THE BENEFITS OF HYDROLOGIC FORECASTING

Submitted to

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October 1997

Report of Eugene Stallings to National Oceanic and Atmospheric Administration
pursuant to NOAA Contract #43AANW701167

INTRODUCTION

Nationally there are significant economic benefits associated with using National Weather Service (NWS) hydrologic forecasts. Using sophisticated models and large amounts of data, the modernized NWS provides hydrologic forecasts for almost 4,000 locations in the United States. Based on these forecasts, flood-control structures are operated to mitigate damage. Then, emergency actions are taken at state and community levels to flood fight, evacuate, or take other measures to lessen the impact of flooding. The amount of lead warning time for floods can mean the difference between life and death.

Economic benefits result from both structural and nonstructural means. There are three categories for deriving economic benefits: reservoir optimization, short-term events, and long-term events. All benefit analyses in this report are based on the test 20-year period from 1977 through 1996 with dollars indexed to 1996 price levels.

The NWS works very closely with operating agencies like the U.S. Army Corps of Engineers (USACE) to provide data forecasts in exchange for reservoir scheduling information to produce hydrologic forecasts at key downstream damage centers. Through this cooperative venture, optimization of water-control projects during flood events is more attainable, resulting in substantial economic benefits that are attributable to both the NWS and USACE. A conservative estimate is made that NWS hydrologic forecasts benefits are equal to 5 percent of the average annual flood damage prevented by the USACE reservoirs during the test period.

The second category involves benefits associated with short-term flood events. Estimates of benefits were obtained by researching historical reports to determine the damages with and without the warning. A conservative estimate indicates a savings of 10 percent of the average annual flood damages in the United States associated with NWS warnings. Additionally, hydrologic forecasting benefits attributable to flood mitigation are described based on the NWS modernization and implementation of the Advanced Hydrologic Prediction Systems (AHPS).

The third and last category of obtaining economic benefits from hydrologic forecasts are those related to long-term flood events which occur when rainfall and snowmelt runoff combine to produce widespread flooding over periods of weeks. With sufficient warning time, communities flood fight and take appropriate actions.

Besides economic benefits from flood mitigation, NWS hydrologic forecasts are very important for other water resources purposes. An analysis of these benefits resulting from AHPS is presented for hydropower generation, irrigation, navigation, and water supply.

Several case histories of operational experiences with corresponding economic benefits are included in Appendix A together with some examples of recent international floods having economic benefits associated with hydrologic forecasts.

BACKGROUND

Water is an essential requirement in sustaining life; its various uses affect almost every phase of human existence. Commerce between continents still depends on ocean transport while elaborate systems of inland navigation serve interior areas of countries (Hathaway, 1952). From a national perspective, water is abundant in the United States. Unfortunately, precipitation is not distributed uniformly throughout the country. As a result, floods and droughts are common (Stallings, 1988). It is not uncommon for large areas of the conterminous United States to be devastated by major floods with accompanying loss of life and extensive property damage while just a few hundred miles away people cope with water shortages.

Floods are a natural and inevitable part of life along the rivers in the United States. In fact, 75 percent of presidential declarations of natural disasters result from floods. The NWS, through its River and Flood Program, maintains an around-the-clock vigil of rivers throughout the country and issues watches and warnings to protect life and property when the threat of flooding does occur (Stallings and Wenzel, 1995). When sufficient warning time is given to the communities that will be impacted by a flood event, appropriate actions are taken and economic benefits occur that are directly attributable to timely NWS hydrologic forecasts.

The NWS is the Nation's agency responsible for providing hydrologic (flood) forecasts and warnings. Its 13 regional River Forecast Centers (RFC) prepare river forecasts for the time and height of the flood crest, the time when the river is expected to exceed flood stage, and the time when the river is anticipated to return within its banks. These forecasts are passed to the public via a local NWS Weather Forecast Office. When developing the river forecasts, every source of data is used. The development and maintenance of a reporting data network for precipitation, river stage, and reservoir data are essential elements in support of river forecasting. The NWS relies on a wide variety of sources and techniques to collect data. Whether flood, drought, or more moderate conditions prevail, the delivery of hydrologic forecasting service begins with data collection. Many of the ground sensors are owned and operated by major NWS cooperators, including the USACE, the U.S. Geological Survey (USGS), the U.S. Bureau of Reclamation (USBR), the U.S. Department of Agriculture (USDA), and Tennessee Valley Authority (TVA).

In addition to real-time hydrometeorological data, historical data are used in conjunction with powerful hydrologic and hydraulic models. Additionally, the RFC hydrologists must possess extensive knowledge of the river basin to assure that data used in the models are accurate and reliable. Crest-stage forecasts can be made a few hours in advance for cities and communities along streams draining small basins, but they can be made 2 weeks or more in advance for some cities and communities along rivers draining large basins. Daily forecasts of river-stage/discharge are prepared routinely for use by those interested in river-related activities such as navigation and water management. Reservoir-inflow forecasts aid Federal, state, and local water-management agencies in the operation of their reservoirs.

Although flood forecasts and warnings are the most dramatic hydrologic products issued by the NWS, interest in long-range water forecasts increases when droughts and/or shortages of water supplies occur. The 1988 drought throughout the Midwest and southeastern United States (Hudlow, 1989) and the 5-year drought over California and other areas of the West (1989-1993) are two of the most severe droughts experienced in the United States since the mid-1930s.

The current year of 1997 appears to be representative of other years with flood damages at least equal to the average annual estimate of both damages and benefits. Preliminary flood-damage estimates for the three major flood events (California in January, north-central United States in the spring, and the Ohio River Basin in early March) total $3.6 billion and represent all three categories of hydrologic forecasting benefits. Although dollar figures are not yet available, early estimates indicate hydrologic benefits, including structural and nonstructural mitigation methods, will probably exceed the $1.4 billion annual estimate.

Much of the flooding over the Ohio River Basin occurred in the lower reaches of several tributaries which decreases the benefits from existing upstream reservoirs. Fortunately, NWS hydrologic forecasts were extremely timely and accurate in the main stem of the Ohio River with sufficient lead time to permit people to evacuate and take effective response measures. Savings attributable to NWS forecast services will be in the millions of dollars.

In the north-central United States, the NWS issued warnings of major floods weeks before their occurrence. Millions of sandbags were placed, and numerous temporary levees constructed. Although the flood reached record proportions at several locations and floodwaters broke through and inundated Grand Forks, North Dakota, many flood fights were successful and substantial hydrologic benefits are anticipated.

In California, flood damages are projected to exceed $1.2 billion from the December 1996-January 1997 flood. The number of evacuees exceeded 100,000 as a result of NWS warnings of impending danger. Early estimates from the Office of Emergency Services in Sacramento (California, 1997) indicate benefits related to NWS hydrologic forecasts may reach $270 million in the Central Valley, principally near Marysville and Stockton.

HOW HYDROLOGIC FORECASTS ARE MADE

The NWS uses many sources of data in developing its hydrologic forecasts. The USGS is the principal source of data on river depth and flow in the United States (Wahl, Thomas & Hirsch, 1995). The USGS network currently comprises about 7,300 stations dispersed throughout the Nation. The stream-gaging program provides a continuous, well-documented, well-archived, unbiased, and broad-based source of reliable and consistent water data. During a flood, the USGS and the NWS work together to collect and use the most up-to-date hydrologic data. The USGS collects the streamflow data, and the NWS collects the precipitation data and combines both types of data when making its hydrologic forecasts. The United States has a long-standing policy to ensure the continuation of the concept of free and unrestricted exchange of data and products (Friday, Gross & Yerg, 1996).

The NWS develops and calibrates complex mathematical models of how the Nation's rivers and streams respond to rainfall and snowmelt. The models are developed for preselected forecast service points that are located along major rivers or on small streams near urban areas that have a history of flooding. In every case, records of river discharge must be available so that the NWS can develop a river model. Modeling procedures, which account for the computation of surface runoff, the determination of groundwater recharge, and the calculation of base flow, have been used for many years by the RFCs to produce flood forecasts. The procedures take advantage of all National Weather Service River Forecast System (NWSRFS) calibration features and can adequately simulate the full range of flow conditions to produce water management forecasts using Ensemble Streamflow Prediction (ESP) procedures. The NWSRFS provides a framework on which to standardize field operations while maintaining the flexibility to meet the unique situations faced by each RFC.

NWS hydrologists use the calibration system to process historical hydrometeorological data and to estimate model parameters for a specified river basin. The model within this system simulates snow accumulation and ablation, calculates runoff, time-distributes runoff from the basin to its outlet, and channel routes streamflow. The simulated streamflow is then statistically and visually compared to the observed streamflow, and the model parameters are adjusted accordingly. The Operational Forecast System (OFS) uses calibrated basin models operationally with real-time hydrometeorological data to forecast streamflow. The OFS contains three major components that are required for operational river forecasting: data entry, the preprocessor, and the forecast. Working in combination, the components describe the basin connectivity of the river system, maintain an account of the current model state, and are used as starting points for subsequent forecasts. OFS has the ability to update these model states using observed data and to display the simulation. Finally, the Interactive Forecast Program (IFP) consists of proven hydrologic physical process models of NWSRFS combined with a graphically oriented user interface to provide (1) information needed for the NWS hydrologist to make decisions about the correctness of data or model results and (2) the capability for the hydrologist to easily and quickly turn the data into forecasts that reflect best judgment about current and future hydrometeorological conditions.

HOW HYDROLOGIC FORECASTS ARE USED

The NWS is charged by law with the responsibility of issuing forecasts and warnings of floods to the Nation to help save lives and to mitigate flood damages. Through the NWS's River and Flood Forecasting Program, pertinent information on river conditions is disseminated to its cooperators: local, state, and Federal decision-makers and the general public. However, a hydrologic forecast is only of value if it induces a response from the floodplain user that leads to an effective action (DOC/NOAA/NWS, 1982). For example, when a flood warning is issued to the general public through appropriate dissemination channels, a benefit can only accrue through evacuations, flood proofing, flood fighting, or shutdown of facilities to reduce potential flood losses.

Flash-flood watches and warnings, river and flood forecasts and warnings, and water-supply forecasts are the major hydrologic services provided by the NWS. The most rapid flood events are flash floods, which can develop anytime up to approximately 6 hours from the time of heavy rainfall. As might be expected, the primary objective of flash-flood warnings is to save lives since there is so little time to save personal belongings and property. For floods with longer lead times (time between the issuance of the warning and the occurrence of the flood), the effectiveness of the warnings is measured in terms of saving both lives and property. Saving property with less than 18 hours lead time is generally restricted to moving highly valued property, such as automobiles and major appliances, out of harm's way. When lead times are longer than 18 hours, floodplain residents can flood proof and flood fight (construct temporary levees, place sand bags, etc.).

Besides the floodplain resident who uses the hydrologic forecasts, there is another group of users who constantly monitor river and stream levels. The most well-known of these cooperators are the USACE, USGS, USBR, and TVA (WMO, 1989). In the United States, there are thousands of reservoirs, from small to large storage capacity, that provide for flood control, hydroelectric power, water supply, irrigation, and recreation. The reservoir may be operated by the Federal, state, or local government or the private sector. The USACE operates over 600 major reservoirs with 116 multiple-purpose reservoirs, principally in the Northwest, for navigation and hydroelectric power. These projects generate over 20,000 megawatts of capacity. Similarly, USACE projects have over 8 million acre-feet of storage available for water supply for communities throughout the United States. The USBR also operates many reservoirs principally for irrigation and hydroelectric power. USBR projects generate 14,000 megawatts of capacity and serve 25 million people. Those projects provide water for irrigating approximately 10 million acres in the western United States. The TVA manages 50 dams on the Tennessee River and its tributaries to control flooding and to enable transportation along the 652-mile Tennessee River system, the fifth largest river system in the United States. Besides preventing floods, TVA's network of dams and locks makes possible the transportation of some 48 million tons of cargo annually.

BENEFITS OF HYDROLOGIC FORECASTS

Benefits associated with hydrologic forecasts are attributed to both structural and nonstructural actions. But, in order to compute benefits from hydrologic forecasts, damage estimates under natural conditions must be developed. It is not possible, either economically or practically, to analyze every structure within a specific floodplain. Therefore, an alternate approach has been developed based on the assumption that a typical floodplain is comprised of common types of residential, industrial, and commercial structures. For example, residences are one- or two-story, wood or brick, with or without basements (Yoe, 1994). It is a valid assumption that 1 foot of water in a one-story, wood-frame house without a basement causes the same amount of flood damage at any location in the floodplain. Similarly, an equal depth of flooding causes basically identical flood damage in a grocery store of like size whether it is located on the east coast or in the southern United States.

The USACE, while preparing its comprehensive River Basin Study Reports, developed stage damage curves for each river reach within the river basin under investigation. The stage damage curves consider the three classes of buildings (residential, industrial, and commercial) and past flood histories in the river basin. First, the number of each class of building in the damage reach are counted and categorized (one- or two-story, wood or brick, etc.). Then, representative field interviews are conducted with the floodplain inhabitants. Interviews focus on recent flood events and known major and/or historical floods. Interview results are summarized and adjusted according to individual biases and available flood inundation area maps. A sample stage damage curve is shown in Figure 1. Flood frequencies are incorporated into the stage damage curves for each river reach. For example, a major flood event obviously inundates larger areas than a lesser event but does not occur as frequently. All

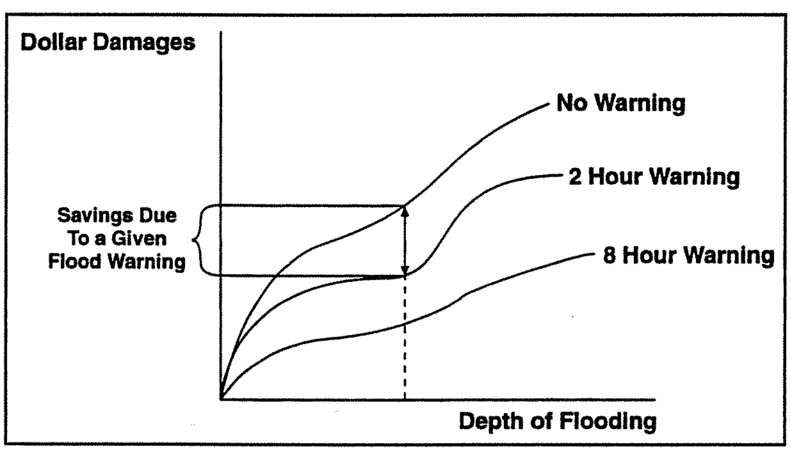

Figure 1. Sample stage damage curve.

degrees of floods must be incorporated into the flood damage curve analysis to display a comprehensive picture of the flood damage possible in a damage/river reach. All stage damage curves within the river basin under investigation are combined.

Benefits From Structural Measures

The USACE and USBR rely heavily upon the NWS's hydrologic forecasts to operate their reservoir projects. The flood-control projects have been designed to reduce damages downstream and are regulated on a prescribed operational schedule. However, floods are unpredictable and obtaining maximum benefits in flood mitigation without hydrologic forecasts is not possible. During some flood events, maximum benefits can be obtained easily because of the amount of flood-control storage capacity available within the reservoir and the magnitude and timing of the event. In the majority of floods, NWS river forecasts of stage and time of crest at key downstream locations make mitigation activities more attainable thereby maximizing benefits from flood-control operations.

For this paper, a hypothetical USACE flood-control reservoir is used as an example to depict flood mitigation estimates. USACE reservoirs are designed to safely accommodate the maximum possible flood while providing flood protection to areas downstream of the project. Each USACE flood-control project is regulated according to a prescribed operational schedule or "rule curve." Once reservoir levels reach a specific elevation, and downstream gages exceed or are forecast to exceed flood stage at the damage centers, an operational decision must be made. The daily exchange of data and information between the USACE and NWS is an excellent example of Federal agencies working closely together to accomplish their basic missions in operational hydrology. Figure 2 shows the information and data exchange procedure between these two agencies. During floods, the hours of operation expand to meet the magnitude and extent of the event at the NWS River Forecast Center and at USACE district or division offices. Similarly, the amount of data and information exchanged between the two agencies increases to fit the occasion. The NWS needs the USACE reservoir scheduling information to make its hydrologic forecasts at downstream damage centers while the USACE needs the hydrologic forecasts to determine the opening and closing of the gates at the flood-control reservoir. This iterative process continues until the river levels return within their banks.

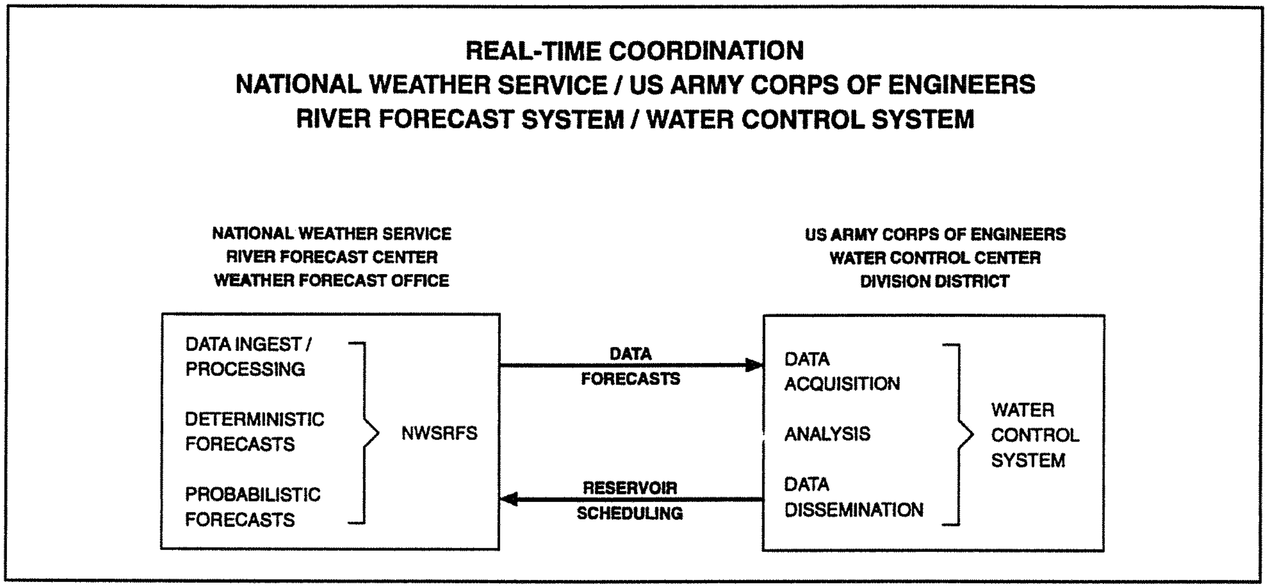

Figure 2. Example of information and data exchange between NWS and USACE.

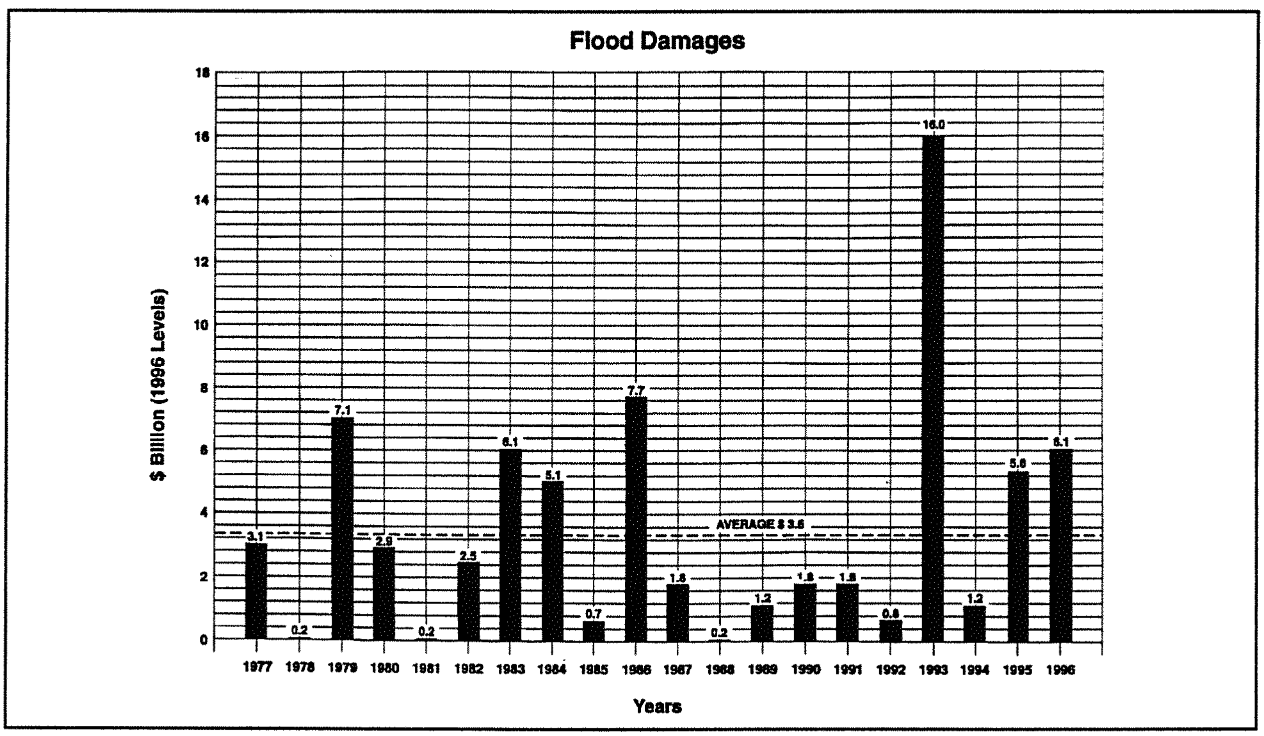

Figure 3. Flood damages (in billions of dollars) during 1977-1996 (1996 price level).

Gates at the flood-control reservoir are closed when the rule curve dictates or when the Water Control Section of the USACE district or division office issues instructions to close them. When the gates are in the closed position, the water is held within the reservoir until the flood condition abates. The excess water is then safely released downstream. The amount of water "held out" represents the benefit of a structural measure and is compared to the water level that would have occurred under natural or pre-reservoir conditions. Then, for each damage reach, the difference in flood damage "with" or "without" conditions on the stage damage curve represents the benefits associated with that reservoir for that specific flood event for that one damage reach. The benefits are computed similarly for each damage reach. Figure 3 shows flood damages that occurred during the 20-year period from 1977 to 1996 ranging from $0.2 billion in 1978 to $16.0 billion in 1993 (USACE, 1996; 1986). The average annual damage is $3.6 billion (indexed to 1996 dollars). Flood damages prevented by USACE during the same period are shown in Figure 4 and range from a low of $2.2 billion to a high of $39.4 billion, with an average annual estimate of $17.8 billion (all indexed to 1996 price levels).

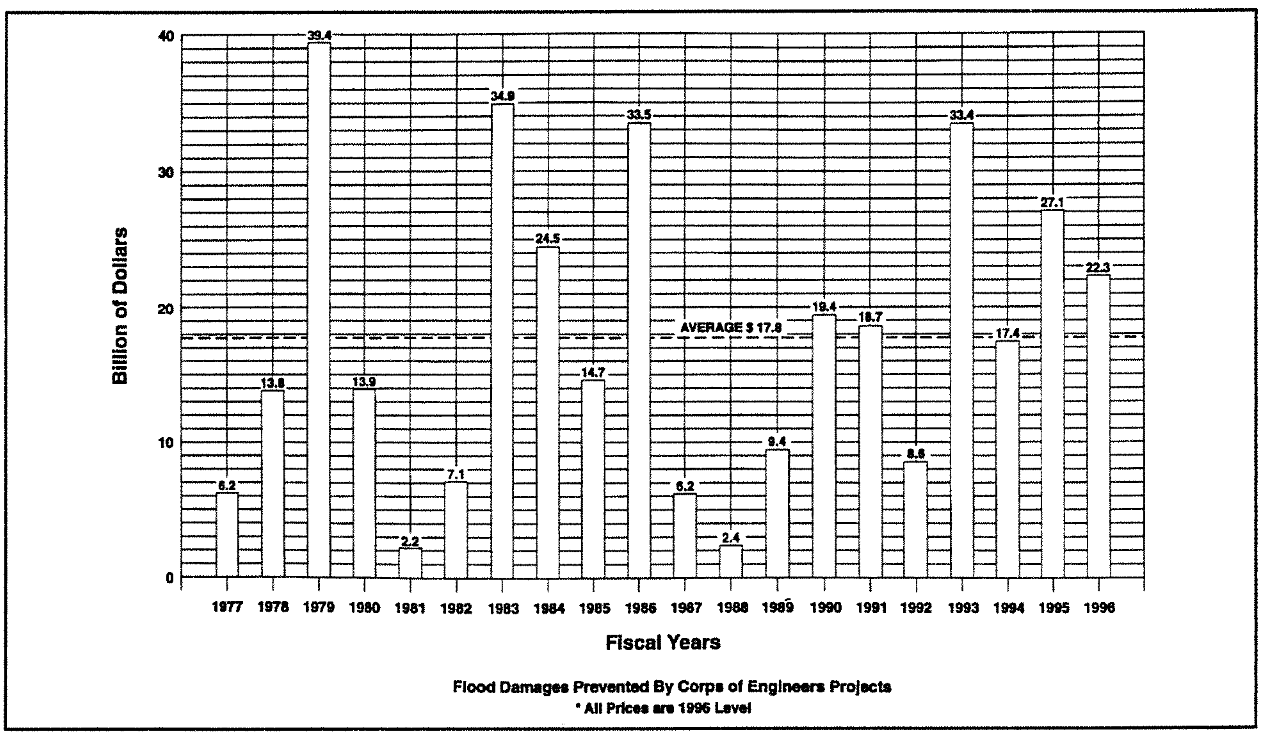

Figure 4. Flood damages prevented (in billions of dollars) by USACE projects during 1977-1996 (1996 price level).

The USACE prescribes flood-control regulations for the USBR and includes these dollars in its estimates of flood damages prevented. Consistent with the operational experiences of the USACE and USBR, senior hydrologists in the NWS and USACE have informally agreed that NWS hydrologic forecasts conservatively account for at least 5 percent of the total flood damages prevented by the USACE reservoir projects nationwide. During some floods, the impacts are minor between using the NWS hydrologic forecasts and the USACE in-house forecast capability combined with application of the rule curves while in other events the differences are more significant, and the 5 percent relationship represents a reasonable but conservative average. For the test period, USACE and USBR flood control prevented an average of $17.8 billion. Applying the 5 percent to the $17.8 billion realizes an economic benefit from NWS hydrologic forecasts of $890 million annually. The average annual combined economic benefit to the United States resulting from the USACE and USBR structures using NWS hydrologic forecasts amounts to approximately $18.7 billion ($17.8 billion plus $890 million) for flood mitigation alone. The estimate is obviously conservative (using a 5-percent adjustment factor) since it does not include numerous other operating agencies that use NWS hydrologic forecasts to regulate their projects with flood-storage capacity to reduce damages.

During The Great Flood of 1993, USACE and USBR flood-control reservoirs on the main stem and tributaries in the Missouri River Basin reduced peak discharges on the Missouri River by storing over 17 million acre-feet of floodwater between June and August. TVA can also claim similar successes in flood mitigation (TVA, 1997). TVA's flood-control program prevented an estimated $1 billion in flood damage across the Tennessee Valley in 1994. Without the protection of TVA's reservoir system, the city of Chattanooga would have been devastated by floodwaters. NWS hydrologic forecasts proved to be invaluable during both flood events. It should also be noted that watershed projects built by the Natural Resources Conservation Service saved an estimated $400 million during The Great Flood of 1993 (Interagency Floodplain Management Review Committee, 1994). Numerous non-Federal reservoirs also prevent flood damage, but those estimates are beyond the scope of this paper.

A flood event that occurred in California in March 1983 represents an excellent example of close and constant cooperation between the USBR and the NWS (WMO, 1983). As a result of NWS hydrologic forecasts communicated to other cooperators during this event, water managers controlled the flow on the Sacramento River at Bend Bridge. Also, officials were able to increase releases at Keswick Dam at the earliest possible time to evacuate storage encroached in the flood space at Shasta Dam. These actions resulted in maximum flood-control benefits. The Great Flood of 1993, which occurred 10 years later, strongly emphasized the need for excellent cooperation between communities in order to reduce flood damages. During The Great Flood, daily teleconferences were held among NWS River Forecast Centers, NWS Forecast Offices, the NWS National Meteorological Center, and the NWS Office of Hydrology to improve forecast coordination. An entire chapter in that flood disaster survey report is devoted to coordination and dissemination (DOC/NOAA/NWS, 1994). That spirit of cooperation continues even more strongly today.

Increased urban and agricultural development occurs downstream from dams which not only accentuates the need for flood prevention but also places more demand on operating the reservoirs to capture as much water as possible for consumptive use during extended dry periods. Hydrologic forecasts from NWS RFCs provide a means to obtain both goals.

Benefits From Nonstructural Measures

In addition to the benefits from structures like flood-control reservoirs, NWS hydrologic forecasts produce benefits from nonstructural measures. Long-term forecasts provide enough time to flood proof by constructing temporary levees or other measures. Long-term hydrologic forecasts are generally related to those areas of the United States where snowmelt runoff is a major factor in producing flooding. A heavy snowpack accompanied by above-normal temperature and/or above-normal rainfall can produce major flooding over large areas of the United States. Table 1 summarizes three snowmelt flood events in the north-central United States and indicates the benefits of the hydrologic forecasts issued by the NWS.

Table 1. Summary of damages (in millions of dollars) at 1996 price levels in three major snowmelt events in north-central United States.

Year	Damages Incurred	Damages Prevented	# of Evacuations
1965	$ 900	$ 1,675	16,000
1969	595	517	25,000
1973	666	1,350	20,000

In 1965, the upper Mississippi and Missouri rivers, and the Red River of the North experienced severe flood damage in excess of $900 million (adjusted to the 1996 price index). However, damages could have been much worse without the benefit of NWS hydrologic forecasts. As early as mid-March, the NWS issued an advisory on the flood potential (Nelson, 1965). On the basis of these warnings, the Minnesota Department of Civil Defense began to make plans for protective measures against the major flooding expected in the state within the next 2-3 weeks.

Other flood-threatened state agencies took similar actions to mitigate the potential flooding. In Minnesota, an earthen levee was built to protect the St. Paul stockyards which remained dry during this flood when during a previous flood event the yards were inundated and large damages ensued. As a result of the extended advance warning provided by the NWS, many residents were able to move valuable possessions out of danger, and over 16,000 people were evacuated in Minnesota, North Dakota, and Wisconsin. A typical situation occurred in Winoma, Minnesota, where flood damages reached $3.7 million but an estimated $19.8 million in damages were averted by the flood fight that was waged. Over the upper Mississippi, Missouri, and Red River of the North, $1.675 billion in flood damage was prevented by flood-fighting measures and subsequent evacuations working in response to the extremely accurate NWS hydrologic forecasts.

In February 1969, the Weather Bureau (which became the National Weather Service in 1970) issued a statement indicating that the potential for very serious spring snowmelt flooding existed over much of the north-central area of the Nation and that conditions warranted preparations for major damaging floods of record or near-record proportions (USACE St. Paul, 1969). The NWS reported that the snowpack had the potential for producing crests similar to those of the second-highest record flood of 1952 in the Upper Mississippi River Basin. Based on those NWS hydrologic forecasts, advance measures were taken to mitigate potential flood damages. The USACE St. Paul District contacted a total of 200 communities, industries, and individuals and advised them to take emergency flood-protection measures. Those actions were a major factor in preventing much greater losses. Communities were given advance warnings of 1-2 weeks and, as the reliability of the forecasts became apparent, many communities were able to construct temporary works which greatly reduced losses (ESSA, 1969). Other actions besides levees, sandbags, and evacuation helped to mitigate flood damage. For example, at St. Paul, Minnesota, during a long-term snowmelt flood event, all planes were removed from the downtown airport. Additionally, a railroad depot took away all movable equipment from its yards and closed its doors. And, because of the lead time, the sewage treatment plant on the Mississippi River downstream from St. Paul was fortified and no damages resulted.

In the spring of 1973, the north-central United States was again subjected to snowmelt flooding (Mondschein, 1976). NWS hydrologic forecasts combined with USACE Operation Foresight activities and local government actions were highly successful in reducing flood damage.

Severe flooding occurred in the spring of 1997 on the Red River of the North in North Dakota which attained record levels at most gaging stations. The USACE responded to the flood threat by constructing temporary levees while local citizens placed thousands of sandbags to protect Fargo and Grand Forks, North Dakota, and Breckenridge, Minnesota. The flood fight was partially successful, but the magnitude of the event overtopped several levees and caused extensive damage at Grand Forks.

Short-term Hydrologic Forecasts

Short-term floods include flash floods which generally occur in 6 hours or less from the inception of heavy rainfall. In flash floods, the warning time is too short to flood fight, but it may allow residents to secure some valuables and drive vehicles out of the flood-threatened area. A subsequent section on vehicular damages describes some of the benefits related to flash floods and the limited response time.

The NWS is in the midst of a modernization effort, which includes the installation of Doppler radars to replace aging radars. One significant benefit expected to arise from the new radar system will be the development of spatial and temporal estimates of precipitation in areas with limited or no real-time rain gage reporting networks. This capability gives increased warning lead time to those areas subjected to flash floods.

Historical References on Hydrologic Benefits

A technique used to predict annual benefits from the use of NWS hydrologic forecasts is based on the probability of floods at a given depth and the dollar damage associated with that depth of flooding (Day, 1966). A mathematical model using field data was developed for predicting damages and savings due to warnings in a community located on the floodplain. After field studies were conducted in Pennsylvania, the Upper Mississippi Valley, and the Dallas-Fort Worth areas, Meadville, Pennsylvania, was chosen for the model because the community has experienced a number of serious floods in the past 50 years. A well-organized, operating disaster group exists in Meadville. Private and public awareness of flood potential and corresponding damages is strong. The USACE Pittsburgh District had conducted an extensive flood damage study soon after the 1959 flood, and results from that study were available (Day, 1966). It was small enough to eliminate many complexities of a large urban floodplain, similar to Pittsburgh yet large enough to provide a sampling of residences, service structures, and both light and heavy industry. Also, the community was easily accessible for additional field visits by the Study Team, if necessary.

The study reported a total of 650 homes in the flooded area incurred damages totaling $1.43 million with no warning and $1.06 million with warning. These figures indicate a 27 percent reduction in damages due to the warnings provided by the NWS. For any flood, the total savings are equal to total flood cost without warning compared to the total flood cost with warning. Although many factors affect the value of damages resulting from a particular flood, the model only considers that flood damages are a function of flood depth (flood duration excluded) and warning.

The steps used in the adjusted mathematical model are the following:

1. Determine the number and type of structures (residential, commercial, and industrial) at various locations on the floodplain.
2. Note the water depth in each structure for a flood of given probability.
3. Use predetermined stage-damage curves for most structures to obtain damage values with and without warning. Some industries will probably require a field check for accurate data.
4. Sum all values of savings over the entire community for one flood level.
5. Repeat for floods of different magnitudes.

Studies (Day, 1970) were also performed on the effectiveness of a warning service coupled with either temporary flood proofing or evacuation of residential structures in mitigating flood damages. Communities in the Susquehanna River Basin floodplain were subjected to a computer simulation similar to the Meadville study and four cities received a detailed investigation. The USACE Baltimore District conducted a flood damage survey of approximately 60,000 structures, principally single-family residences, which were classified into multiple categories. Flood damage information was also amassed for some commercial and all industrial structures. Flood damages with no warning was estimated to be $3 million at 1970 price levels while mitigated damages are estimated at $1 million. Reliable warnings, allowing 6-12 hours of lead time, approximate two-thirds of the mitigated damage, or 22 percent of annual flood damages.

Such studies were continued on flood damage reduction potential associated with hydrologic forecasts in the Connecticut River Basin (Day & Lee, 1976). This study uses the same procedures as in the two previous reports. Again, the report assumes a range of actions: no warning, limited warning, maximum practical evacuation, and flood proofing one-story houses. The investigation considered only mitigated damages and commercial and residential elements of the floodplain. The report concludes that mitigated damages associated with industrial structures nationwide often are the same order of magnitude as residential and commercial. Using this assumption, the residual damages or benefits associated with using and reacting to the NWS hydrologic forecasts represent 21 percent of the average annual flood damage incurred in the Connecticut River Basin.

Average annual flood damages are estimated to be about 10 percent higher if flood warning services did not exist (DOC/USWB, 1959). Some historical references contain estimates of flood damages mitigated by river forecasts (Bock and Hendrick, 1966). Bock stated that additional savings of unknown magnitude result from forecasts of river behavior other than flooding--such as low flow, pollution, and water supply forecasts--but documentation of these savings is lacking. However, more recent references do contain information on benefits related to other than flood mitigation. Gilbert White's *Choice of Adjustment to Floods* (White, 1964) states that the primary aim of river forecasts is to permit users to take appropriate action in response to flood warnings and other river forecasts. In an earlier paper, White (1939) determined that a 15 percent reduction in flood damages is likely from forecast-prompted emergency actions. Kates (1965) indicates a potential savings of 12.5 percent from an idealized situation of accurate, timely flood warnings and appropriate response action. Finally, Houghton (1962) estimates flood savings during a 15-year period equivalent to approximately 43 percent of the total potential damages without NWS hydrologic forecasts. Table 2 summarizes seven historical reports that provide estimates in percent of flood damage mitigated using hydrologic forecasts versus total flood damage experienced.

Table 2. Historical reports of mitigated flood damages from short-term hydrologic forecasts.

Historical Report	Flood Damage Mitigated (%)
Meadville, PA (Day, 1966)	27*
Susquehanna River Basin (Day, 1970)	20-33
Connecticut River Basin (Day&Lee, 1976)	21
National (USWB, 1959)	10
National (White, 1939)	15
Lehigh Valley, PA (Kates, 1965)	12.5
Western Pennsylvania (Houghton, 1962)	43

* Considers only residential flood damages

From the flood damage mitigated figures set forth in the above table, 10 percent is the most conservative and is selected for calculations in this paper for short-term forecasts. No attempt is made to include any benefits associated with prevention of loss of life during these short-term flood events. Using the average annual flood damages nationwide of $3.6 billion, shown in Figure 3, short-term NWS hydrologic forecasts prevent an average of $360 million annually (or 10 percent).

Vehicular damages

When the NWS issues a flood and flash flood warning and people respond by taking proper actions to remove their vehicles from danger, the benefits associated with hydrologic forecasts can be enormous. One example occurred in March 1997. The NWS and State of Ohio flood-warning programs saved lives and potentially tens of millions of dollars in property (NWS, 1997). With flood forecasts and warnings issued for the main stem of the Ohio River up to 4 days in advance, residents and businesses had time to prepare for the worst flooding since 1964. Cooperation between state and Federal agencies was critical as flood-warning information was developed and disseminated to the public. An estimated $425,000 in vehicles, office equipment, and other goods were saved because a single car dealership had sufficient time to move its inventory to higher ground.

Other examples of prompt responses involving automobiles include: (1) a flood event in July 1990 at Las Vegas, Nevada (Sutko, 1997), when evacuation of all the automobiles from a hotel garage, with only an hour of advance notice, mitigated the loss of cars and (2) a similar success event in Roseville, California, in 1993 (Rutherford, 1993) when numerous automobiles were moved out of danger from a flash flood. Figure 5 shows what happens when no action is taken in response to an NWS hydrologic forecast.

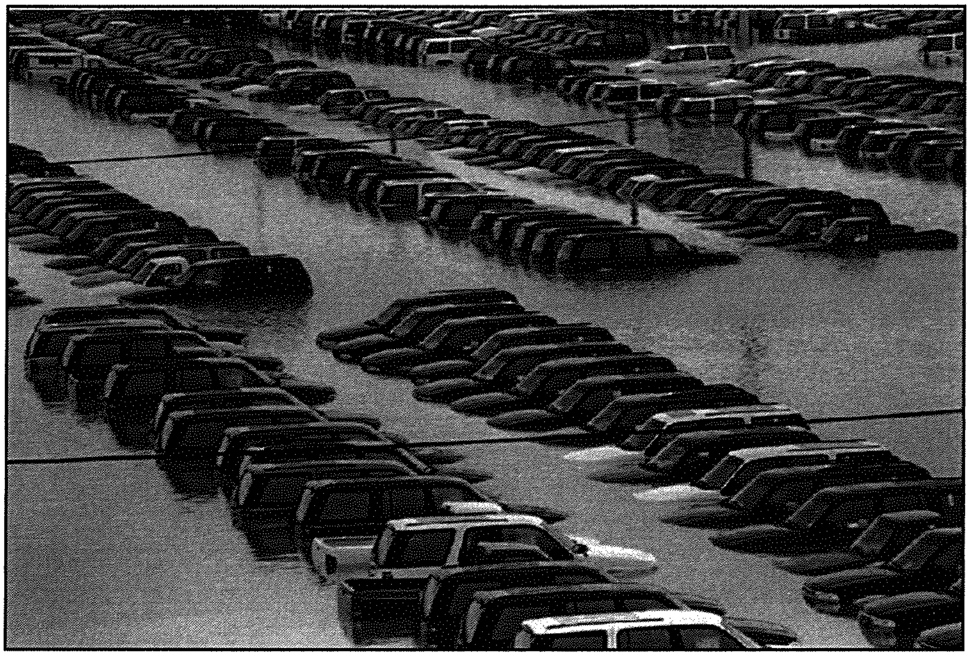

Figure 5. Flooded vehicles near Louisville, Kentucky, March 1997 (AP photo by Michael Clevenger).

While 1 foot of water may cause minimal vehicle damage--up to hundreds of dollars--3 or more feet can cause extensive damage to the engine and interior of the vehicle ranging into the thousands of dollars. During a March 1997 flood near Louisville, Kentucky, a conservative damage estimate to approximately 1,000 new vehicles at one car lot in up to 3 feet of water is $5 million because company officials failed to respond to the warnings (O'Donnell, 1997).

Total Benefits Related to Flood Mitigation

This report has so far addressed only the economic benefits associated with NWS hydrologic forecasts related to flood mitigation under existing operating conditions. There are three categories of obtaining flood mitigation benefits: optimum reservoir regulation, short-term, and advance measures (long-term). Total benefits from these three categories of flood mitigation are $1.39 billion. Table 3 shows the economic benefits for each of these categories for the sample period (adjusted to

1996 price levels). Figure 6 shows hydrologic forecasting economic benefits by category.

Table 3. Benefits from flood mitigation that are derived from hydrologic forecasting, in billions of (1996) dollars during the 20-year period 1977-1997.

Year	**Optimum Reservoir Operation**	**Short-term Forecasts**	**Long-term Forecasts**	**Total**
1996	1.12	0.61	0.02	1.75
1995	1.35	0.56	0.02	1.92
1994	0.87	0.12	E	0.99
1993	1.67	1.60	0.21	3.48
1992	0.43	0.09	E	0.52
1991	0.94	0.18	0.18	1.30
1990	0.97	0.18	0.06	1.21
1989	0.47	0.13	0.03	0.63
1988	0.13	0.02	0.01	0.16
1987	0.32	0.18	0.09	0.59
1986	1.68	0.77	1.43	3.88
1985	0.73	0.07	0.02	0.82
1984	1.23	0.51	0.07	1.81
1983	1.75	0.61	0.41	2.77
1982	0.36	0.25	E	0.61
1981	0.11	0.02	E	0.13
1980	0.70	0.29	E	0.99
1979	1.97	0.71	0.16	2.84
1978	0.70	0.02	E	0.72
1977	0.31	0.31	0.03	0.65
Average	0.89	0.36	0.14	1.39

NOTE: E = less than $5 million

The NWS is presently undergoing modernization that will produce additional benefits for flood mitigation in the near future by providing more lead time for flood-threatened people to take the steps necessary to protect life and property. A report by the Susquehanna River Basin Commission (SRBC) on the Susquehanna stated that the proposed flood forecasting system for the river basin would reduce flood damages an additional 10-15 percent (Susquehanna, 1985). However, at that time, the SRBC was not aware of the enormous technological advances associated with the NWS modernization and its impact on further reducing flood damages not only in the Susquehanna River Basin but nationwide. Therefore, the upper band of 15 percent verifies the conservatism of the estimate of economic benefits associated with NWS hydrologic forecasts. Senior NWS hydrologists concur that AHPS will produce up to 15 percent, or approximately

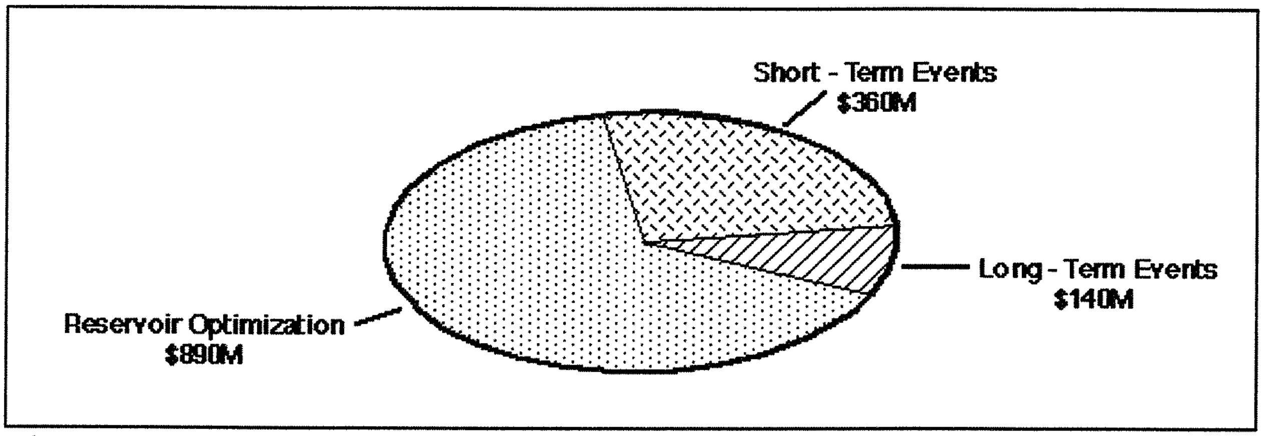

Figure 6. Flood mitigation economic benefits of NWS hydrologic forecasting.

$200 million ($1.39 million times 15 percent), improvement in each of the three categories of benefit realization: optimization of reservoir operation, short-term, and long-term forecasts. Further corroboration of these numbers is provided by Hudlow et al. (1984). The combined economic benefits, when modernization is fully implemented, from the NWS hydrologic forecasts toward flood mitigation is conservatively estimated to be $1.59 billion ($1.39 billion plus $200 million) annually.

ADDITIONAL BENEFITS RESULTING FROM AHPS FORECASTS

This report has primarily focused on the benefits that result from warnings issued by the NWS during flood events and actions taken to mitigate flood damages. The forecasting of both high and low flows during nonflood conditions also constitute important input to the efficient operation of any water resources system: hydropower generation, irrigation, navigation, and water supply (WMO, 1992).

In an average year, there are 296,000 gigawatts of hydroelectric power generated in the United States (van der Leeden et al., 1990), which amounts to an annual expenditure of $7.4 billion based on an average rate of $.025 per kilowatt hour (Howard, 1997). One study (Castruccio, 1981) shows total annual benefits by improved forecasts for hydroelectric power generation in the 11 western states are based on a 6 percent improvement in hydrologic forecasting. An updated report by the Office of Technology Assessment (OTA, 1983) on water-related technologies reflects a figure of 7.5 percent for the 11 western states. In a more recent report by Riverside Technology, inc. (RTi, 1994), annual power benefits for three small reservoirs near Denver, Colorado, show improved long-term hydrologic forecasts using AHPS-generated forecasts could increase economic benefits in the range of 2.5-15.5 percent. Even if we use an extremely conservative number, such as 1 percent improvement in hydroelectric power operation for the entire country, implementation of AHPS throughout the United States would realize an economic benefit of $74 million ($7.4 billion x 0.01).

The second category of benefits associated with hydrologic forecasts, exclusive of flood mitigation, is irrigation. According to *The Water Encyclopedia* (van der Leeden et al., 1990), 8.2 million acres in the United States are irrigated with on-farm, pumped water using surface water. The value of irrigated cropland in the United States is estimated at $531 per acre (1982 price level). Typical crops include corn, sorghum, wheat, barley, oats, rice, cotton, and soybeans. A monetary value for each of these crops was determined, and all crops were weighted by acreage to obtain the value (Day, 1987). Another study (Castruccio, 1981) indicated that a 6 percent improvement in irrigation practices was possible from improved hydrologic forecasts in the 11 western states. Nationwide, the amount of irrigated land acreage is approximately the same as that of the western states. However, in this paper, extremely conservative estimates are used for all economic benefits associated with improved NWS hydrologic forecasts; therefore, a 2 percent improvement for irrigation is assumed using AHPS. This results in economic benefits of $144 million annually (8.2 million acres x .02 x $531/acre x 1.65 cost-of-living adjustment factor).

Improvements in hydrologic forecast accuracy benefit the navigation industry which provides inland commercial shipping. Knowledge of the river stage along navigable rivers is essential for planning the loading of commodities onto barges and other cargo vessels and for the scheduling of river traffic.

Navigation benefits, with AHPS fully implemented, is expected to significantly increase revenues using inland harbors. The NWS conducted a study, the Program Development Plan (PDP), for the Columbia River at the Dalles, Oregon (DOC/NOAA/NWS, 1986). Approximately 570 grain ships visit the port of Portland in a normal year. While it is difficult to convert the river runoff to an increase in depth at every critical point in the estuary, full implementation of AHPS will allow cargo ships to raise their draft bringing an additional $20 million to grain shippers each year. This $20 million covers only the benefits for grain ships leaving port. It is likely that if the necessary draft were available with a high probability, tankers would carry more oil, car carriers more cars, and container ships more electronics, appliances, lumber, etc. It is safe to assume that these other ships could produce benefits equal to $40 million annually. Economic benefits for tankers and grain ships using AHPS enhancements in the port of Portland would total $60 million ($20 million plus $40 million). Adjusted to 1996 price levels, this figure is $77 million. The amount of inland freight carried on inland waterways in the United States indicates that the Pacific Coast waterways carry only 5 percent of the national total (van der Leeden et al., 1990). Similarly, *Waterborne Commerce of the United States* reveals that Portland ranks 21st in total tons among U.S. ports (USACE, 1995). Therefore, it is safe to assume that other ports (e.g., New Orleans, Pittsburgh, Mobile) in the country would also realize annual economic benefits at least equal to the Portland navigational benefits for a total of $154 million ($77 million x 2) for the Nation.

The fourth category of water management resources is water supply. However, if we assume that only 2 million acres of the potential acreage under cultivation were subjected to improved water management conditions, substantial benefits could result. Additionally, 23 million acres of land could be added to the total irrigated acreage if assurance of suitable water supply were made. Not using any of the 23 million acres is consistent with the conservatism in this paper in developing economic benefits related to AHPS. Therefore, water supply benefits are obtained by applying the 6 percent improvement factor for improved hydrologic forecasting techniques (Castruccio, 1981) to the $531 per acre (van der Leeden et al., 1990) in crop value times 2 million acres to achieve a 1982 figure of $63.7 million. Adjusted to 1996 price levels, the average annual benefit for water supply from implementation of AHPS is $105 million.

Another category of benefits associated with hydrologic forecasts is recreation. However, since detailed studies in this area are not readily available, this paper does not address recreation. Advance warning resulting from implementation of AHPS could mitigate damage to property, such as campgrounds, picnic areas, marinas, and boats by allowing property owners and users time to move property or take protective measures. Other related recreational benefits would ensue from whitewater activities.

With AHPS, the benefits exclusive of flood mitigation are $477 million annually (in millions of dollars: hydropower, 74; irrigation, 144; navigation, 154; water supply, 105). Table 4 shows the categorical breakdown of economic benefits associated with NWS hydrologic forecasts.

Table 4. National benefits, excluding flood mitigation, associated with NWS hydrologic forecasts when AHPS is implemented, in millions of (1996) dollars.

Water Resource Activity	Benefits Resulting From AHPS
Hydropower	74
Irrigation	144
Navigation	154
Water supply*	105
Total	$477

*Municipal and industrial water supplies are not included.

MODERNIZATION OF THE NATIONAL WEATHER SERVICE

Since its inception, the NWS River and Flood Program has continually endeavored to modernize its tools and technologies (Fread et al., 1995). Increased water demands, pollution, and climate variability have at one time or another made water a scarce resource in most areas. These factors constantly stress our water resources systems and challenge daily our water management decision makers. Reservoirs are constantly operated with the competing objectives of providing flood control, water supply, and hydropower generation while maintaining or improving water quality, navigation, and recreation. Modernization activities in the hydrologic program have advanced the science of real-time forecasting and the supporting computer and telecommunications systems of data processing and data transfer. This technology, together with the appropriate training of NWS hydrologic forecasters, has resulted in improved hydrologic information available to water managers across the country.

Following The Great Flood of 1993, the NWS chose the Des Moines River Basin to test a new process for preparing longer-range hydrologic forecasts (Riechenbaugh, 1996; Stallings and Ingram, 1995). As part of AHPS, the NWS Forecast Office in Des Moines plans to enhance its entire flood forecasting program by issuing more detailed and frequent Flood Potential Outlooks during the spring flood season. If flooding occurs, the office will issue more frequent Flood Statements and Warnings using the latest stage and 5-day forecast hydrographs. These forecasts will help emergency managers to better evaluate the risks of flooding by assessing forecast uncertainty. AHPS (see Figure 7) will provide data on quantitative precipitation forecasts and long-range forecasts, including full hydrographs and inundation maps and will show probability forecasts using both text and graphics that will be most helpful to its users (emergency managers and other decision makers, media, general public). When fully implemented nationwide, AHPS is expected to provide flood mitigation benefits in addition to the $1.39 billion shown in Table 3. AHPS flood mitigation benefits will accrue principally from long-term forecasts and optimization of reservoir operation although there will be some minor benefits during short-term events. Based on report results (Susquehanna, 1985; Hudlow et al., 1984), it is conservative to assume an additional 15 percent improvement will occur using AHPS. Since each flood event has its own characteristics, economic benefits from hydrologic forecasts will vary from negligible to over 25 percent for some events. Benefits for improved hydrologic forecasts build upon the work of Professor Day in the Susquehanna River Basin and his damage curves shown in Figure 1. The NWS (Summer, 1997) performed similar analyses for adjacent basins to the Susquehanna River Basin and concluded that similar economic benefits are likely because of the additional warning time that AHPS will provide to residents of the floodplain and emergency operations personnel. For the purpose of this report, improvement is defined as increased response time with enhanced accuracy of the NWS hydrologic forecasts. Thus, additional flood mitigation benefits of approximately $200 million ($1.39 billion times 15 percent) are assumed when AHPS is implemented nationwide.

Besides the economic benefits that result from greater forecast lead times of ensuing flooding, AHPS is expected to provide substantial benefits for other purposes, i.e., hydroelectric power generation, irrigation, navigation, and water supply, as shown in Table 4 under "Benefits Resulting From AHPS." The PDP for Improving Water Resources Forecasting Services (DOC/NOAA/NWS, 1986) refers to an American Society of Civil Engineers' workshop on reservoir system operation held in 1979 where participants determined that supplemental benefits could be realized by improving management of reservoirs. For example, the value of power could increase up to 10 percent from the California Central Valley Project and up to 20 percent at TVA facilities by improving operations. Economic benefits are associated with water management applications that exist from improved precipitation estimates available from NEXRAD (Hudlow et al., 1984).

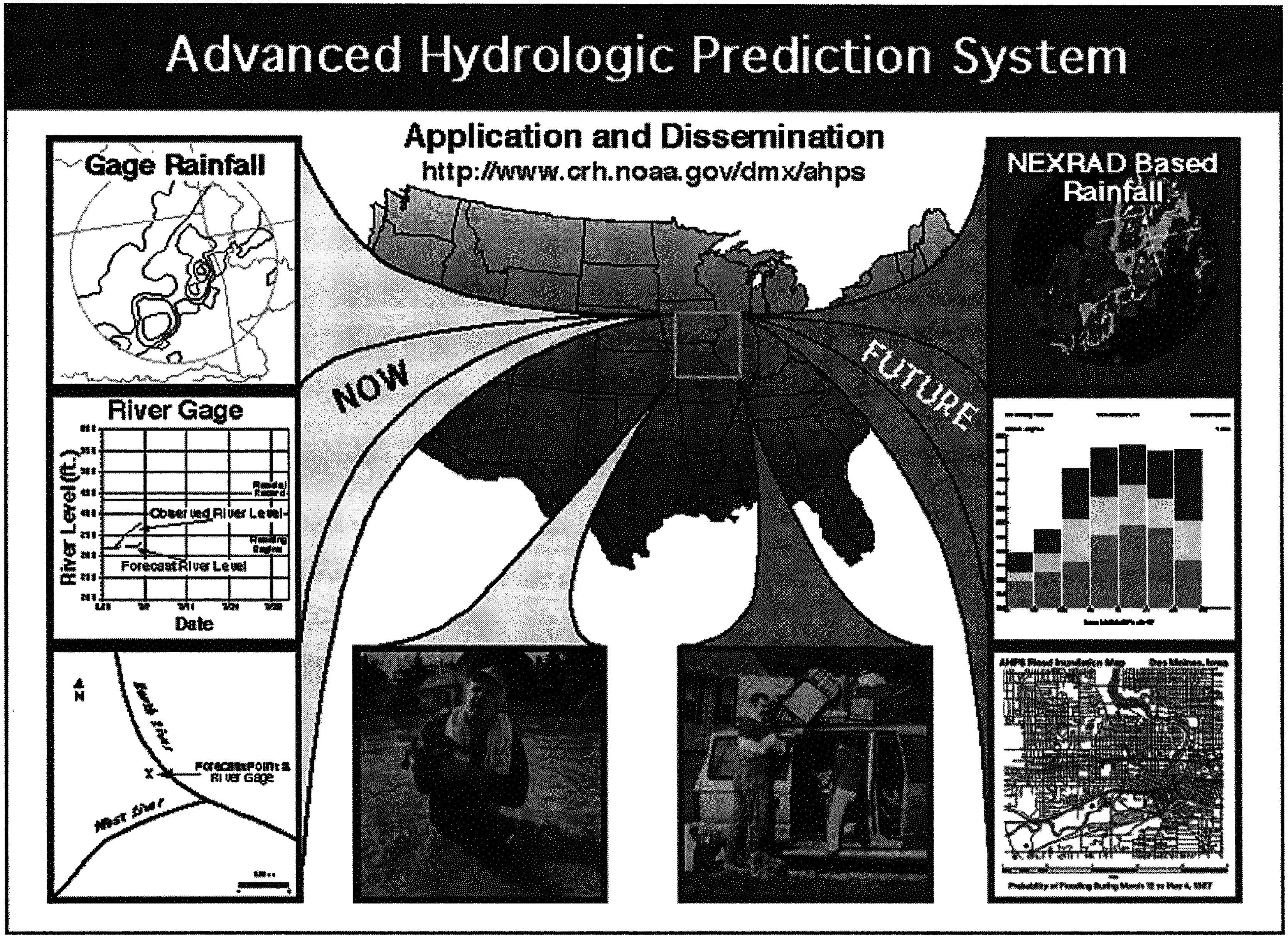

Figure 7. Future AHPS capabilities when implemented.

SUMMARY

NWS hydrologic forecasts are extremely effective in reducing flood damage. Advanced warnings for floods can mean the difference between life and death and in reducing property losses. Even 1 hour of lead time can result in a 10-percent reduction in flood damages. Economic benefits are derived from three categories: reservoir optimization, short-term floods, and long-term flood events. First, benefits result by incorporating hydrologic forecasting data and information with operating schedules of cooperators such as the USACE and USBR. NWS benefits from this optimization of reservoir operation are estimated to be $890 million annually. During snowmelt runoff and other long-term flood events, forecasts and warnings alert the threatened communities to take action by sandbagging and constructing levees. These benefits amount to $140 million each year. The NWS forecasts for short-term also are quite effective in reducing flood damages. This report reveals that a safe assumption of average annual flood damage incurred would be 10 percent higher without the NWS hydrologic forecasts, or $360 million annually. These three categories of annual savings due to hydrologic forecasts amount to $1.39 billion annually (see Table 3).

Although mitigation of flood damages resulting from timely and accurate NWS hydrologic forecasts accounts for $1.39 billion annually under existing conditions, the effects of improvements in long-range hydrologic forecasts are also quite substantial. Another $200 million in benefits is expected to result when AHPS is fully implemented, making a total of $1.59 billion annually by using NWS hydrologic forecasts to mitigate flood damages.

In addition to flood mitigation, AHPS will benefit other water resources activities, e.g., hydropower, irrigation, navigation, and water supply by an extremely conservative estimate of $477 million (see Table 4). This brings the total benefits from NWS hydrologic forecasts, with AHPS in place, to an estimated $2.1 billion annually.

Although total benefits from NWS hydrologic forecasts, including flood mitigation and with modernization in place, are estimated at $2.1 billion annually, it is important to point out that AHPS alone, when fully implemented, will add $677 million in economic benefits from improved water resource management and long-range forecasts--$200 million in flood mitigation and $477 million for other water resources purposes.

Since people consume water daily for a variety of purposes, such as drinking, washing, hydropower, agricultural, and many others, it is essential to provide the best support for our Nation's water resource decision makers. Hydrologic forecasting has proven to be a vital link in providing economic benefits to the Nation and must continue to improve to meet the increasing demands of the people of this Nation.

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AUTHOR'S NOTE. Over 200 publications were researched for this report, many of which contain valuable background information but were not included in this report.

APPENDIX A - CASE HISTORIES

DOMESTIC

Benefits related to NWS hydrologic forecasts are very difficult to quantify for a variety of reasons. Similar floods of magnitude and frequency do not necessarily equate to identical benefits. Often, when a second flood strikes in the same place, the residents react more effectively because they have already experienced great loss. They take immediate action to reduce or prevent further flood damage. There are occasions when the heavy rainfall with rising water levels does not occur near flood-control reservoirs and water cannot be captured to reduce flood levels at downstream damage centers. Even when the NWS uses its sophisticated hydrologic models to issue timely hydrologic forecasts, the impacted people cannot always effectively respond and take all necessary steps to reduce property damage and potential loss of life. However, in general, flood-control structures, automated local flood warning systems, and hydrologic forecasts accomplish their intended purpose of mitigating damages and loss of life from flooding. Following are several case histories that show these successes.

In the state of Pennsylvania, 66 out of 67 counties have implemented manual self-help local flood warning systems. In Lycoming County, the Sprout Waldron Company, in cooperation with county officials and the NWS, has documented substantial savings by implementing flood warnings in tandem with flood-proofing procedures. In the 1975 flood, over $800,000 ($2 million at 1996 price levels) in damages were prevented by operation of a local flood warning system and flood-proofing measures (WMO, 1983).

Following a flood in Ventura County, California, in February 1980, flood-control district officials (Burnash, 1984) estimated that $500,000 in damages were prevented because of a recently installed $50,000 Automated Local Evaluation in Real Time (ALERT) flood-warning system. Estimates of the benefit-to-cost ratio for ALERT systems have varied from 50:1 to 10:1. The NWS estimates that the number of automated local flood warning systems nationally is approximately 400 indicating that benefits from these systems are in the millions of dollars annually.

The city of Fort Wayne, Indiana, suffered flood damages in excess of $50 million in 1978 and again in 1982. As a result, the city adopted an "18-Month Work Program" to minimize the impact of future flooding. An ALERT system and the NWS Airborne Snow Survey (Carroll and Marshall, 1985) were added to the Plan, and flood damages of $24 million were averted in February 1985 when a severe flood event struck Fort Wayne. The NWS Airborne Snow Survey estimated direct program benefits from $0.7 million to $2.4 million. The cost of conducting the snow survey was $7,700 and thus reaped substantial benefits compared to the projected flood damages that were prevented as a result of the early warnings and flood forecasts based on the airborne snow water equivalent data provided by NWS.

INTERNATIONAL

Internationally, floods occur frequently just as in the United States. Similarly, national services in those countries issue hydrologic forecasts with resultant economic and social benefits. Three international case histories are presented here: the 1996 floods on several rivers in the People's Republic of China, the January 1995 flooding in Germany, and the May 1994 storm in Bangladesh. The first two case histories express benefits in U.S. dollars while the Bangladesh storm primarily involved an enormous reduction in loss of life during a storm event.

In the People's Republic of China (Jun Wang, 1996), severe flooding occurred on the middle and downstream reaches of the Yangtze River in both 1995 and 1996. Nearly 75 million people reside in the floodplain, and structural means proved extremely effective during both floods which prevented damages in the billions of (U.S.) dollars. Additionally, flood forecasting proved extremely accurate, winning time for flood-control decision making and gaining significant social and economical benefits. The People's Republic of China Water Resources Commission estimated that the disaster reduction benefits from hydrologic forecasting was $1 billion in the 1995 flood and $1.76 billion during the 1996 flood. The hydrologic forecasting benefits averaged 10-15 percent of the structural flood-control measures. Flood disasters were very serious in 1996 on many rivers with 20 million hectares of farm land inundated and a death toll of approximately 3,000 throughout the People's Republic of China (Juemou Wang, 1996). Total flood damages were estimated at $26.5 billion but major reservoirs alone prevented another $14 billion. Approximately 3.4 million persons were safely evacuated as a result of the accuracy of the hydrologic forecasts.

Between December 1993 and January 1994, a number of European countries experienced damaging flood events that were caused by precipitation more than double the amount of the long-term average at many locations. Total flood losses along the Rhine and Moselle rivers in north-central Europe exceeded $575 million

(Fed. Inst. Of Hydrology, 1994). Only 13 months later, another extreme flood event of similar size, duration, and water level occurred in the Rhine River Basin but with flood damages totaling only $287 million.

One benefit of hydrologic forecasting is revealed at the floodwall in front of the old city of Cologne. The wall provides protection up to a maximum water stage of 10 meters at the stream gage at Cologne. In the 1995 flood, forecasts indicated this threshold might be exceeded 36 hours in advance so that necessary precautions were taken. Because of the experience gained from a Christmas 1993 flood, people took the flood warnings seriously in the 1995 flood and evacuated their houses. Even though the January 1995 water level was actually higher, the people experienced only 50 percent of the flood losses than they had in the 1993 flood.

In Bangladesh, a Flood Action Plan was recently completed in cooperation with the World Bank following the disastrous riverine flooding of 1987-88. The objective of the Plan was to develop a long-term program for achieving a comprehensive and permanent solution to the country's flood problem. Although the Plan is mainly premised upon a structural approach, flood proofing and a flood-warning project are also incorporated into the Plan. The Flood Forecast and Warning Program (Kachic, 1993) was completed in 1993 with success results as early as May 1994. The comparatively low death toll in the huge storm that whipped across parts of southeastern Bangladesh was attributed to a combination of modern technology and simple steps that led to the evacuation of hundreds of thousands of villagers to higher ground and storm shelters. Similarly, a major cyclone killed over 100,000 persons in 1991 but in 1994 only 500 deaths occurred.