originally to provide the selected level of protection, we conclude that for this case, a longer record would have defined more accurately the true value. If so, the subsequent costly modifications could have been avoided, thus saving the $1 billion or more investment. If that cost is amortized over 50 years, with a discount rate of 6%, the annual equivalent cost is about $63 million. Such a cost savings—for this project alone—offsets much of the annual cost of operating and maintaining the USGS streamgage network. Considering that the Corps alone operates 541 reservoirs and has interests in another 150 – 200 for flood control issues (USACE 1992), the potential savings in dam modifications alone may far exceed the cost of the entire streamgaging network.

Is it fair to attribute all this benefit to the gages alone? Perhaps no more fair than attributing the success of our drive to the office this morning to a bolt that holds in place the steering wheel on the car. In that case, and in the case of the gages, the absence will surely preclude success, even if we cannot claim that success is only due to the presence.

Central Valley levee system

...overspending for 20 miles of levee repairs in a year would offset the annual cost of operating the USGS streamgage network...

The need to strengthen the flood defense system in California's Central Valley provides an additional example of the value of streamgages and the benefit attributable to long records of river stages and flows.

The Sacramento River Flood Control Project, planned, designed, and constructed in the early 1900s, protected agricultural areas with a network of levees and flood bypasses. With rapid urban development in recent decades, these same system levees now protect residential, commercial, and industrial property with high value. This growth, coupled with the larger flood events that have occurred in recent decades, has spurred investigation of the system reliability and capability to provide the desired level of flood protection.

Since 1986 the federal government, State of California, and local agencies have spent hundreds of millions of dollars to raise levees, construct deep slurry walls inside them, or place seepage berms alongside. Representative unit costs for levee explorations and these repairs include the following (Mayer 2006):

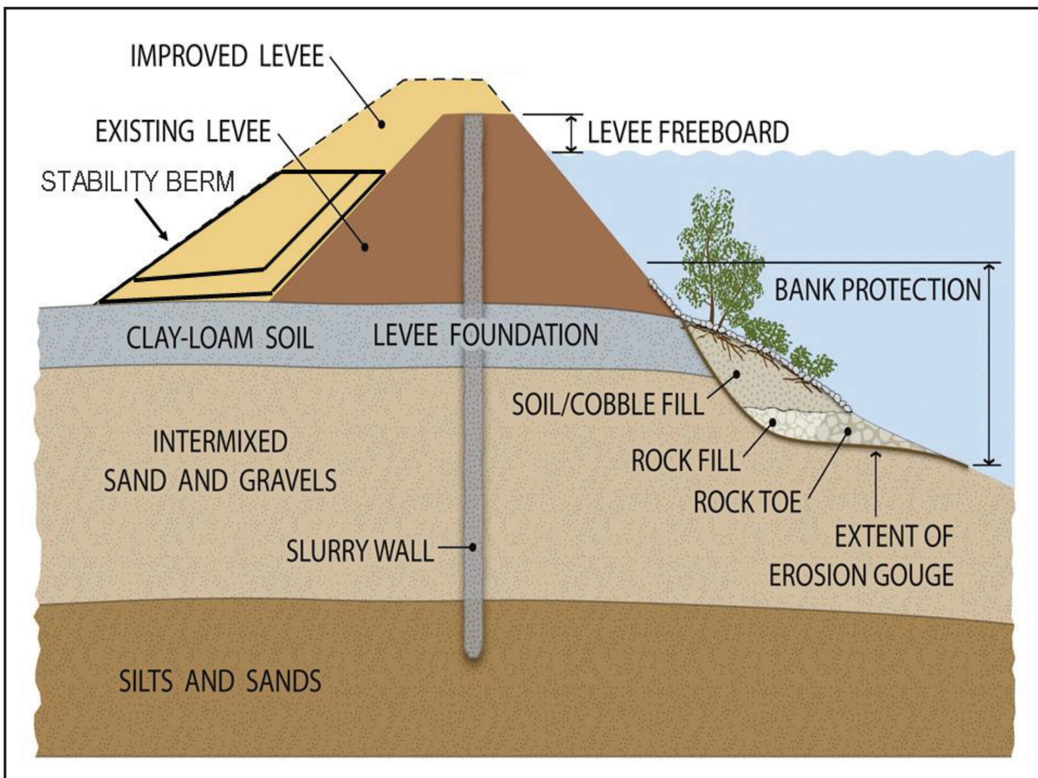
- Geotechnical borings of levees cost approximately $100,000 / mile for explorations at the riverside toe, landside toe, and a deep boring from the levee crest.
- Levee bank protection ranges from $1,000 to $9,000 / foot.
- Seepage berms cost approximately $500,000 / mile with existing right-of-way; however, some projects cost several million dollars / mile.
- Deep slurry walls cost at least $3 million / mile. A recent study to fix 25 miles of levees in Sutter County estimated the cost at $7 million / mile (Dickey 2006).
- New levees cost approximately $20 million / mile.

Levee repairs in California's Central Valley (photo courtesy of California DWR)

Clearly with these high costs, decision makers do not want to err in determination of appropriate remedial actions. That is where the requirement for data enters the picture.

The appropriateness of a slurry wall or a seepage berm is determined from seepage computations. These consider the height of the water against the levee for the design event. This height is found, as it is for floodplain mapping, by finding first the flow rate of specified probability, then determining with a hydraulics model the corresponding water level.

Error in the design flood elevation, the likelihood of which increases with short or inadequate streamgage data, could lead to incorrect decisions about the need for repair or the best measure to use. The difference is significant, with an additional $3 to 7 million / mile required for the slurry wall. Overspending for 20 miles of levee repairs nationwide in a year would offset the annual cost of operating the USGS streamgage network. Considering that the Corps has responsibility for maintenance and repair of almost 10,000 miles of levees nationwide, the cost savings could be tens or hundreds of millions of dollars. Similarly, failing to repair or strengthen levees for which that work is justified could lead to failures and the consequent avoidable damage.



Sacramento area levee improvements (photo courtesy of SAFCA)

What is the benefit of meeting the information need for flood warning and reservoir operation?

Flood warning and successful reservoir flood operation share a common objective and a common requirement. Both seek to provide more time to make better decisions about responding to and managing floods. To do so, both flood warning and flood operations require timely and reliable precipitation and weather data for forecasting. Combined with timely and reliable data on current and recent streamflow these permit confirming and adjusting the forecasts to conform to reality.

Where does the time go?

Figure 3 illustrates how time is spent responding to floods as they occur. The triangles represent milestones in the process, the last of which is exceedence of a threshold at which property is damaged, injuries occur, or lives are lost. If warning is available prior to that, some mitigative actions can be taken. The goal of a flood warning system is to ensure that this is so. Similarly, with flood operations of a reservoir, the goal is to provide more time to use better the storage available, perhaps releasing water now in anticipation of future inflows.

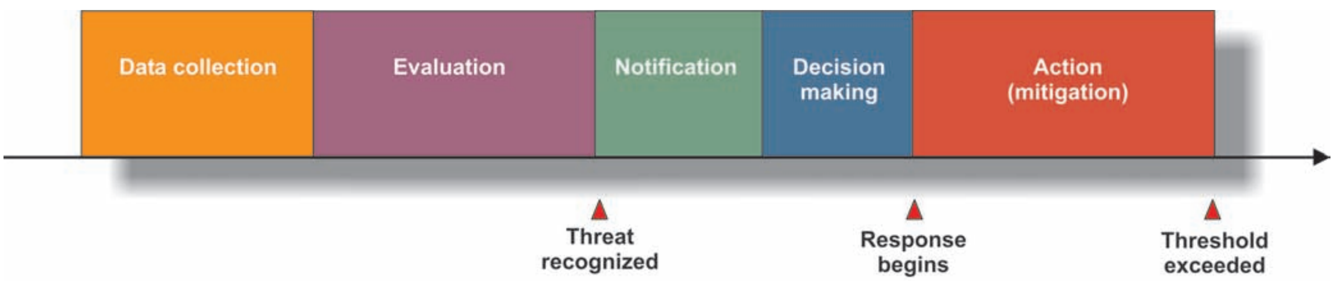


Figure 3. Illustration of warning timeline (Carsell et al. 2004)

The maximum potential warning time is the time between the first detectable or predictable precipitation and the time at which water level exceeds the threshold for damage or threat to life at a critical location. Of course, this time varies from storm to storm and location to location. For example, if damageable property in a watershed is near the outlet, and if a short duration thunderstorm is centered near the outlet, the maximum potential warning time would be small. On the other hand, if the storm is centered at the far extent of the watershed or if a forecast of the precipitation is available before it actually occurs (a quantitative precipitation forecast), the maximum potential warning time for this same location would be greater. Similarly, the watershed state plays a role in determining the maximum potential warning time: If the watershed soils are saturated, the time between precipitation and runoff is less than if the watershed soils are dry. Snow pack conditions are important as well. Storms may add to or rapidly deplete the snow pack, thus causing greater potential for flooding.

Practically, response to a flood threat, either for reservoir flood operations or for flood emergency response, does not occur from the very onset of or prediction of precipitation. The actual mitigation time—the time that exists to protect people and property or to adjust reservoir operations—is less than the maximum potential warning time. Some time is required to detect the event—to collect and transmit hydrometeorological data (labeled *Data collection* in the time line in the figure), to review these data and to forecast future conditions to the precipitation (labeled *Evaluation* in the figure). After the forecast is developed, additional time (identified as *Notification* in the figure) is required for forecasters to provide the product to emergency responders at critical locations in the basins or to reservoir operators. These responders or operators take some time to evaluate the product, to identify vulnerable people and property or reservoir operation options, and to make decisions about what to do. This time is labeled *Decision making* in the figure.

Finally, response begins and actions are taken. The block labeled *Action* in the figure represents this. For emergency response, these actions include protection of lives and property. For reservoir flood operation, these actions include adjusting releases to accommodate the need for more or less empty flood-control storage in the near future.

How are threats detected and forecasts made?

Procedures for flood threat detection and forecasting for emergency response or for reservoir operation vary from site to site in the US, depending on the needs. For example, snowmelt runoff forecasting, critical for the Central Valley of California, is not considered for the Rio Grande Valley of Texas. The requirements for forecasting runoff in a small urban watershed differ from those of large rural watersheds. Nevertheless, the threat evaluating and forecasting procedures followed by the National Weather Service's (NWS)

Flood Operations Center, California DWR (photo courtesy of California DWR)

California-Nevada River Forecast Center (CNRFC) illustrate well the sequence of events and tasks completed. Those include:

1. Inspecting the current state of the system to identify any existing threats due to high water in rivers or streams.
2. Predicting future runoff into channels and reservoirs from observed and forecast precipitation on watersheds.
3. Identifying and incorporating operation of water control features.
4. Predicting stream response as a flood wave moves through the system.
5. Predicting performance of the levee and weir system and the consequences of any failures of that system.

Threat detection: current conditions

Flood threat detection relies on receipt of field reports and on inspection of data available in the CNRFC database (which is operated and maintained cooperatively with the California Department of Water Resources [DWR]). The database includes near real time reports of river and reservoir stage at 154 locations in the Sacramento River Basin and 95 locations in the San Joaquin River Basin (USACE 2001*a*/2001*b*). Graphical products are also available to permit quick examination and detection of stages approaching or exceeding thresholds.

If threats are detected, the CNRFC will issue a river forecast bulletin that is disseminated to state and local officials and to the NWS Weather Forecast Offices (WFOs). Based upon the CNRFC products, the WFO staff will issue public warnings.

Runoff forecasting

The CNFRC uses a variety of mathematical models to forecast future runoff at dozens of locations in the Sacramento River and San Joaquin River watersheds. Typically, forecasts are made daily. The hydrologic models currently operate on a 6-hour time step. Model input data, which are generally available hourly, are integrated into 6-hour time steps for inclusion in the model. During high water, the model can be updated as needed.

The models used to make these forecasts are integrated through the National Weather Service River Forecast System (NWSRFS), as illustrated by Figure 4. The first module in the forecasting system determines the rain / snow line during the period of observation just prior to the forecast to determine if recent precipitation is in the form of rain or snow. The temperature of the air at the precipitation location controls this evaluation. For flow and stage forecasting, CNRFC combines estimates of current and recent historical conditions with forecasts of future temperature and precipitation.

When precipitation in the form of rain reaches the ground, some infiltrates, and the remainder runs overland and into stream channels. Infiltrated water may move both vertically downward and laterally, and may enter stream channels as base flow after some delay. The processes of storage and movement of water below the ground are modeled with soil moisture accounting procedures. This is a critical component of the streamflow forecasting, for which the CNRFC uses a soil moisture accounting model originally developed by Burnash (1973).

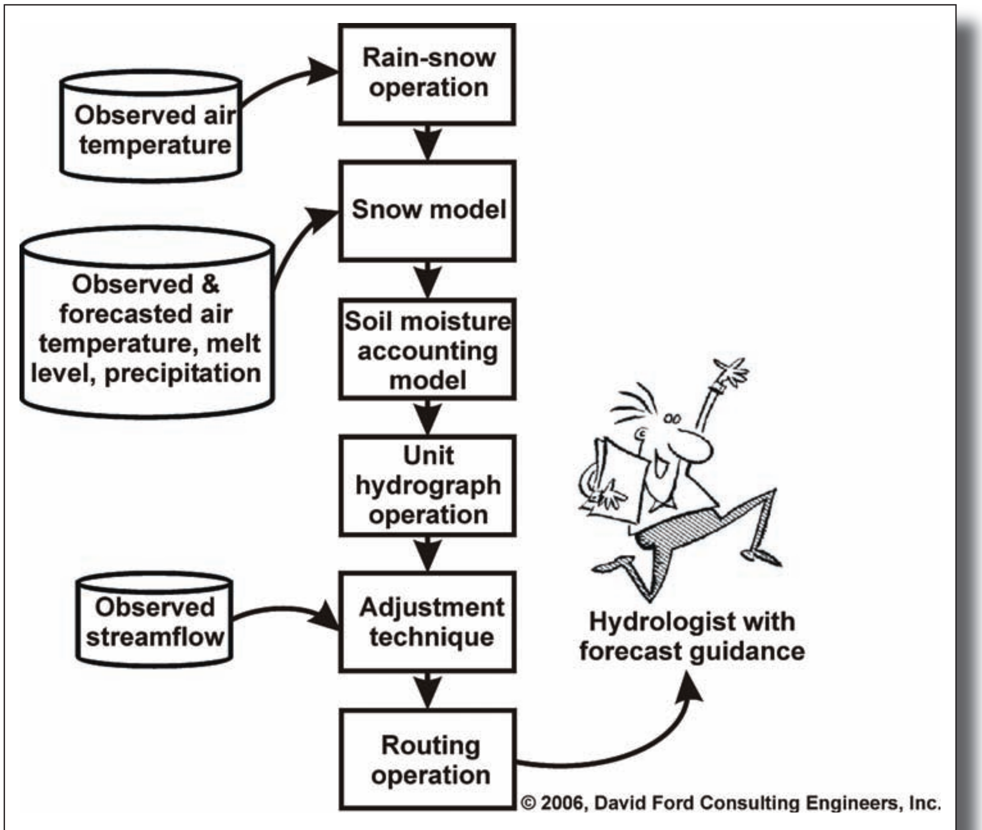


Figure 4. Typical NWSRFS configuration

When precipitation is in the form of snow, it is stored on watershed surfaces until it melts and runs off. Various modifications to the snow pack occur with time, and these are evaluated with a model of the pack. The surface runoff hydrograph is determined using a watershed response function–a unit hydrograph.

Channel evaluation

An additional component of the evaluation predicts movement of water through streams, rivers, and reservoirs. This so-called streamflow routing uses a mathematical model that solves the open channel flow equations. The model computes the outflow hydrograph from a reach, given the inflow hydrograph, accounting for the impacts of storage in the channel and energy loss of flowing water. CNRFC staff typically use a simplified hydrologic routing model; they judge this adequate for forecasting in the basins.

The availability of these streamflow data is key to success here. First, the availability of historical flow data permitted CNRFC staff to calibrate their model, configuring it to represent well the complex channel system. Second, the availability of streamflow data in real time permits CNRFC staff to validate the model, and if necessary, to adjust the model during floods to improve forecasts. (River forecasters nationwide use observed streamflow data for calibration and adjustment.)

Water-control system evaluation

Analyses of watershed runoff with observed and forecasted precipitation and temperature provide forecasts of reservoir inflows. Reservoir outflows have significant impact on water levels in the Sacramento and San Joaquin river systems, and thus these must be included in the evaluation. The CNRFC simulates operation of the reservoirs, using a model that is included in NWSRFS to account for the state of the system, given the forecasted inflows and local runoff and releases. For the most part, reports of current and anticipated releases are provided by the system operators. Anticipated releases are included also. In the absence of release information from the operators, the CNRFC begins by modeling system behavior with the flood operations release schedule prescribed by the Corps. If observations at downstream gages indicate that the operation has not followed those rules, CNRFC staff will contact the reservoir operator directly for updated or corrected information.

Levee performance evaluation and inundated area prediction

Much of the property adjacent to the rivers and major streams in the Sacramento and San Joaquin basins is protected by levees. Consequently, evaluation of levee overtopping during high-water events is a critical component of operational evaluation.

Levee failure can occur when the river stage exceeds the levee height; this is referred to as overtopping. Occasionally, an opening (a breach) forms in the levee, and water flows through this opening into the protected area. The rate and potential extent of the resulting flooding can be estimated by analyzing the terrain behind the levee and the river stage near the breach. Engineers from DWR work with NWS staff to accomplish this during high-water events. Levee inspectors at the site provide estimates of the water surface elevation near the breach and the width and creep rate of the breach itself. Those data can be used to forecast a flow hydrograph through the breach for several hours into the future. Emergency actions can be taken once the rate of rise and extent of the inundated area are predicted.

Levee breach (California DWR)

Where do streamflow data fit into this?

Streamflow data from the USGS streamgage network are used throughout the flood threat detection and forecasting process outlined, including, but not limited to, the following:

- Historical stages and corresponding flows are used to configure and calibrate initially the watershed runoff models. The parameters of the soil-moisture accounting model and the unit hydrographs are found through a trial-and-error process in which computed values with trial estimates are compared with observed flow data.

- Historical stages and corresponding flows are used to configure and calibrate initially the channel models.
- Observed stages are used in real time to identify any existing threats due to high water in rivers or streams.
- Observed stages and corresponding flows are used in real time to judge the quality of forecast models. If the computations do not reflect well the observations, forecasters adapt the model, adjusting parameters and states to improve the fit, prior to issuing a forecast.
- Observed stages and corresponding flows are used in real time to judge the quality of water control system simulation, and to some extent, the efficiency of the operation. If NWS forecasters see that simulated values do not match well the observed, they will adjust the models, contact the operators for additional information, or—in some cases—contact the operators with information that the actual operation is other than what is intended and expected.
- Observed stages and corresponding flows are used in real time to quantify the impacts of levee overtopping and breaching. Data about conditions upstream of a breach and those downstream permit forecasters and emergency responders to infer the properties of the breach, thus leading to better decisions about appropriate response.

What are the benefits for flood warning and emergency response?

Forecasting and warning, when coupled with effective response plans, enable citizens and public servants to act to protect people and property before floodwaters reach critical levels. With sufficient warning, for example, actions shown in Appendix II can be taken. If those actions are taken in a timely manner, tangible benefits accrue, especially in terms of inundation damages reduced.

Emergency flood response, Des Moines, IA (photo courtesy of A. Booher/FEMA)

Day (1970) proposed the function shown in Figure 5 to estimate the value of the damage prevented as a function of warning time increase. With this, we would predict, for example, that if the warning time increases from 0 to 4 hours with data collection, evaluation, notification, and response, damage incurred would be reduced by about 10%. If the potential annual damage due to flooding with no warning is $100,000, damage with warning would be only $90,000. Similarly, if the warning time is increased from 4 to 12 hours through addition of features or enhancement of the warning system, Day's curve predicts an incremental decrease of 12% in the annual damage.

In a study for the NWS, NHWC (2002) used Day's curve and similar methods to estimate the benefit of all NWS forecasting activities. The study estimated that economic benefits of NWS hydrologic forecasts were $1.6 billion annually (adjusted to 2000 price levels). Of course, this benefit is attributable to the entire forecasting and warning system, and not simply to the gages that provide the data used. However, we argue again that the benefit is not separable—it is all or nothing. Without the data from the streamgages, the models cannot be calibrated. Without calibration, and subsequent adjustment in real time, the forecasts may not be accurate. If the forecast is not accurate, lead time does not truly increase.

This impact can be illustrated with an anecdote provided by a NWS forecaster (Dian-Reed 2005). Due to funding shortfalls, a number of USGS streamgages in Ohio were discontinued. During the flood events of January 1996, March 1997, June 1998, July 2001, and both January 2004 and 2005, the NWS was forced to limit the products provided to less quantitative, more qualitative products—statements of minor, moderate, or major flooding instead of forecasts of magnitudes of stage expected. Area emergency managers and residents of the floodplain were fully aware of the potential impacts of rises to various threshold levels. However, the categorical forecasts did not provide the information necessary for decision making as usual. Consequently, damage that might have been avoided was not. After these flood events, the USGS streamgages were re-activated. Data collection platforms were added also, which provide stage data on an hourly basis. This action was taken as the emergency managers and floodplain residents recognized the true value of the information provided by the streamgaging network in the flooded area and arranged funding.

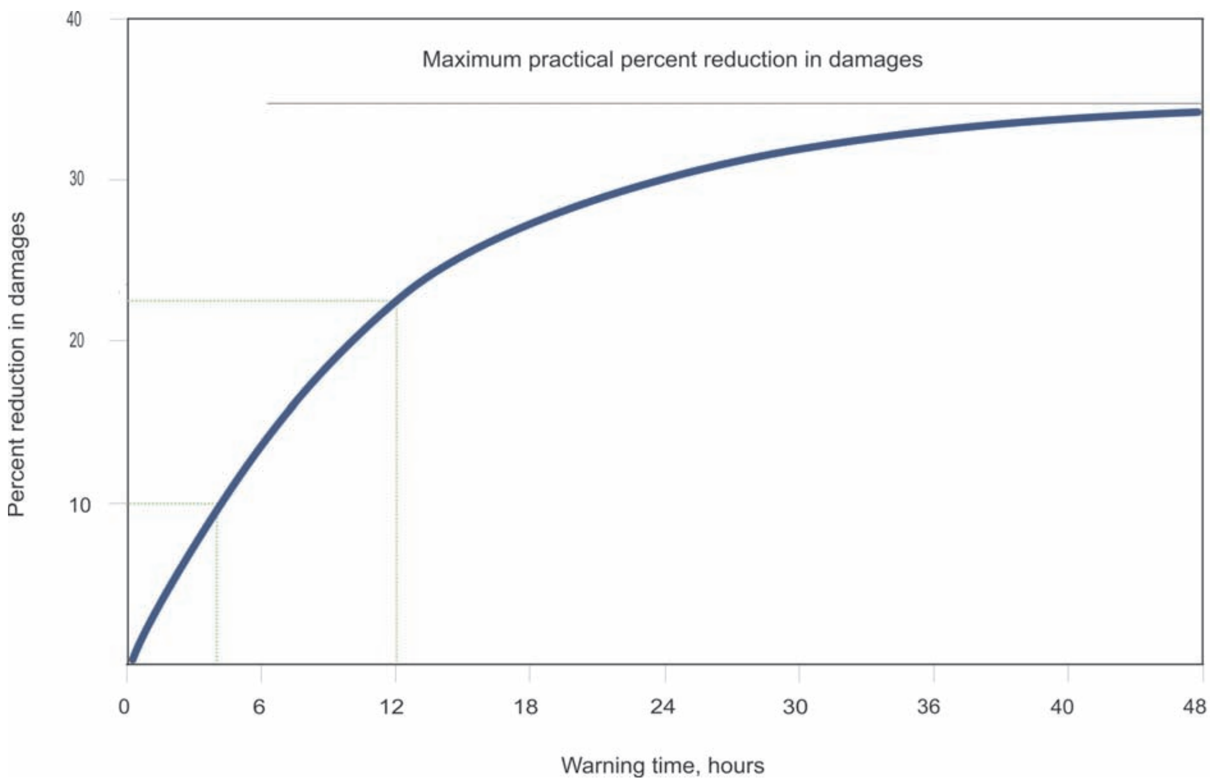


Figure 5. Day's curve for estimating flood warning benefit

Similar discontinuations of gages have been occurring in other states as well. For example, Figure 6 shows the recent reduction in streamflow stations in Texas. The number of gages there has dropped back to 1960s levels. Unfortunately, this is a national trend, with the USGS reporting a consistent loss of streamgages with 30 or more years of data, arguably the most valuable in the entire network. The cumulative loss of these gages, depicted in Figure 7, well illustrates this problem. Consequently gages that were traditionally used for forecasting no longer provide the information required, and situations similar to that arising in Ohio may evolve elsewhere.

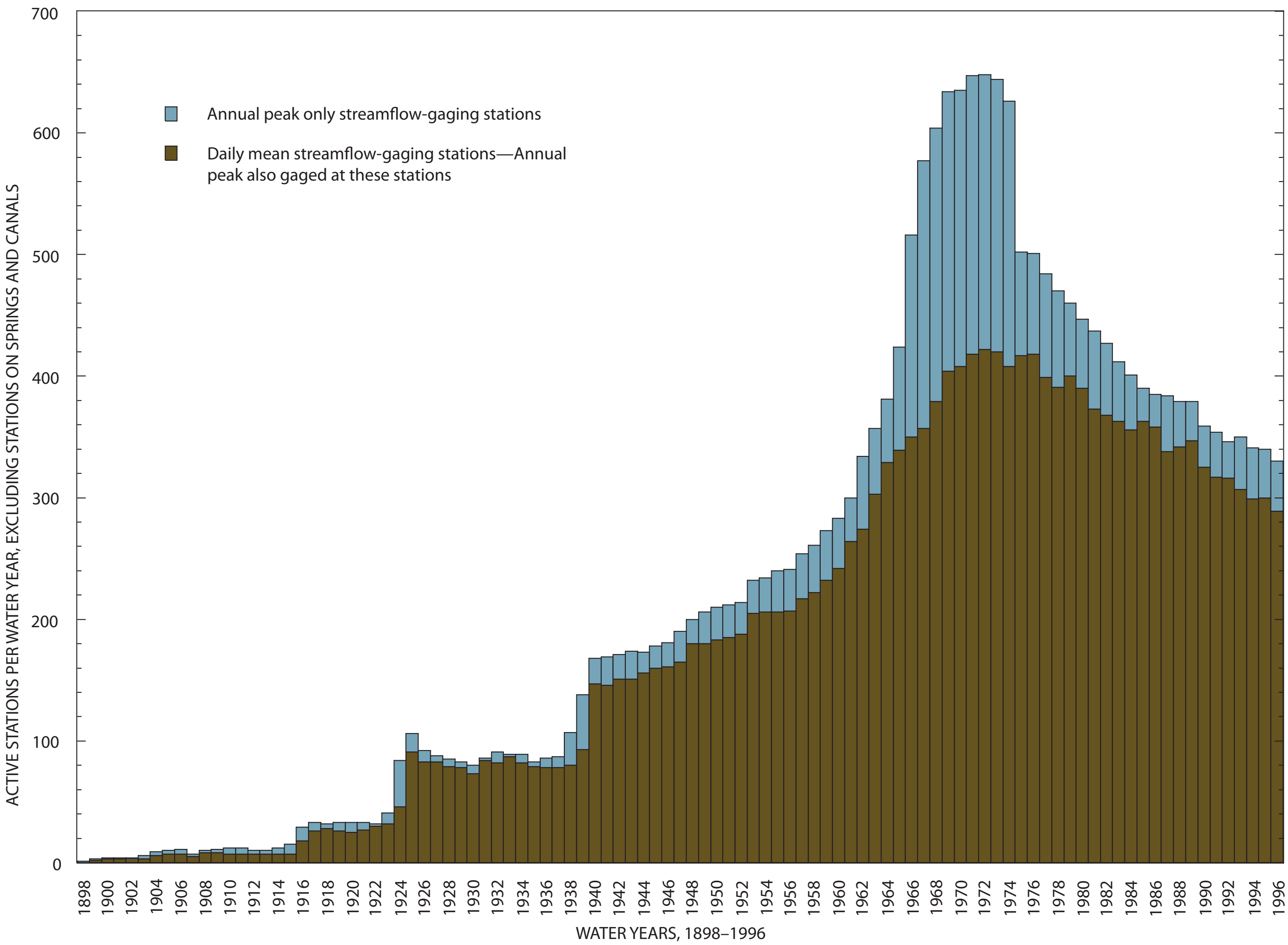


Figure 6. Number of daily mean and annual peak streamflow stations in Texas, 1808-1998 (Slade Jr. 2001)

What are the benefits for reservoir operation?

For reservoir flood operations, the forecasting tasks are the same, but the actions taken are different. Whereas with a flood warning system, the actions taken are to move property and people out of harm's way, with a reservoir system, the actions taken include adjusting releases as appropriate to reduce the downstream damaging effects of excessive flows.

The NWS works closely with operating agencies like the Corps, the US Bureau of Reclamation, the Tennessee Valley Authority (TVA), and other reservoir operators to provide inflow forecasts. The operators, in return, provide reservoir release schedules to permit the NWS to forecast conditions downstream. Other organizations—particularly electric utilities that own and operate reservoirs—make forecasts in a similar manner. They use mathematical models of watersheds, channels, and water management features, calibrating and adjusting those using historical and real-time streamflow data.

...streamflow data availability contributes to the $23.2 billion of flood damage prevented annually...

The Corps of Engineers presents an annual report to Congress, with detailed information on flood damages prevented by Corps projects. The average annual flood damage prevented by Corps projects between 1983-2002 is $23.2 billion (USACE 2003). This damage-prevented figure represents, in part, the benefit of the Corps. This benefit is attributable to the integrated system of data collection, evaluation, and operation, and thus is not a separable benefit attributable to one component. However, an investigation by NHWC (2002) suggested that $1.02 billion annually was attributable to NWS forecasts that were used for reservoir operation decisions. If the benefit attributable to the gages is only 3-5% of the total, this is $30-50 million annually—which is almost half of the cost to operate the USGS streamgaging network.

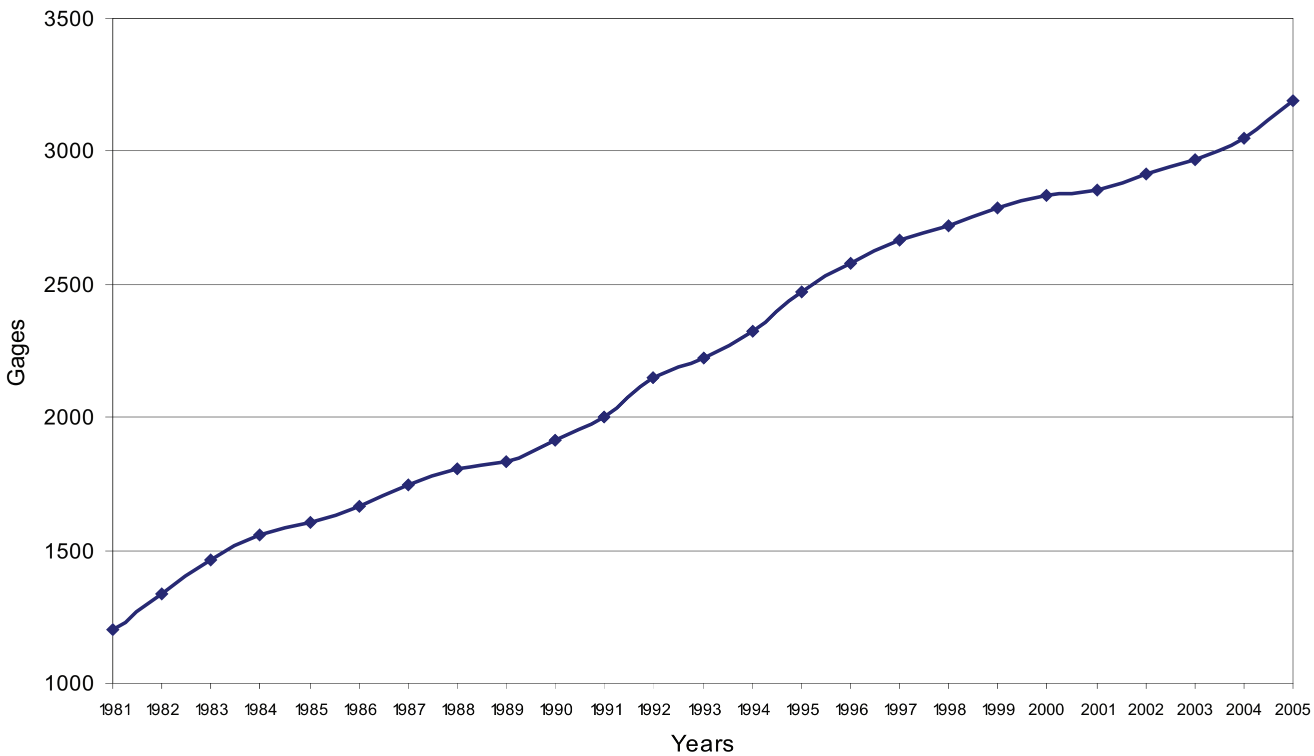


Figure 7. Cumulative loss of USGS streamgages with 30 or more years of data, 1980-2005 (modified from USGS 2006)

So what is the benefit for flood management in the US?

In summary, the questions that we set out to answer were: (1) Does the benefit derived from the streamgage network exceed the cost of building, operating, and maintaining this network, thereby justifying the investment, and (2) Does the incremental benefit of an expanded network equal or exceed the incremental cost of the expansion?

As shown in Appendix III, researchers in other countries have applied a value to gage data. We found that these questions cannot be answered directly because the benefit attributable to collecting the data cannot be separated from the benefit of analyzing and using the data for decision making. Instead, we can only infer values, based upon the economic benefit due to wise flood management.

For example, we found that for design of Folsom Dam, CA, design possible with a long record of streamflow data could avoid an expense equivalent to $63 million annually. This savings is more than 50% of the annual cost of the streamgaging program.

Accurate design of levee improvements, using a long record of flows to make decisions about the improvements, may save as much as $7 million / mile. If 20 miles of levees are repaired in communities adjacent to rivers across the US, the total savings of about $140 million would easily exceed the cost of operating the entire USGS streamgaging network, which is about $114 million per year.

Similarly, we found that the potential economic benefit due to reducing hydrologic uncertainty in mapping for floodplain land use regulation in Mecklenburg County is comparable to $330 million in damage avoided. If that cost is amortized over 50 years, with a discount rate of 6%, the annual equivalent cost is $20 million, or about 1/5 of the total nationwide cost of operating and maintaining the streamgage network. If other communities realize similar benefit, this floodplain mapping related benefit alone will offset the total network cost.

FEMA suggests that approximately 64,000 flood maps need to be updated. FEMA values data in hydrologic analysis at $4,400 / map. Thus, the value of updating the flood maps is about $56 million annually when spread over the 5 years outlined in FEMA’s original flood map modernization project.

We found that the availability of streamflow data for flood forecasting for warning and reservoir operating yields a real, although difficult to separate, benefit. An earlier NHWC studied estimated the value of hydrologic forecasts as $1.6 billion annually, and that report attributed $1.02 billion savings due to successful forecasting for reservoir operation. If 3 to 5% of this total is attributed to the gage network that provides the data necessary for forecasting, the benefit is $30-50 million annually.

Moreover, a general theme in all examples discussed herein is that a tangible benefit is attributable to the availability of long, continuous record of streamflow data from a large gage network.

Thus, we conclude that, even though we cannot assign with certainty a total benefit to the network, the benefit clearly exceeds the estimated cost. Each of the uses that we consider herein, in fact, yields benefits that exceed much of the cost, even when considered in individual cases. In the aggregate, nationwide, the benefits of gages in the context of reducing flood damages greatly exceed the costs of collecting the data used for decision making.

Flooding along North Carolina's Tar River (photo courtesy of D. Saville/FEMA)

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Appendix I. Methods for developing information to solve flood problems

Statistical model fitting for design flow estimation

For design of structural flood management measures, the need is for information about the risk or exceedence probability of flows, volumes, or water levels that incur flood damage. For many design cases, the information need is reduced to a requirement for knowledge of risk of annual maximum flows at a given location. This is a consequence of procedures employed for economic analysis of flood damages. In those, the annual flood damage is predicted as a function of annual maximum water level, which in turn, is related to annual maximum flow rate. Expected value computations with this information yield estimates of the long-term risk-weighted damage potential at a selected location.

Gate in floodwall, Harlan, KY (photo courtesy of USACE)

Information about hydrologic risk commonly is derived through empirical analysis of historical hydrologic conditions, leading to development of a statistical model. Procedures for the statistical analyses are well known, with—at least for now—the standard of practice defined by *Bulletin 17B: Guidelines for determining flood flow frequency* (Interagency Advisory Committee on Water Data 1982). The procedures described in the bulletin call for use of the Pearson type III statistical model, with model parameters estimated from properties of annual maximum flows observed at a site, coupled with properties of flows observed at other sites within the region.

Streamflow data must be available to complete this recommended statistical analysis. Ideally these data will be a continuous, unbroken record, of homogeneous flow data. From the perspective of estimating statistical model parameters, this data set should be long. (In fact, Bulletin 17B suggests that this record should be *…at least 10 years to warrant statistical analysis…*) Figure 8 illustrates why. Here, we used a set of streamflows for a watershed in an unusual way: We successively added 1 year of data, refitted the statistical model from Bulletin 17B, and re-estimated the p=0.01 flow, presuming that flow would be the basis for design of a flood control structure. As you can see, the value thus estimated varies from about 2400 to 11,200 cfs, depending on the record length. It appears to be converging on a value of approximately 7,000 cfs with 25 years of record. In fact, our streamflow data set for this illustration is a hypothetical data set for which we know that the “true” value of the *p*=0.01 flow is about 8,700 cfs.

This creates a dilemma for designers and floodplain managers. Only a single flow or water level value can be used as the basis for design or regulation. An estimate that exceeds the true value means that the structural measure will be larger than necessary or that the floodplain delineated will include land that is not truly subject to flooding with the stated risk. Similarly, an estimate that is smaller than the true value means that the design or regulated floodplain does not provide the presumed level of protection.

A remedy is to acquire and use a longer record of data with which to fit the model to estimate the flow of specified risk. Several hundred years of data, for example, would provide a more certain estimate of the true value—presumably one that converges on the true value. Of course, few streams in the US have such long record lengths, but the lesson is clear: If we want to estimate well the design flow with selected risk, we need a long, continuous data set with which to fit a statistical model. That data set needs to be at the location of interest.

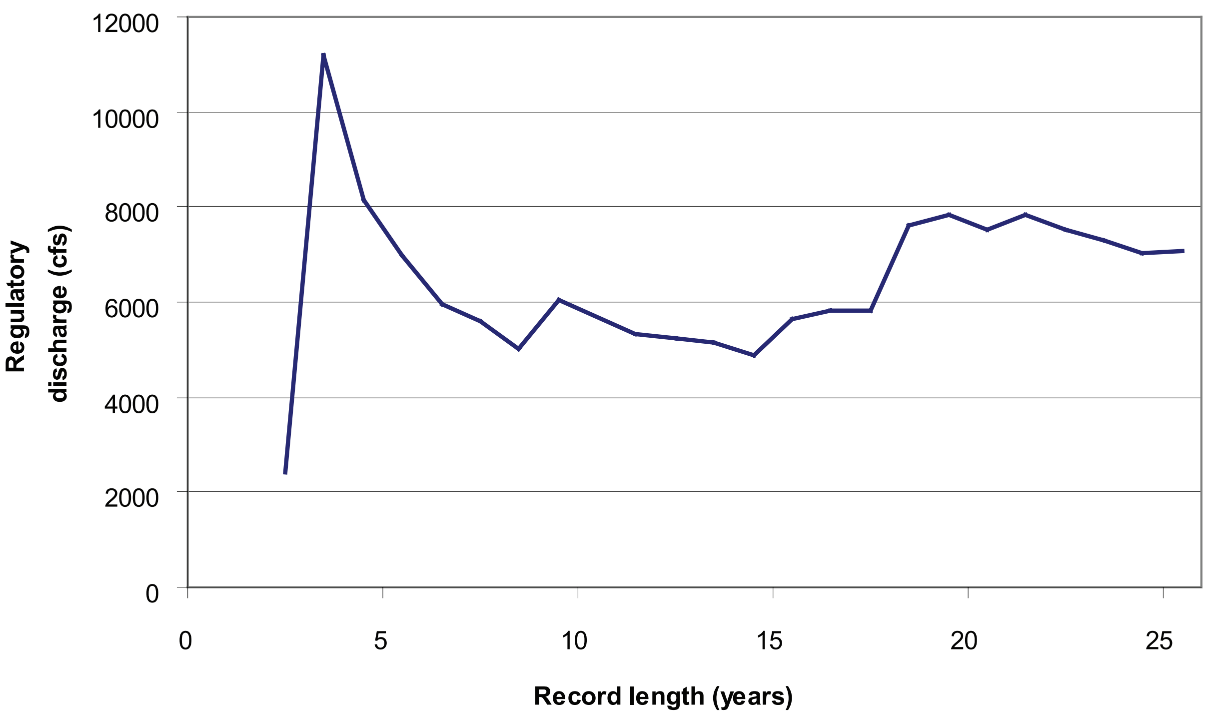


Figure 8. Illustration of sensitivity of regulatory flood estimate to record length

Empirical models for design flow estimation

Practicing engineers and designers of flood control structures quickly learn 2 important, disappointing facts about establishing design flows as described in the previous section: (1) They seldom have access to *any* streamflow data at the location of their interest because no gage exists at that location; and (2) if they actually have access to streamflow data at the site of interest, the record available is short, perhaps broken, and often dated, as the gaging at the site was discontinued.

The first problem arises simply as a consequence of an ever-expanding area for which flood problems must be described and solved in the US. As the population increases, the need for housing increases and in many parts of the county, this need is satisfied by urbanizing rural lands. When that happens, creeks and streams that were of lesser economic interest when their flooding impacted only farm lands now are of great interest as their overflows adversely affect residences and put occupants at risk. While the streamgaging program in the US has sought to provide information about water across the country, demands for data are greatest where the water has the greatest impact on people and property. Thus the gage network is most dense where the population is most dense.

In response to this, the USGS, and other federal, state, and local agencies have developed empirical relationships for estimating the required design flow rates or other hydrologic conditions. These regional regression equations relate the required design flow, or condition of selected risk to watershed characteristics. Those may include, for example, drainage area, channel length, channel slope, basin slope, and basin shape. Separate equations typically are developed for rural and urban watersheds. For example, Figure 9 shows the geographic regions of Texas for which the USGS has developed such regional regression equations, and Table 4 shows the equations for region 1. With these, a designer can predict the 100-year flow as $Q_{p=0.01} = 371\ A^{0.847}\ SH^{-0.307}$, using measurements of the watershed area, and channel length.

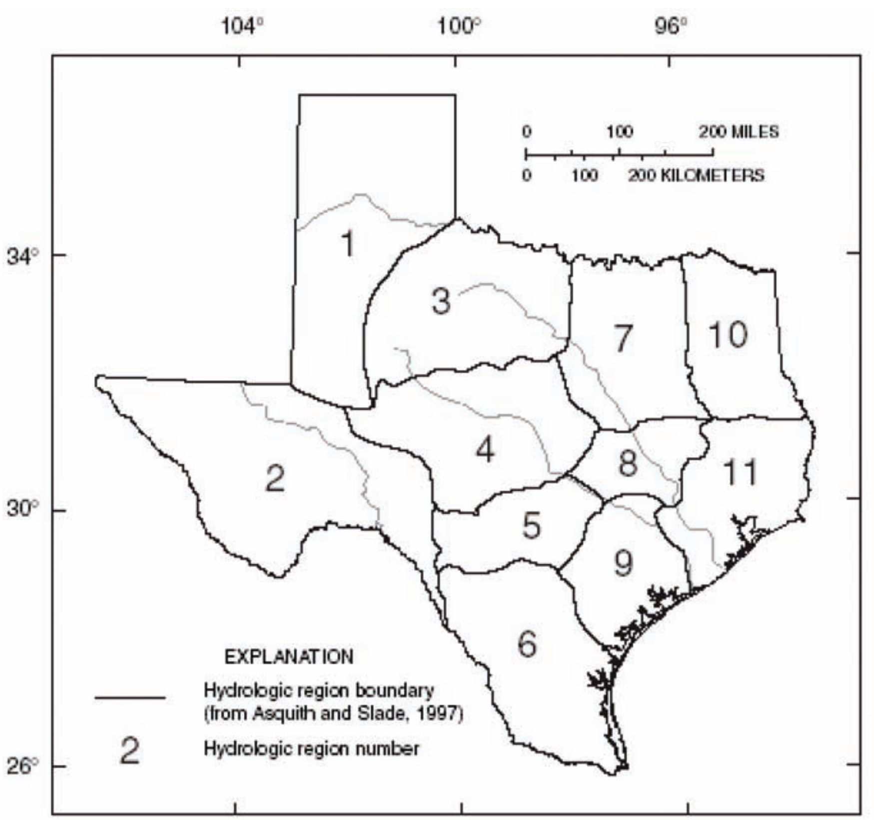


Figure 9. Boundaries of regions for regression equations for Texas (TxDOT 2004)

Table 4. Example regression equations (TxDOT 2004)

$Q_{p=0.50} = 16.1\ A^{1.040}\ SH^{-0.537}$
$Q_{p=0.20} = 53.2\ A^{0.958}\ SH^{-0.444}$
$Q_{p=0.10} = 96.0\ A^{0.921}\ SH^{-0.400}$
$Q_{p=0.04} = 178\ A^{0.885}\ SH^{-0.356}$
$Q_{p=0.02} = 263\ A^{0.864}\ SH^{-0.330}$
$Q_{p=0.01} = 371\ A^{0.847}\ SH^{-0.307}$
in which $Q_{p=<>}$ = the design flow of specified probability; A = watershed area, in sq mi; SH = watershed shape factor, defined as $L_s^{\,2}/A$, with L_s = length of stream to headwaters, in miles

At first glance, these regression equations seem to eliminate the need for streamgages and statistical analysis. Why bother with collecting those data when these simple equations provide the needed information in a simpler, easier to use manner?

This is analogous to asking why we should bother with dairy cows when we can just buy milk at the store. The cows provide the milk, or in this case, statistical analysis of long-term flow records provides the design flow estimates that become the dependent variables in the regression equations. Streamflow data are collected, statistical models are fitted to those, and design flows are computed. Then watershed properties are determined, and predictive equations defined with standard regression techniques.

This method clearly depends on the availability of data from a network nearby to represent the runoff response of the basins. If the gage network within a region is dense, with gages at favorable locations and with adequate record lengths, the equations will predict well the probability of flooding to various levels, with results that compare favorably to results from statistical analysis of gaged data. On the other hand, in areas where the number of long-term gages in the overall network is small or declining over time, the equations thus developed may not predict well.

This certainty or confidence in results is illustrated by Table 5, which is from Corps of Engineers' guidance. Here, we see that the standard against which the Corps measures confidence in results is statistical analysis of streamflow data. If that is not possible, the Corps views results of regression analysis as equivalent in certainty or confidence to results from statistical analysis of a data set the length of which is the average of all gages used to develop the regression.

The regression equations cannot be established with uniform confidence and reliability nationwide. In some regions, the streamflow data required for the foundation statistical analyses are not available in the form necessary to develop predictive equations of high reliability. As noted earlier, the data used for the statistical analyses should be long, unbroken, homogeneous records.

To ensure quality and utility for decision making, these equations must be updated with long records in a timely manner. According to Thomas (2004), 11 states have equations that were developed more than 20 years ago. California's regression equations were last updated in 1977, so these do not include consideration of major flood events of 1983, 1986, 1995, and 1997 in Northern California and events of 1980, 1983, 1992, 1993, 1995, 1998, and 2005 in Southern California. This is a consequence of lack of resources for updating, which can be found in many other states. Typically a cost-sharing arrangement between the USGS and a local partner funds the analysis. The local partner often is, for example, a state transportation agency needing reliable design flows for highway drainage facilities. In Connecticut, for example, a 3-year study to update statistics and develop regional regression equations for estimating flood flows cost $350,000 (Ahearn 2006). Additional work, of similar or greater cost and effort, will be required to develop low-flow equations. A 6-year study to develop flood frequency relationships for Mississippi scheduled for completion this year cost $340,000 (Mississippi DOT 2005). These funds are not uniformly available and are costs beyond those required to maintain the network of surrounding gages.

Table 5. Record length equivalents (USACE 1997)

Method of frequency function estimation (1)	**Equivalent record length [1] (2)**
Analytical distribution fitted with long-period gaged record available at site	Systematic record length
Estimated from analytical distribution fitted for long-period gage on the same stream, with upstream drainage area within 20% of that of point of interest	90% to 100% of record length of gaged location
Estimated from analytical distribution fitted for long-period gage within same watershed	50% to 90% of record length
Estimated with regional discharge-probability function parameters	Average length of record used in regional study
Estimated with rainfall-runoff-routing model calibrated to several events recorded at short-interval event gage in watershed	20 to 30 years
Estimated with rainfall-runoff-routing model with regional model parameters (no rainfall-runoff-routing model calibration)	10 to 30 years
Estimated with rainfall-runoff-routing model with handbook or textbook model parameters	10 to 15 years

[1] *Based on judgment to account for the quality of any data used in the analysis, for the degree of confidence in models, and for previous experience with similar studies.*

Rainfall-runoff modeling

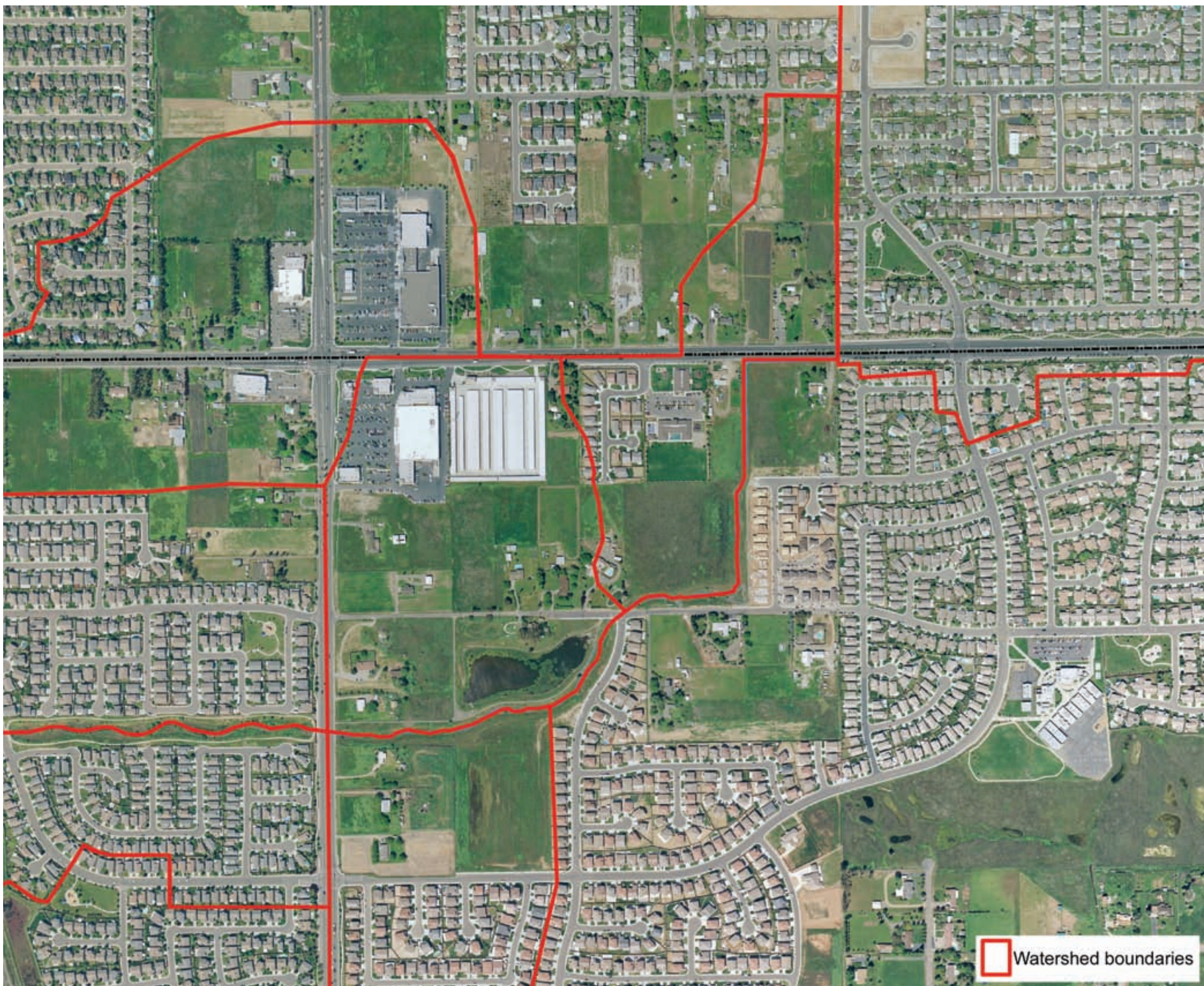
For a variety of reasons, fitting a statistical model with observed flows or applying regression equations may not yield information required for flood management decision making. For example:

- The regression equations described in the previous section typically do not account explicitly for impacts of flow regulation. Additional accounting that is not well done with simple empirical relationships is required to account for the impacts of storage and diversion upstream of many urban areas.
- The regression equations described in the previous section often do not account explicitly for impacts of urbanization and minor variations of land uses that may come with urbanization. In some regions, specialized equations are presented for urban areas, but even these typically reduce the representation of land use to a single term in the equation. Detailed accounting of modern stormwater and drainage practices, for example, is not well defined with these simple empirical relationships.
- Neither the regression equations nor the statistical models provide information about the dynamic response of a watershed. This information is required in many cases for decision making about design when storage is significant, or for floodplain delineation when ponding occurs. In those cases, peak flow *and* volume *and* timing must be estimated and considered. This type of information *always* is required for flood operations and flood warning and emergency response. Information in the form of hydrographs describes historical and current conditions, as measured at a streamgage.

Rainfall-runoff modeling is the analytical process used to develop dynamic information required in these cases. This strategy relies on a mathematical model of the relevant watershed and channel processes. The analyst conducts a study of past storm events and calibrates the model, adjusting parameters and states to represent response, as exhibited by the streamflow data available. For design and floodplain management decision making, the calibrated model then is used with statistically-derived rainfall depths to predict design flows. For forecasting and emergency response, the calibrated model is used with recently observed and forecasted rainfall to predict future flows and the timing of those flows.

For either application of rainfall-runoff modeling, properly calibrating the model is critical and key to the success of the application. The calibration is a trial-and-error process in which historical rainfall data are input to a model with a trial set of parameters and initial states. Runoff is computed and compared with observed runoff from the same events. Parameters and states are adjusted until a satisfactory fit is achieved. In the case of flood forecasting, this is also done on-line, by forecasters who adjust the states to reflect rapidly changing conditions. Streamgage measurements confirm in all cases that the model is properly tuned to represent the basin's physical features and rate-dependent runoff processes.

Estimating parameters and states for a model in the absence of historical gage data is possible, of course, but difficult. Without observed flows, the hydrologist will calibrate a rainfall-runoff model with data from a nearby gage, transposing model parameters and states to the watershed of interest after carefully considering the differences in the physical characteristics of the watersheds. Alternatively, the analyst may use “handbook values”; these are national or regional averages or even theoretical or laboratory-derived estimates. Either approach yields a model and model results about which the analyst is less confident. For example, Table 5 from the Corps shows that from the design flow perspective, flow estimates from models with parameter estimates from handbooks are viewed as equivalent to having a streamgage with only 10-15 years of data. On the other hand, design flow estimates from models calibrated with short-interval gage data are viewed as equivalent to those derived from statistical analysis with 20-30 years of data.



Delineated watershed for rainfall-runoff modeling (photo courtesy of David Ford Consulting Engineers)

Appendix II. Actions taken after flood warning

The Corps (1994) described the following actions that can be taken after a flood warning that yield a direct benefit:

- **Temporary removal of property from floodplain**. Floodplain property owners can move belongings such as televisions, stereos, computers, important documents, and personal memorabilia.
- **Moving property to a safe elevation within the floodplain**. Residents and businesses occupying multi-story buildings may have the opportunity to protect moveable property by relocating it from basements and ground floors to higher levels.
- **Temporary flood-proofing**. Warnings issued with sufficient mitigation time allow property owners to temporarily flood-proof property with, for example, temporary closures of windows and doors. These activities can reduce flood damages by preventing inundation.
- **Opportune maintenance**. Warnings can provide officials and individuals with more time to undertake opportune maintenance, such as closing a shut-off valve on a gas line, halting discharge of certain materials into the sewage system, or safeguarding water supplies and sewage treatment plants.

Residents filling sandbags, Saint Charles, MO (photo courtesy of A. Booher/FEMA)

- **Early notification of emergency services**. Increased warning time can reduce the cost of emergency shelter and emergency care as individuals have more time to arrange to stay with relatives, friends, or elsewhere. The cost of public assistance and long-term emergency shelter for evacuees can be reduced if these evacuees have time to secure their property and prepare before evacuation. Communities with limited emergency personnel and other resources will benefit from additional time to ready emergency services.
- **Orderly disruption of network systems.** Warning and response systems offer opportunities for network systems (phone systems, utilities, pipelines, cable TV services, transportation patterns and traffic levels, and local area networks) to prepare for disruption in a more orderly and cost-effective manner. With sufficient warning time, businesses may make alternative plans for network services.

- **Suspension of sensitive works**. For products that require lengthy production processes, sufficient warning time may provide the opportunity to suspend the production processes to minimize the destruction of the product or minimize the possibility of hazardous materials seeping into the waterways. Similarly, sufficient warning may allow crews to sequence repair work in a way that minimizes disruption to a utility.
- **Related effects of emergency cost, cleanup cost, and business losses**. Warnings may reduce emergency costs and cleanup costs by allowing emergency responders and residents to take preventative actions. Similarly, warnings may allow for reduced unemployment and income loss, smaller losses in sales, and smaller reductions in taxes collected by increasing the chances of a quick recovery. Also, the cost for flood insurance may be reduced as warnings result in decreases in the amount of coverage required by residents and businesses.
- **Traffic control**. Advance flood warning may provide the opportunity for authorities to decide which roads to close and which to keep open before flooding begins. Traffic can be re-routed in a more efficient manner and personnel can be deployed in a timely manner to block access to potentially dangerous areas as well as to direct traffic on detour routes.

Flooded roadway (photo courtesy of NASA)

Appendix III. Findings from researchers outside of US

Following are examples of studies conducted by researchers in other countries to estimate economic benefit of gage data:

Azar *et al.* (2003) estimated the economic benefits of the British Columbia hydrometric program for project design (transportation, hydroelectric generation, agriculture, water supply, and flood protection); flood warning and avoidance; and resource management. Their procedure estimated benefits as a fixed percentage of costs for each sector of the economy. They obtained an overall benefit-cost ratio of 19.1 for the British Columbia streamgage network. About two-thirds of the benefits were in the sustainable resource management category, about one-forth were design-related benefits, and the balance from flood warning and avoidance.

Cordery and Cloke (1991) computed benefits of streamgage data for design of waterway crossings, flood mitigation works, water supply storage, urban drainage systems, and major structures in New South Wales, Australia. They obtained a minimum benefit-cost ratio of 9 for just these uses. In a subsequent study (1992), they found flood mitigation benefits as high as 80 times the cost of annual data collection for specific levee construction projects. They also estimated that the benefit-cost ratio for designing water storage capacity was about 5 for the existing New South Wales reservoirs.

CNS Scientific and Engineering Services (1991) evaluated streamgaging for five water authorities in England and Wales, estimating benefits for water supply, irrigation, flood alleviation, and flood warning. Their benefit-cost ratio estimates for just these uses ranged from 1.2 to 7, with a best estimate of 2.3. The largest fraction of this benefit was attributed to water supply benefits.

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Swiftcurrent Creek gaging station, Glacier National Park, MT (photo courtesy of J. Costa/USGS)

National Hydrologic Warning Council