A NEW REAL-TIME WEATHER MONITORING AND FLOOD WARNING APPROACH

by

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The final copy of this thesis has been examined by the signators, and we find that both the content and the form meet acceptable presentation standards of scholarly work in the above mentioned discipline, but do not necessarily represent the views of the signators.

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A New Real-time Weather Monitoring and Flood Warning Approach

Thesis directed by Professor Frank Barnes

A case is developed for implementing a highly effective, integrated local and regional real-time weather monitoring, data dissemination and flood warning system using standard computer systems and software, data formats, network and telecommunications technologies. The approach incorporates private enterprise as a funding base into today's primarily government-funded approach. Success will require cooperation among the National Weather Service (NWS) and other federal agencies, software and telecommunications vendors, and local and state emergency managers. The new architecture will serve both the private and the public sectors.

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CHAPTER I: INTRODUCTION

Floods are “acts of God,” but flood losses are largely acts of man.

White, *Human Adjustment to Floods*

Weather monitoring is one of the oldest human activities, if not the oldest profession. Severe weather consequences range from changing our weekend plans to triggering other disasters, widespread injury, death and destruction of property due to flooding, fires, disease and famine, and devastation of local or regional economies.

People have always dealt with floods, and flood warning has always been critical. Judeo-Christian religious history records in the Book of Genesis the story of Noah and the great flood, allegedly the first flood attended by humans, shortly after their inception (Genesis 6:6-8, The Holy Bible, Revised Standard Version). The story chronicles what was also as early use of flood warning; God was upset with the corruption He perceived in the humans He’d created, so He decided to wipe them all out by arranging a 40-day rain storm with consequent flooding. God thought Noah was not so bad, however, so He warned Noah about the flood and told him how to preserve himself, his family, and members of each of the other species by building an ark and preparing to ride out the flood. In this case, Noah required quite a bit of warning for success, but God's timing allowed for that and the Ark venture succeeded as planned.

The ability of organizations to receive relevant, real-time (in this context, real-time means within a few minutes) information about the weather in their area empowers them to react to impending danger in an effective manner. "Mission-critical" type users have some very special needs. Their primary job is to get people out of harm's way. In the case of public safety organizations and emergency managers, having real-time weather information allows them to effectively plan their resource deployment and to decide as quickly as possible whether, when and where it is appropriate to escalate their response.

Receiving real-time weather information allows other types of operational organizations (e.g., private companies, hospitals, school systems, public utilities and transportation entities) to prepare and use plans that minimize potential damage and optimize the use of resources. Their primary job is to keep chaos and cost to a minimum while protecting the people who rely on their organization for products and services.

Warning systems caveat

Any technology used for early warning must be viewed in light of the human consequences of its use. A system that gives its users imperfect information about current or future conditions (unlike God's warning) is one that may do more harm than good. A flood warning system, for example, can be conceived as having three components: a weather monitoring component, a forecasting component, and a decision component. If these three components together produce either not enough warnings (misses) or too many warnings (false alarms), then the system can actually be detrimental to the communities relying on it. An approach to quantitatively estimating the reliability of a warning system is presented by Krzysztofowicz, Kelly and Long (1994).

With this caveat in mind, the following thesis explores a new approach to provide integrated weather data services in real time on a regional basis for the primary purpose of flash flood warning.

Thesis organization

Chapter II contains an examination of some of the challenges brought by flash flooding. Chapter III reviews and assesses existing automated monitoring and forecasting technologies. Chapter IV reviews the organizational and economic aspects of existing flood warning systems, including economic and human factors that constrain the success of current weather monitoring systems.

Chapter V proposes a new method and architecture for data collection and dissemination based on standard technologies. The proposed method of funding is to leverage the secondary market of non-mission critical users as a primary economic driver. A case is made for an alternative, public-private partnership approach.

CHAPTER II. USEFULNESS OF FLOOD WARNING

A flood can be defined as the presence of “too much water in areas that are not normally under water” (Ludlum, 1995, p. 538). Flooding is a natural consequence of rainfall and snowmelt. A flood event’s implications for a community depend on the degree to which people are prepared for it.

Some floods are annual and largely predictable. In the United States over the last hundred years, mitigation structures such as dams, levees and flood channels have been built to manage and divert the “main channel” floodwaters brought by large rivers and seasonal runoff, largely the mission of the U. S. Army Corps of Engineers (COE).

Flash floods are “sudden rises and falls of streams, usually resulting from brief but intense rainfalls over localized areas” (Ludlum, 1995, p. 538). Flash floods are inherently more difficult to manage because of their unpredictability and relatively short lead times, and structural mitigation approaches by themselves are less useful. The use of warning systems in flash flood-prone areas is very important.

The annual flooding of big rivers that are fed by large snow and rainfall catchments traditionally has provided a resource of enormous value to humans. Agriculture first thrived in fertile flood plains that were washed with new soil and nutrients every year by rivers that were huge and reliable in their flooding. The residents of such areas have always had to strike a balance between the risk of being caught in the flood plain in high water years, and the convenience and desirability of living near the river. Occasionally people find their settlements in the path of the river and experience tremendous losses as a consequence. The potential for damage is great, but the reliability and time course with which seasonal flooding can be predicted has enabled many communities to mitigate the flood danger today.

A different sort of flood potential is presented to communities that are located in or near hills or mountains with smaller, faster-responding streams. Often the hilly terrain is steep and rocky so water from rainfall runs off more quickly and thoroughly. The ground surfaces of areas recently burned by wildland fires actually take on hydrophobic qualities and virtually no water is absorbed before it runs off. In these scenarios the flooding potential is closely tied to the location and intensity of specific weather events. This type of flood event inherently provides a much shorter time of preparation for flooding than does a large river valley or plain.

Flood danger has increased with human developments

The destruction due to flooding in general has been increasing over the years. In the United States, according to the U. S. Department of Commerce, annual flood damages nationally are now about $4 billion and rising. Some of the increase is due to the increased population and higher value of associated settlements, but other factors are more directly causal.

> "Why does anybody live there?"
> "They're not well informed. Most folks don't know the story of the fire-flood sequence. When it happens in the next canyon, they say, 'Thank God it didn't happen here.'" (McPhee, 1989, p. 229)

Modern urban development creates large areas of asphalt and concrete that are much more impervious to water than were the natural surfaces, and a given rainfall event today produces much more runoff than it would have when the cities were less developed. Finally, more people are building in flood-vulnerable locations chosen for their natural beauty, such as in and at the mouths of mountain canyons and arroyos.

Other areas are becoming more prone to flooding because of forest destruction and consequent erosion of pervious materials. Heavy deforestation of large catchment areas in recently controlled larger basins has resulted in an enormous increase in the size and frequency flood events, including a large increase in shorter concentration-time inundation events – larger basins are now flashier.

The role of global warming

Global warming due to vastly increased carbon dioxide emissions may still be treated as a political controversy in the United States, but in the very pragmatic worldwide insurance industry there is no controversy about its existence. The discussion today surrounds how to address the now rapidly accelerating rate of annual losses being observed throughout the world due to natural catastrophes caused by global warming.

One estimate is that current effects of a warmer climate have had an average (across economies) annual impact of 1-2% of gross national product (GNP), with the impact at 10% GNP or greater for some countries, and that these numbers will be much higher in the 21st century (Berz, 1998, p. 405). A report released by the Worldwatch Institute and Munich Re (Münchner Rückversicherung, the world's largest reinsurance firm) estimated that the worldwide losses due to storms, floods, droughts and fires in the first 11 months of 1998 (US $89 billion, inflation-adjusted for comparison at US $82.7 billion) exceeded those for the entire decade of the 1980s (US $55 billion) (c.f. Abu-Nasr, 1998).

In a 1998 year-end press release, Munich Re reported that windstorm events (240) and flood events (170) together accounted for 85% of the economic losses and 90% the insured losses experienced globally in 1998. In the same press release they made the following statement:

> "Comparing the figures for the 1960s and the last ten years, Munich Re has established that the number of great natural catastrophes was three times larger and cost the world's economies – after adjusting for inflation – nine times and the insurance industry fifteen times as much. The main reasons for this dramatic increase are the concentration of population and values *(sic)* in an ever growing number of larger and larger cities, which are often located in high-risk zones, the greater susceptibility of modern industrial societies to catastrophes, the accelerating deterioration of natural environmental conditions, and also, as far as insured losses are concerned, the increase insurance density in the sector of natural hazards. A change in the trend is not in sight." (Munich Re, 1998)

Every year there are deaths due to flooding in the United States. The sudden transformation of placid streams, mountain rivulets or dry washes into raging torrents occurs in all regions and can happen at any time of year. Most of the deaths occur because people either underestimate or are unaware of the danger until it is too late to escape.

Warning about main channel flooding has very different characteristics from flash flood warning, and is usually much more effective in preventing fatalities. Main channel floods have a long lead time, on the order of days or weeks. The areas that are the source of flooding are large and relatively flat, the water velocities are low, and the time of melt or rain collection long. Snowpack can be measured in advance, and the melt rate can be estimated by seasonal and short-term temperature forecasts. Large-scale weather tools such as satellite photos and radar are effective in predicting future rainfall and modifying forecasts in advance of the rain itself.

The flood forecasts derived are reasonably accurate in predicting both the size and the time of peak flow at particular locations along the rivers, well in advance of the event. Individual, localized weather events don't have a significant impact on the outcome. Sometimes unavoidable property damage may still be incurred and small errors can have large effects (e.g., the Grand Forks, ND, flooding in 1997, in which the river depth peaked just above rather than just below the 50 feet forecast and had devastating results). Nevertheless, people have a chance to prepare for the flooding, emergency managers and the media have time to educate the community about public safety issues, and organizations have time to make choices to protect their investments.

Flash flood events have a different time course, on the order of hours or even minutes, and effective warnings are much harder to achieve. The area affected is much smaller and the primary source of relevant information is real-time local weather data. The accuracy of satellite and radar tools for small specific areas is not as good as for larger areas. There is little time in which to prepare a forecast, and the accuracy of the forecast may be poorer. Even with an accurate forecast, there often isn't adequate time to let people know what to do. The most valuable tools are those that can increase the forecast accuracy and advance notice time of a flash flood, combined with unambiguous, effective and practiced response plans.

The critical value of flash flood warning

In a flash flood situation, it's often the case that the first warning received by affected individuals is the event itself. As a consequence, they either make bad decisions or they are simply caught by surprise and helpless to escape. For example, people too often make the lethal choice to drive their cars across city streets that are acting as significant waterways during an intense rainstorm. They do this because they underestimate the danger of the water's depth and power; to the driver's amazement, the vehicle is swept away by the torrent and the occupants drown.

These types of fatalities occur on a regular basis in cities such as Houston, Dallas, and Phoenix, where intense storm water runoff is channeled into usually dry areas that are also roads. In those areas, flood warning is provided by road signs and light signals that identify the locations of "low water crossings" (meaning it's safe to cross during low water) and instruct drivers not to cross when water is present. But fatalities have also been recorded in areas where such events rarely occur such as Minneapolis, and drivers had no warning information. With no additional information or experience they are more likely to make a bad decision.

Other times the location and the intensity of a storm event are such that normally ample mitigation structures are overwhelmed or fail catastrophically and the runoff is delivered as a large and uncontrolled pulse, wreaking widespread destruction in its direct path. Even with warning, property loss may be unavoidable in these cases, but damage can be mitigated and loss of life can be prevented and if people have time, for example, to turn off the machines in a smaller flood, or to escape the flood's path for the big one.

For organizations willing and able to prepare for floods, adequate warning time may mean having the chance to move valuable products and equipment out of the water's path thus saving their business, re-routing shipments to avoid costly delays, or calling the baseball game well in advance of disaster. Those people who attended a now infamous baseball game in Kansas City in the summer of 1998 sat helplessly and without shelter as the water poured down the stadium steps. There had been no warning (Miller, 1998).

A prototypical modern event

A large storm occurred near Estes Park, Colorado, on July 31, 1976. The Big Thompson River flows from Lake Estes 25 miles east and down through the foothills into Loveland. There are several small communities along Highway 34 in the canyon, and many tourists were camping and staying at motels that Saturday. That evening an intense, stationary thunderstorm over the western watershed of the Big Thompson dropped as much as 12 inches of rain in less than five hours, several times the average rainfall for the entire month of July. The resulting runoff produced a wall of water that gathered force and debris on its way down the canyon. Normal flow at the mouth of the Big Thompson at that time of year is on the order of a few hundred cubic feet per second (CFS), as it was before the storm. The peak flow recorded that night was 31,200 CFS, four times the previous maximum flood values recorded over 88 years, and almost twice the flow expected for a 100-year flood.

The flood toll included 316 homes, 45 mobile homes, 52 businesses and much of Highway 34 swept away or destroyed by debris. Eighty-eight people were injured, 139 were killed, and five were never found (McCain et al., 1979).

There was no warning process in place, and a Colorado State patrolman who drove up the canyon to warn people was among those killed. Despite the catastrophic outcome, the death and damage costs of this flood were much lower than they would have been had the storm stalled out just a few miles to the south over the Boulder Creek drainage. The city of Loveland was largely unaffected, lying four miles out in the plains, but downtown Boulder is at the mouth of Boulder Canyon.

This storm, now more than 22 years past, is still the most recent flood event to cause more than 100 deaths anywhere in the United States. As a result of this and several other catastrophic events (Hurricane Camille, VA, 1969; Hurricane Agnes, NE United States, 1972; Rapid City, SD, 1972; Buffalo Creek, WV, 1972), federal, state and local emergency management agencies developed technologies and methodologies to provide more effective local flood warning systems (Gruntfest, 1986).

The Challenges of Flood Warning Systems

There are at least two challenges to meet in designing an effective flood warning system. The first challenge contains the technology issues; how can we collect and present the information human observers need to make flood warning decisions? The second challenge involves decision-making tools and human behavior; what are the design factors that enable humans to use the information effectively and make good decisions?

This thesis addresses specific aspects of the technology issues, in particular, the telecommunications channels and data architecture by which relevant information can be presented to users. The human behavioral aspects, however, are equally important in developing the information products thus presented, with particular emphasis on the ease of use and relevancy of the information to the user.

Recently, modern telecommunications and electronics have combined forces to enable widespread dissemination of information about the weather. The ongoing success of The Weather Channel on cable television serves to demonstrate the strong interest of many people in the weather, local and remote. Media and network providers' web pages always include links to a variety of weather sources on the Internet. Radio stations broadcast severe weather information, a special NOAA weather radio band broadcasts weather information 24 hours per day, and most broadcast television network affiliates carry "crawlers" with severe weather information of local interest.

The information requirements of decision-makers overlap with, but aren't the same as, those of the general public. People with ordinary weather-watching interests can peruse available weather information from several broadcast and Internet sources, with many of the resources offering data in between ads and other material. Most of us consider it acceptable, even advantageous, to be able to learn different things from a variety of sources.

However, publicly-accessed Internet weather web sites are not intended to be mission critical and they often slow down or even crash during major events due to extreme traffic loads. These sites do not carry the latest information, but rather make available information that is updated relatively rarely, or only after it is no longer “real-time”. This choice of timeframe is a bottom-line decision for the providers, as the mission-critical customers will pay for timely, frequently-updated data.

There is also a great deal of weather information on the web that has not undergone any quality control. The data offered may be inaccurate (i.e., read from uncalibrated or poorly-located weather instruments). As for content, the primary purpose of public web sites, broadcast and cable TV programs is to present advertising along with other compelling material to consumers. Most of the “content” on these channels has nothing to do with weather data.

Mission-critical users cannot afford to lose data access during a severe weather event. They need the latest and highest quality information, with no irrelevant accompanying materials. During a severe weather event, an emergency manager must continually receive, process and integrate large amounts of general and specific information about the weather, in addition to other reports on community status and resources. The more incoming information channels he or she must attend, the harder it is to accomplish the task of making correct and timely decisions.

Watching the Weather Channel and local TV stations, listening to the NOAA weather radio and looking at some web sites presents an unacceptably large number of channels with lots of irrelevant material to a mission-critical user. These users should be provided a few information channels carrying highly relevant data, as specific as required and in a summary form that enables quick integration across domains.

In summary, weather information users who have mission critical needs require accurate, real-time, integrated weather data products to accomplish their goals. There isn't currently a weather data system that does a good job of this. There are, however, many data sources that could be integrated to produce the required information stream.

CHAPTER II. REVIEW OF EXISTING TECHNOLOGIES

Hydrology, the science of water and its movement on land, and hydrometeorology, the study of the interrelationships between the atmospheric and land phases of water (U. S. Department of Commerce, 1997a), have experienced tremendous advances since the advent of automated remote sensing technologies. In particular, remote sensing techniques have enhanced the accuracy of models used to accomplish rainfall modeling, estimation and forecasting (Foufoula-Georgiou and Krajewski, 1995) and surface water hydrology (Engman, 1995). Remote sensing techniques include rainfall, snow and stream gauges as well as radar and satellite imagery. Such information and associated models form the information core of a flood warning system.

The National Weather Service (NWS), a branch of the National Oceanic and Atmospheric Administration (NOAA), has as its primary mission to protect life and property. They do this by providing flood forecasts and warnings to emergency managers and to the public. They took the lead in the development of the first automated local flood warning systems, with the most important work occurring in the middle and late 1970s, when the NWS California-Nevada River Forecast Center (RFC) first developed the Automated Local Evaluation in Real Time (ALERT) system (U. S. Department of Commerce. 1997b).

At this time, many of the other tools available today did not exist or were primitive (radar, satellite imagery). The development of ALERT was an innovative, cost effective approach to enabling local emergency and flood plain managers to control their own destinies, so to speak, by having access to locally relevant weather changes as soon as they occurred. Today, radar and satellite imagery products have managed to expand the set of tools available, but having access to local weather variables in real time, "ground truth" data, has not yet been replaced by the more sophisticated techniques that do offer better coverage. The current trend is to combine data from these sources to enhance the accuracy and/or coverage of each.

ALERT-based automated flood warning systems use equipment that can measure environmental variables at selected locations and report data automatically by broadcast radio (RF, either VHF or UHF bands) signals. The transmitters are programmed to transmit on an event basis, meaning that whenever a given variable surpasses some pre-programmed threshold for change, a four-byte data report is sent containing the sensor's ID and current value. This minimizes radio traffic yet assures that any change will be noted. Transmitters can also be programmed to send data on a regular interval. A PC base station receives the broadcast transmission via an antenna, receiver and decoder connected to a serial port.

These systems are relatively cost effective. A new sensing site can be installed for a few thousand dollars. The only recurring costs are for site and sensor maintenance (nevertheless too often ignored). The sensor and data communications systems are quite low-tech by today's remote sensing standards, yet the impact of having real-time data has been invaluable.

The most commonly deployed sensor types measure precipitation or water level, the two most basic pieces of information required for rainfall monitoring and flood warning. Modern systems are now capable of measuring many other weather variables, including air and water temperatures, wind speed and direction, relative humidity or dew point, barometric pressure and more. The same technology is being used increasingly often for monitoring water quality in real time.

In cooperation with state and local disaster and emergency services as well as the COE, the Federal Emergency Management Agency (FEMA), and the U. S. Bureau of Reclamation (USBR), local flood warning systems based on this type of technology have achieved fairly extensive coverage in flood-endangered areas throughout the United States. Systems based on ALERT technology have also been deployed in other parts of the world, primarily in Asia, Australia and South America. The two primary architectures currently deployed are described in the next sections.

The IFLOWS Automated Flood Warning System (AFWS)

The NWS supports a computer software and network application designed to assist state and local emergency services as well as NWS offices in detecting and managing flash flood events. The software receives and disseminates data from a network of real-time weather sensors, primarily rain gauges, that covers part of the eastern region of the United States. The system as a whole is known as the Integrated Flood Observing and Warning System (IFLOWS). The software/network application in use today is called PC/IFLOWS, produced by Jack Peterson at Horizon Data Systems.

IFLOWS raw data collection

The remote sensors in the IFLOWS system use the ALERT data protocol. Today, many of those base stations are running PC/IFLOWS to process the incoming data and store them in a local file of proprietary design. Associated PC/IFLOWS application programs allow users to display or print data from the database. The PC/IFLOWS software was originally designed for a Digital Equipment Corporation PDP-11 machine in 1981. It was updated to run in Microsoft DOS on IBM PC-compatibles in the late 1980s, and today it runs in Windows 95.

Data exchange on the IFLOWS network

A central purpose of IFLOWS is to provide real-time rainfall and stream flow observations to local warning agencies for the basins and headwaters that affect the public in their area of operations. Where possible, the warning jurisdiction receives the sensor telemetry signal directly because this offers the most robust architecture. However, the rugged terrain of flash flood prone mountain areas often precludes a direct radio path between the sensor and its warning agency base station. This means it is necessary to share data among data collection points.

Thus, in addition to storing directly received data locally, the PC/IFLOWS program transmits data to, and receives data from other IFLOWS computer systems in the network (see Figure 1). It does this via a second serial port connection and an attached modem (usually an RF modem) on the data collection PC base stations. The data exchange protocol is proprietary and internal to the PC/IFLOWS software.

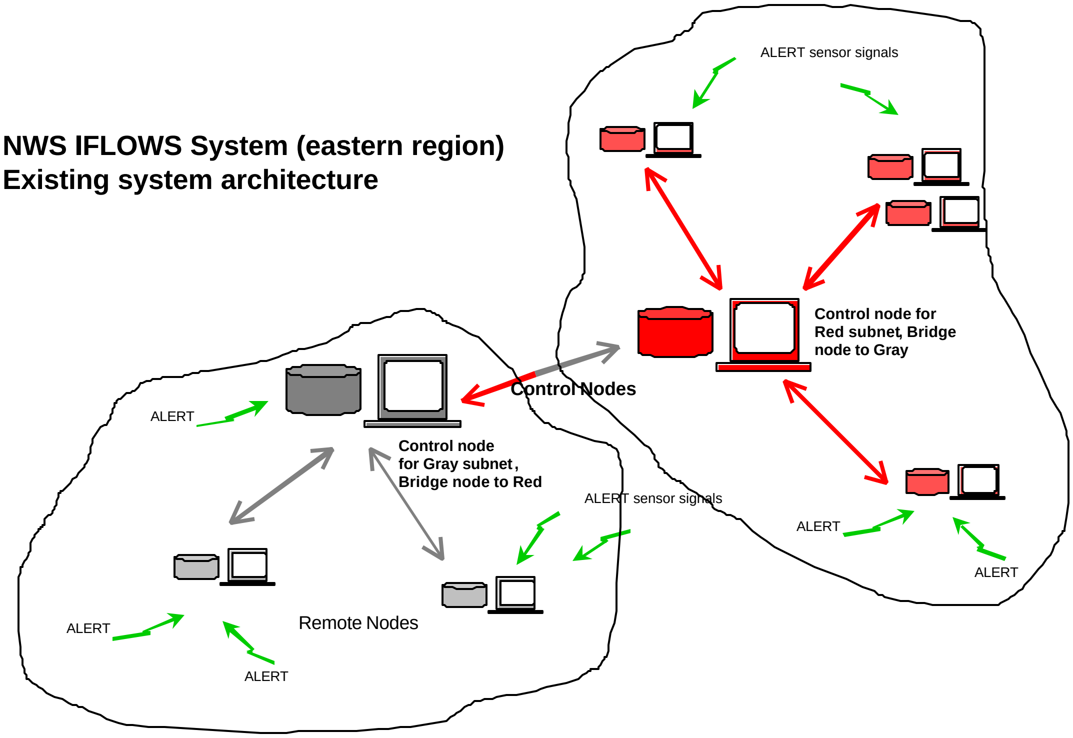

Figure 1. A schematic of the IFLOWS network depicts how bridge nodes interconnect the subnets for data exchange. The control node on the gray network is just another remote node on the red network, and vice versa. In this way data are shared among all the base stations.

The IFLOWS network is divided into a series of sub-networks, each containing one control node computer and a number of remote nodes. Some nodes act as bridges (i.e., they belong to two networks and pass data between them).

A control node polls each of the remotes in its network on a continuous, round-robin basis, requesting that they send new data or re-send data. All remotes receive all transmissions from the control node, whereas only the control node sees the polled responses. A remote responds to a poll when it sees its own address on the poll message. After the control node receives new data from the remotes, it re-broadcasts the data to all remotes. In this way, data from all sites on the network are available to all sites.

IFLOWS data exchange advantages

An extremely positive aspect of the IFLOWS architecture is the principle that every node should receive every other node's data. The control node polls its remote nodes every 15 minutes and then re-broadcasts the polled data after completing a round. Once a day each control node re-broadcasts all the data for that day, permitting nodes that were unable to receive some data to be filled in.

IFLOWS data exchange constraints

The IFLOWS software was a well-designed application for its time. It made creative use of limited hardware and software resources, and it used a parsimonious networking architecture to share data fairly quickly and inexpensively among many faraway sites. However, the application has neither progressed forward at the speed with which technology has been updated, nor has it fulfilled all of its original goals. Its constraints can be summarized in part as follows:

- Proprietary data storage format prevents both users and non-PC/IFLOWS applications from freely accessing data for other tasks.
- Proprietary network protocol limits data exchange and dissemination to methods included in PC/IFLOWS.
- The polling architecture and slow RF hardware in place result in actual data exchange transpiring much more slowly than "real-time" (sometimes hours instead of minutes) because of the number of sites covered today. If

the round-robin polling takes too long, then the re-broadcast doesn't take place and data aren't re-disseminated to the local nodes.

- The application has only recently begun to support more than rain-type sensors and is still limited in sensor types it recognizes.
- The application, the networking and the data exchange are inextricably tied to the PC/IFLOWS platform – users cannot choose other applications to collect, share or access the IFLOWS data without being left out of the network, and without removing their own data from the network.

Other "ALERT" Automated Flood Warning Systems

The NWS in the western region took a different path to develop data collection and display software for ALERT systems. While IFLOWS was developing in the eastern region, the Sacramento RFC developed the Hydromet application. Just to confuse things, this approach is generally referred to as "ALERT" (see Figure 2).

Hydromet started on the QNX platform, a Unix-like PC operating system used primarily in manufacturing control systems, where it remains today. Unlike the PC/IFLOWS software, which was developed under contract with a private vendor, NWS staff continued to develop and maintain Hydromet.

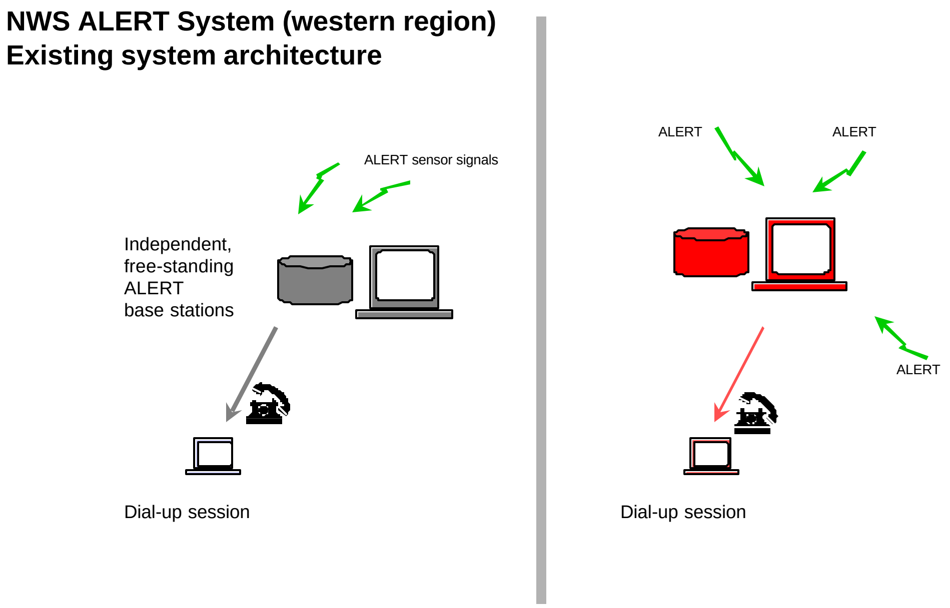

Figure 2. A schematic of the primary deployment style for "ALERT" systems (until the last couple years). Until STORM Watch was introduced there was no opportunity to share data in real time among base stations. Remote access was accomplished only by transient, dial-up access to a proprietary platform (QNX).

Hydromet advantages and constraints

The advantages to Hydromet and some of its "ALERT" relatives (described below) over IFLOWS are several:

- The data received and displayed are actually real-time.
- There is a much higher level of functionality built into the products. They support a wide variety of sensor types and provide many different ways of displaying the data.

- They support advanced tools, including graphics displays, automated paging, and flow forecast models (see below).

The Hydromet application itself has some serious constraints:

- The data collection and display platform is designed for local use and transient dial-up access only – there is no wide area networked data sharing enabled.
- The database is proprietary and access is limited to Hydromet-provided methods to retrieve data.
- The QNX operating system is relatively expensive and incompatible with many PC hardware components, making it difficult for users to acquire, network or support.
- The NWS no longer has the resources to support Hydromet, and both staff and outside users are aware of this limitation. The primary programmers and support staff (Wayne Martin and Andrew Morin) have been assigned to other projects.

The hydrologist authors of the first Hydromet application, David Leader and Don Colton, left the NWS shortly after Hydromet was released and began to produce private sector applications related to Hydromet. The products being sold today that fall into this category include NovaStar from HydroLynx, Inc. (Leader), Data Command from Vitel, Inc. (written by Colton), and DataWise (written and marketed by Colton). The first two products run on QNX, and the third runs on Windows NT but not Windows 95/98; DataWise is Data Command ported to Windows.

All three of these applications store their data in related proprietary database formats designed for streamlined long-term storage. The databases cannot be opened by other applications. Although they all support direct remote and dial-up session users, the remote sessions are transient and do not have the capability to build their own local databases. The Data Command and DataWise applications incorporate the proprietary PC/IFLOWS connectivity, but none of the three enables regional data sharing via standard network protocols among base stations.

DIAD released an ALERT data collection and display software application called STORM Watch, designed by Don Van Wie, in 1996. STORM Watch runs in Windows 95/98 and NT environments. It stores data in Microsoft Access format, an open, relational database that is accessible by standard ODBC methods to other applications and database engines. The STORM Watch application is not required to open and use the database.

The STORM Watch host application is built to a client-server architecture. The distributed application ties into LAN, WAN and inter-networked environments and affords dial-up networking support for mobile and remote users. Remote users (STORM Watch client applications) use standard Windows networking applications to gain access to the host database and collect data into their own local databases, rather than relying on a proprietary and transient direct interface between base station and remote applications. The network exchange mechanisms and protocols reside outside STORM Watch's proprietary code.

Flow forecast models

Unlike the PC/IFLOWS application, all the applications described above either directly incorporate flow forecast models (Hydromet, NovaStar, Data Command and DataWise incorporate the Sacramento RFC soil moisture accounting model) or support companion applications that do the modeling (STORM Watch integrates FLOOD Watch using the Sacramento RFC model by Riverside Technology, inc., and also supports CFS, an HEC-1F implementation by David Ford Consulting Engineers).

These models estimate both the amplitude and the time of flood crests, allowing more detailed estimation of the potential for problems during a weather event. This additional tool set is extremely valuable to those users who have the ability to support and run the models; modeling requires an additional commitment and hydrology skills on the part of the user organizations to correctly maintain and interpret the model outputs.

Other Data, Products and Tools

Other methods used to monitor environmental variables remotely include telephone- and radio-polled gauging systems, satellite-enabled transmitters and on-site data loggers. With the exception of some radio-polled systems that can poll based on alarm transmissions from a gauge and some use of "random-transmission" capable satellite-enabled transmitters, these technology choices are not event-based and thus do not offer real time information in the same sense as do those based on ALERT technology. In addition, both the initial implementation and recurring costs of these alternatives (with the exception of the data loggers) are considerably higher than for ALERT. Today's automated flood warning systems frequently use a mixture of technologies to accomplish their mission.

Other types of data and tools used in flood warning systems include NEXRAD and local radar products, satellite imagery, NWS text products such as flash flood guidance, weather warnings and hydro-meteorological forecasts that provide probabilistic information about rainfall and river flow potentials.

Few of these tools are integrated in any way with the others. The products mentioned are distributed using completely different channels and running in different computer environments.

A set of real-time (5- to 15-minute) radar products can be subscribed to from one of the vendors charged with adding value to the NWS NEXRAD system, for example, WSI Corporation or Kavouras, Inc. The products are received over a dedicated satellite link, then stored and displayed on either a Unix workstation or a PC running Windows NT. A lower-cost product suite that includes satellite imagery can be had from DTN, Kavouras' parent company, also by satellite feed but to a dedicated PC with no data storage. Some users receive the NWS internal radar products over wide area network links or via the NWS Satellite Network.

Finally, the NWS text products are provided over satellite or RF re-broadcast within local areas via the EMWIN program and received for display using third-party Windows software packages. These products can also be received via the NOAA Weather Wire, an older version of EMWIN.

There are at least two reasons to integrate the variety of weather products available: (1) Integration provides more information in fewer information channels, and (2) some of products will be improved after integration. For example, local real-time rainfall measurements sample the rain that has actually fallen to the ground over a small area, and radar coverage estimates rainfall over a large spatial extent. Combining the local "ground truth" data with the radar creates a better estimate of the rainfall, still with the coverage of the radar (Hartzell et al., 1998).

Given the advances in computer applications, telecommunications and computer networks made in the last decade, it is possible today to build a real-time weather-monitoring network that will far better serve its designated function than do the existing applications, that will integrate a variety of products and tools, and that will preclude dependence upon a single proprietor or application in the future.

Summary of Existing Technologies

Since its inception 20 years ago, ALERT sensor and transmitter technologies have expanded both functionally and geographically. Multiple vendors produce hardware compliant with the ALERT standard, offering the benefits and protections of a competitive market. ALERT systems are used today around the world to monitor not only rainfall, but water level, wind and other environmental parameters of all types. In choosing ALERT, the NWS and their clients have invested in a sensor network that is highly functional and can be built out as their requirements grow and change.

Serious constraints in the IFLOWS system today stem primarily from its software and networking platforms, plus the fact that the database is proprietary. The constraints in existing “ALERT” packages emerge from the non-standard operating system used by several products, the relative dearth of data exchange facilities, and the proprietary databases used by most of them. Neither approach has fully integrated other weather products.

CHAPTER IV. REVIEW OF ECONOMIC AND HUMAN FACTORS

Most flood warning systems today are entirely funded and supported by government entities, whether at the local, state or federal levels. A number of special flood control districts have been formed in the last decade or two, particularly in urban areas where storm flooding is a common occurrence (e.g., Denver's Urban Drainage and Flood Control District, an entity whose participants include Douglas, Denver, Jefferson, Adams and Boulder Counties and the city of Aurora). In other cases, city or county departments such as streets and utilities, storm water management or drains and sewers take on the responsibility of supporting a gauging network. In some cases, local emergency management agencies initiate and maintain systems (for example, the Boulder County Sheriff's Department supports their own gauges that fall outside the area covered by UDFCD but are relevant to watersheds in the western part of the county).

The cost components of implementing a flood warning system fall into three categories: Initial costs to research, plan and install the system components, recurring costs to maintain and operate the system, and flood event-incurred costs.

Implementation options

Potential sources of federal funding and technical assistance include the following agencies and activities:

- COE: Provide technical services and planning guidance on flood issues, and help during an emergency event when state resources are overwhelmed. In limited cases may provide cost-shared construction. They don't maintain systems.
- NWS: Provide technical assistance in developing systems, provide forecasts, watches and warnings, gather local real-time data to help create their products. Outside of IFLOWS, the NWS does not maintain flood warning systems (see the IFLOWS story, below).
- U. S. Department of Agriculture - Natural Resources Conservation Service (NRCS): Provide technical and financial assistance to develop and install local flood warning systems. They do not maintain systems.
- U. S. Geological Survey (USGS): Post provisional data from their network of several thousand stream gauges throughout the country on their web site, some of them close to real time (15 to 30 minutes). Half the gauges are funded (installed and maintained) by 50-50 cost sharing with the cooperating agency, another 40% of the cooperators pay the whole cost.
- U. S. Bureau of Reclamation (USBR): Operate dam safety programs including real-time weather gauging networks for USBR dams, usually in

remote locations. They maintain their own gauges. Local agencies can receive data if relevant to them.

Maintenance options

A conclusion that can be drawn from the above information is that, although there is federal help available to plan and build flood warning systems, the funds to maintain them are not forthcoming. This turns out to be the Achilles heel of many such projects. To have a successful system, ongoing funding must be procured. Unfortunately, there are quite a number of local agencies that received help with new systems but have not been successful in maintaining them, and the data from such systems are worse than no data and thus not used. Because this entire process is primarily government-funded, free-market advantages are not to be found.

As a way to find resources, some local entities try to take on the system maintenance as an internal operation. In a few cases this is highly successful (for example, Houston's Harris County system is a showcase, as is Phoenix's Maricopa County Flood Control system). Just as often, however, the resources charged with providing the service have full-time jobs doing something else. For example, in a county agency the radio shop is commonly chosen as the appropriate maintenance entity, given that they know how to fix radios and change batteries. Unfortunately, maintaining a flood warning system requires its own special expertise, and such systems, when examined closely, often turn out to be virtually non-functional.

An important human factor in a flood warning system's success is the frequency with which it is used. Systems intended solely for emergency use often fall into disrepair and are unavailable when critically needed. Some of the existing applications described were developed by hydrologists for hydrologists and require special training to use at all, thus making them relatively difficult for emergency managers and infrequent users to use. The fact that they run on the QNX computer operating system increases the barrier to use.

Another problem with dedicated flood warning systems derives from the fact that some of the sensor systems in use today are pretty quiet except during major events. The best assurance of availability at a critical time is having an easy-to-use system that conveys information used every day. For example, systems providing the following information are likely to be used regularly: general weather information, low flow, irrigation scheduling, water quality monitoring, fire weather and fire danger computation. In this case, users' daily activities function to maintain their expertise.

Non-IFLOWS flood warning systems

Automated flood warning systems outside the IFLOWS areas are often built by a variety of federal, state and local agencies that have banded together to fund and participate in these systems. For example, in the state of Arizona, the statewide flood warning system is supported by the following federal agencies: NWS, COE, USGS, NRCS, and USBR. At the state level, the Arizona Department of Water Resources (ADWR) and the Arizona Division of Emergency Management (ADEM) participate. Other participants are at least nine counties, including several with special flood control districts, the Central Arizona Water Conservation District (CAWCD), the Salt River Project (SRP), several towns and cities, Indian tribes and other local users (Miller et al., 1997).

This level of statewide integration is not yet common but is becoming more so. Among other advantages, it offers a variety of budgetary resources making the system success less vulnerable than it would be with a single budget. Most systems in place today are smaller, however, and they have been put in place by motivated local agencies who have created their own budgets out of local funding sources. In general, the implementation of these systems originated at the local or state level, with federal agencies asked to participate. This puts the locus of responsibility for the system closer to the local users and bodes well for its success.

Smaller systems are more common throughout the west and southwest U. S., where the sponsoring agency is often a quasi-governmental entity such as a water district. These agencies add great value because they want the data for their own purposes and they tend to have much more money available than do the emergency users. In the eastern U. S., automated flood warning was conceived and deployed as an integrated network in the form of IFLOWS.

In some areas outside of IFLOWS, independent local systems are approaching the density and coverage of a regional system. There is growing interest and experimentation among agencies in sharing and consolidating their information by a variety of means (e.g., concentrating raw data in a single location via microwave and RF repeaters, bringing data into NWS or USGS databases, and sharing data via the web). Areas with multiple systems include Texas (Harris County, Austin, Lower Colorado River Authority, Lavaca Navidad Reservoir Authority, Trinity River Authority, Jefferson County); county, municipal and state systems throughout the state of California; Colorado's Front Range (Denver Urban Drainage and Flood

Control District, Boulder County, Colorado Springs and Pueblo area agencies, the USBR-Estes Park system and, in the near future, the city of Fort Collins).

Oklahoma has a statewide mesonet system developed by the University of Oklahoma and Oklahoma State University, funded through the Oklahoma Department of Commerce by two million dollars of oil-overcharge funds. They have five- and 15-minute data for soil and air temperature, relative humidity, wind, solar radiation, pressure and rainfall, carried on the state's public safety telecommunications channels to the Oklahoma Climatological Survey at Norman. Products from this state of the art system are widely disseminated on the Internet and other networks and bulletin boards and used by many public and private agencies. This is a model public system built at local (i.e., state) initiative.

The IFLOWS story

The IFLOWS program came about by Congressional mandate in 1980. As a result of a bill sponsored by Senator Robert Byrd, West Virginia, Congress mandated that the NWS develop cooperative agreements between the NWS and certain Appalachian state emergency agencies. The purpose was to provide flood warning systems to highly vulnerable communities in extremely poor areas.

The responsibilities are split as follows: The NWS provides and maintains the sensor and computer hardware, software, updates and technical support, and the participating state agencies operate and maintain the systems. Agencies outside the mandated group may also acquire the software and choose to participate, but they are responsible for the other equipment costs (U. S. Department of Commerce, 1997).

The NWS' ability to support IFLOWS has been degraded over the years as the number of positions allocated to the program within the NWS has shrunk to essentially one full-time coordinator. This year's NWS budget allocation for IFLOWS was just under $1 million (Francis, 1998). The budget can be applied to relevant expenses incurred in continuing to develop and upgrade systems and the NWS has taken to using outside contractors to fill in for their waning internal resources.

Likely because IFLOWS is mandated for selected states, the level of participation from the targeted states varies widely. Some states have taken the IFLOWS program seriously and built upon it (e.g., Pennsylvania), using their own resources to maintain and enhance their systems. Other states have never paid their share of the bill and their systems are functioning very badly, if at all (e.g., West Virginia). Unfortunately this situation is not easily fixed, as the NWS has no clout to enforce the states' participation. In some cases the COE, another federal agency that is charged with installing flood warning systems, has been unable to negotiate a highly functional system because they can't elicit NWS support for it, and thus they must fall back to minimal implementations. This in turn creates a less useful system for the clients, who are less likely to value, use or pay for it.

Some non-IFLOWS states have chosen to participate and funded their own programs. The most progressive is the state of Ohio, whose system is described in greater detail below. They cooperate closely with the NWS offices in Cleveland and in Wilmington to bring real-time data from the entire state into an on-line database and have multiple users benefit from all the resulting products. Their goal is to integrate as many products as possible with their local flood warning data to create highly usable weather information products in real time. They support not only county and state emergency operations but also state level water resources planning, with the Department of Water Resources being one of the primary users of this system. This sort of arrangement optimizes the benefit gained from a flood warning system and is really a model for what can be done with government funding.

Non-government users

A few private industry organizations have installed small systems for their own use (e.g., Allied Signal Corporation in Kansas City, KS, who also coordinate with the nearby Overland Park, KS, system). Others cooperate with their local public agency user to receive the data for their own benefit. For example, several flood plain-resident companies in Salem, VA, are using IFLOWS hardware and software to collect data. They use the data to decide whether they should initiate moving their equipment out of harm's way, a several hundred thousand dollars project, and thus avert millions of dollars of damage. They are supported by the local fire department, whose IFLOWS system is in turn supported by the state (Bristow, 1998). In general, for communities that have flood management issues (and most do), there are many organizations that would benefit from receiving real-time data and integrated weather products but that do not have the expertise or resources to acquire and support the systems available today.

Summary: You Get What You Pay For

The perceived value of any commodity to human beings is influenced strongly by the price of the commodity, in that pricier commodities tend to be valued more highly than cheaper ones, other things being equal.

Most owners and primary users of automated flood warning systems today are government or quasi-government agencies. The way in which they acquire and pay for these systems varies greatly by locality as described above, and the effects of this are noticeable. Those entities that have taken the initiative to build a system, either with their own special district or with the help of other entities, and found ways to pay for its implementation and maintenance are the ones with successful systems that perform well under duress. Those that receive a system by mandate have a much poorer track record and are very likely not to participate at many levels.

Tragically, it often takes a disaster to demonstrate the impact of not managing the human and economic aspects of such systems. This was the case last summer in Kansas City, MO, which has had an ALERT system in place for a number of years. The flooding that followed the baseball game storm last summer produced several fatalities. In the aftermath it was discovered that the ALERT base station computer in the city’s emergency communications center, which no one there knew how to use anyway, was not even running during the storm event (Miller, 1998). We don’t know whether using the system might have changed the outcome for those victims, but we do know that not using it didn’t help them.

CHAPTER V. TECHNOLOGICAL AND ECONOMIC METHODS

This chapter presents a new approach to serving real-time, integrated weather information to both the primary, public safety and flood plain management users, and to a secondary market tier of highly motivated weather consumers (businesses and organizations with weather-affected missions). The alternative approach has two major components: 1) a technological infrastructure built on standard platforms, and 2) an economic architecture built on a blend of public and private funding.

The next section addresses the design and deployment of technology to accomplish the goals of providing integrated, real-time weather data to a variety of users. For the purposes of this chapter, the NWS will be selected as the responsible organization. In fact, this design offers an opportunity to re-engineer the mandated IFLOWS system to save money and serve their clients much more effectively. Please note, however, that this design can be used by any organization that intends to provide integrated regional weather products to both mission-critical and secondary users.

The section following proposes a new economic architecture with which to support the technology architecture.

Network Design

Design objectives

The objectives of a real-time weather-monitoring network include the following:

- Preserve the investment in ALERT sensing equipment and enable its expansion to other areas of real-time weather and hydrologic data;
- provide participants with accurate, reliable, real-time data to support local and regional emergency management functions;
- integrate data from multiple sources and NWS products and provide them near-real time to end users in a simple usable interface;
- serve as a decision support system to non-technical emergency management personnel by providing summary information which is graphical and intuitive;
- function economically and reliably.

Basic system requirements

The design and approach of the software applications, operating system environments and network platforms must enable the deploying organizations to meet these objectives now and for the foreseeable future. The following list identifies the requirements that will make this possible:

- The software interface should present as few separate programs as possible to the users. Ideally there is a single user interface from which all other programs, data and functions can be accessed. The user interface should be highly intuitive and require little or no training to use (i.e., should follow well-established graphical user interface design standards).

- The user interface must present data in a variety of formats, permitting users to customize it to their needs. For example, data should be viewable as text reports or graphically.
- The applications must run on a standard, widely used, interoperable computer and operating system to ensure they will be widely supported and easily understood by the great majority of computer users.
- The networking must be open and standard. The networking system may not be tied to particular computer programs, platforms, communications media or hardware. The methods of data exchange must be accepted standards.
- The applications and network must be highly reliable. A site must be able to access data from more than one source. Data concentration and dissemination processes must be deployed redundantly. Network links must be easily replicated over a variety of communications media and channels to compensate for failed links. Any centralized data processing should take place in a 7 X 24 network management center designed to maintain high-availability applications and networks.
- The applications must use client-server architecture, rather than rely on brittle, programmatic ties between data collection and end user processes.
- The data service architecture must buffer the data collection and processing applications from activity surges due to increased user demands. A “push-pull”

method accomplishes this – data are pushed onto network servers by host applications and pulled from the network independently by clients.

- Data collection and data dissemination processes must reside on separate, independent platforms, helping to ensure increased client demand has no impact on data collection and processing performance.
- All of the application component platforms must be easily upgraded by adding standard hardware and telecommunications bandwidth to accommodate system growth.
- The application must include a relational database structure that is open via open data base connectivity (ODBC) and direct application tools to its users. Data must be readily transferable from the database to other software applications such as enterprise databases, word processors, spreadsheets and web pages, and users must have opportunity to readily develop custom applications with common software tools.
- The data products and networking architecture must allow interoperability among disparate client platforms.
- Each participating site must be able to collect and maintain its own database in near-real time, even if the data were retrieved from a remote site.
- The application must use geographic information processing so data can be selected, distributed and processed by region. This capability will be used to create and distribute regional subsets of data and products that are relevant to the remote users.

Meeting the above requirements will enable the most effective acquisition and maintenance of software, hardware and telecommunications components. The NWS can independently develop or purchase enhanced features and functionality as the system matures. Most important, the open environment and standard protocols will allow the NWS and their clients to design or choose new tools and to add new functionality without being trapped by a proprietary set of tools or a single vendor relationship.

Prototype: Ohio Emergency Management Agency (OEMA) / NWS project

The state of Ohio is currently implementing a real-time data network that serves as a prototype for a new infrastructure. The OEMA is deploying STORM Watch, one of the ALERT software applications, on a wide area network that interconnects the OEMA center in Columbus and the NWS offices in Cleveland and Wilmington. STORM Watch is a Windows application with an intuitive, graphical user interface that stores data in an open relational database, thus complying with the user interface requirements. Figure 3 shows the implementation architecture.

The system has one primary data collection host at the OEMA office and two backup hosts. The backups normally operate as clients of the primary host, but they will begin collecting and validating data directly if they lose their connection to the host. One backup host is at the OEMA and one at the Cleveland NWS. Other clients can connect with the host on the state office LAN, a WAN connection to the Ohio Department of Natural Resources, and dial-up networking. This portion, Phase I of the project, has been completed.

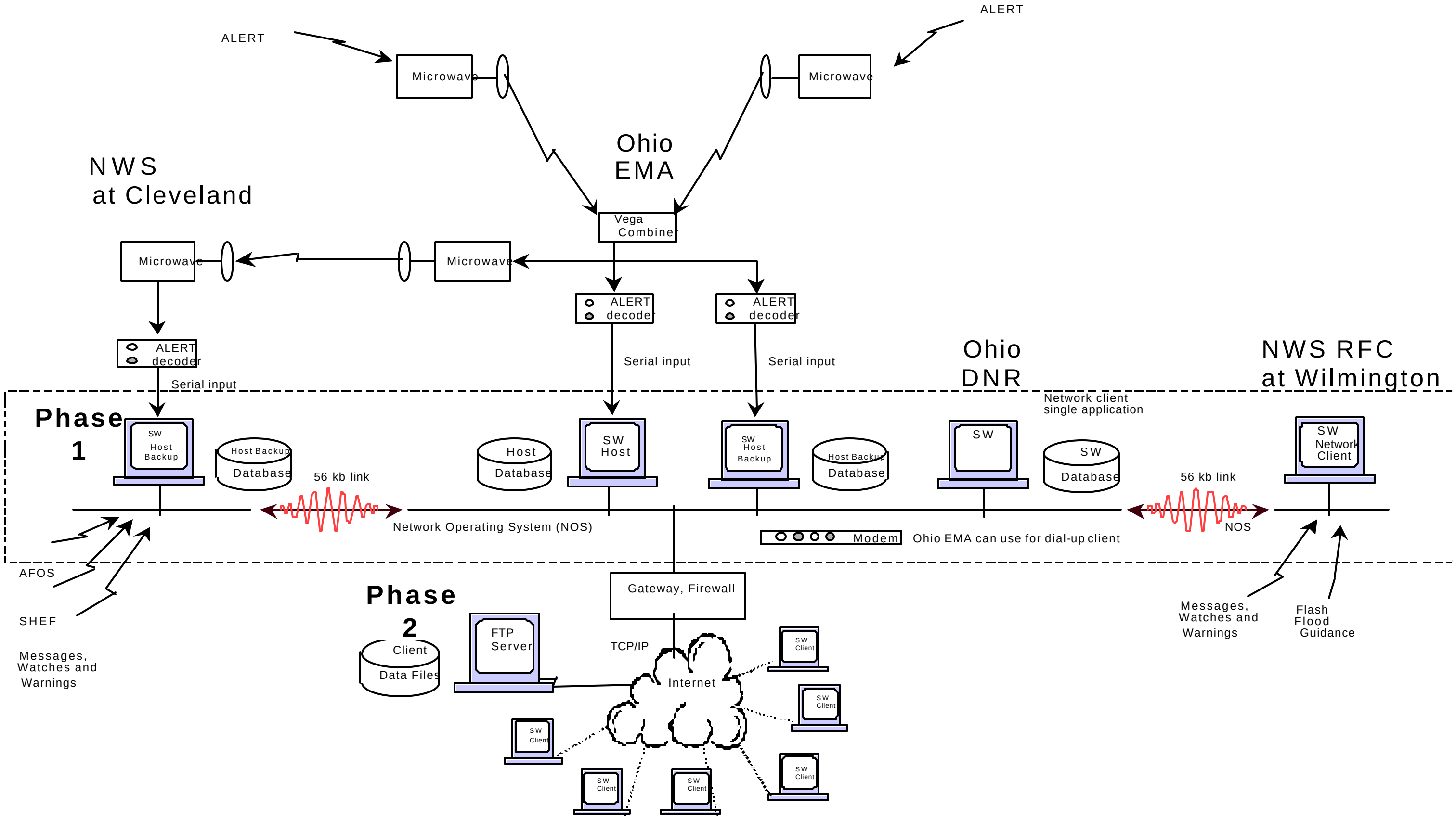

Figure 3. OEMA and NWS Ohio regional real-time weather monitoring implementation architecture.

The data types available in this system include the ALERT sensor data from around the state, data from other sensor systems (USGS and NWS) encoded in the NWS standard hydrometeorological exchange format called SHEF, a readable text format for encoding data reports from a variety of sensor types (Bonnin et al., 1983), NWS weather watches and warnings, flash flood guidance, and radar products. STORM Watch will be able to process, store and display the NWS text products in early 1999. It already processes ALERT and SHEF data, and by 2000, STORM Watch will be able to ingest radar images and use a calibration algorithm to adjust radar rainfall estimates from local rainfall data reports.

A novel feature of the Ohio implementation is the deployment of a host-client architecture that will disseminate near-real time data and related NWS products to all 88 Ohio county emergency management agencies and other authorized users. The system will use an internet-standard file transfer protocol (FTP) host-client version of STORM Watch. The STORM Watch FTP host (primary and backup in OEMA) will maintain an FTP server as the dissemination platform for validated ALERT data from around the state as well as for NWS products such as flash flood guidance, messages, watches, warnings and SHEF-encoded data from other data acquisition systems. In the future, data maintained on the FTP server may include radar and other products. This section describes Phase II, which will be completed in the first half of 1999.

The password-secured FTP server will allow a selected set of users, in this case primarily Ohio county emergency management agencies, to access data in near-real time (i.e., within a few minutes from the time a report was generated by an automated sensor or received by other means) across either private or public inter-networked connections using a STORM Watch client application. These client applications will provide locally the same interactive interface, relational database and graphical tools as the standard STORM Watch application. At least some, and perhaps all, of the data files pushed to the FTP server will be formatted as readable text files, including standard reports in the IFLOWS format and SHEF-encoded data. This permits non-STORM Watch users and other data applications to retrieve the data.

The advantages of this regional system are clear. In the best case, end users throughout a large region can have high-speed, private inter-networked connections to real-time data and value-added products. In the worst case, end users can have almost the same level of service using the same standard network protocols and public Internet access points. There are no application-proprietary networking protocols involved, everyone is using the same tools, and the low-end solution is inexpensive. In fact, each day finds more end users tied to the Internet with higher speed and more reliable connections, so the channel used for real-time data is more often the same as that used for other daily activities.

Generalized regional, inter-networked architecture

In Ohio, the state's microwave backbone concentrates raw, real-time, ALERT-formatted data packets from sensors throughout the state into the OEMA office in Columbus and the Cleveland NWS office, making the validation and consolidation of state-wide data into the FTP host both simple and geographically redundant. No such simple solution exists for other IFLOWS area systems, in which raw ALERT-formatted data are collected and validated at a variety of points. The general-case architecture must expand on the Ohio solution to meet the NWS requirements.

The proposed architecture can be viewed in Figure 4.

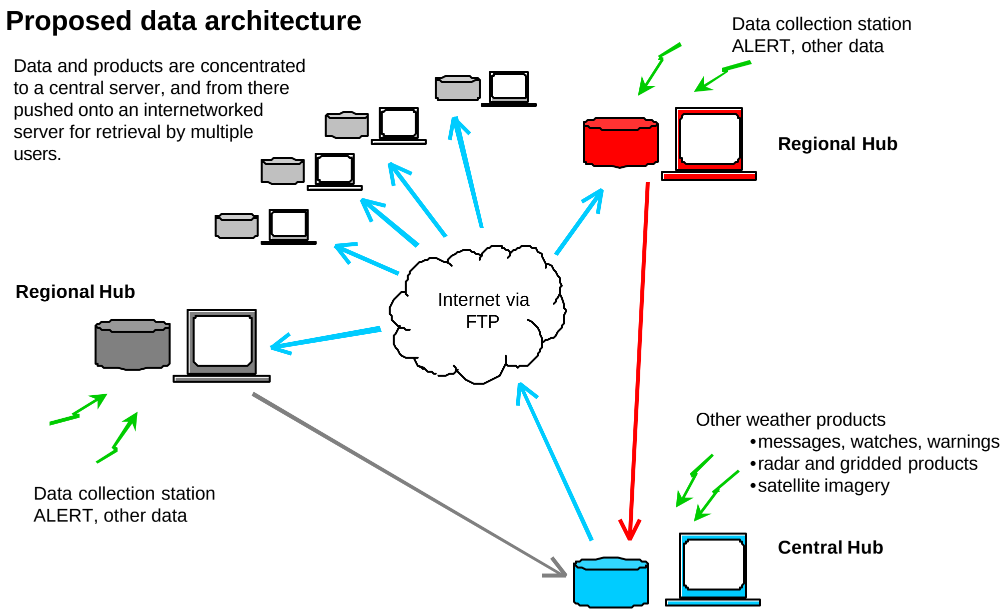

Figure 4. Data flow for a regional inter-networked system. Real-time data are collected at regional hub sites and passed to a central site. The central site adds other available products, regionalizes data sets and pushes them to a server where internet-connected user applications can retrieve them.

STORM Watch will collect and validate raw data at the regional offices receiving ALERT transmissions directly or via RF repeaters. The data will be available locally in real time. From these regional hubs, validated data periodically will be pushed over network connections to the central hub. The central hub processes the data for dissemination and puts them on the FTP servers.

Regional hub processes

A process running on each regional data hub station will retrieve data from the local database and prepare packets of validated data on a regular basis (e.g., every minute or every five minutes). It will then FTP them across an internet-standard network link to the central data hub.

Central hub processes

Once data reach the central data hub they are consolidated into an overall regional database by a concentration process. A separate data dissemination process regularly opens the database and retrieves data into regionally-targeted files. These files are placed on redundant password-protected FTP servers outside a firewall. The FTP servers are connected via redundant telecommunications providers and Internet service providers (ISPs) to the Internet backbone.

Application host-client data collection and dissemination

This section describes in greater detail the processes outlined above. The software application, in this case STORM Watch, is designed to provide either a two- or a three-tiered data collection and dissemination network architecture.

First tier

The first tier is the initial ALERT-formatted data collection platform, or data collection host. This is a base station that collects and validates raw data, storing them in its database.

Two-tiered architecture - network clients

Once the data have been validated and written into the base station database, they are available immediately to networked clients. When a client connects over the network, it opens the host database and retrieves data updates directly on a periodic basis. The network connection can be accomplished via local area network (LAN) using Windows peer-to-peer or domain-based network operating systems, wide area network (WAN) based on dedicated landlines, packet radio links, or Windows dial-up networking via telephone modem.

This architecture works for a limited set of clients. A STORM Watch host database can support 1-20 or more networked clients, depending on the horsepower of the host computer, the nature of the various network connections, and how often the clients are set up to receive updates. To achieve a more robust architecture, the three-tiered approach is preferable.

Three-tiered architecture – data dissemination agents

This middle layer application opens a first-tier database and assembles the data into regional bundles on a periodic basis, perhaps once per minute.

> The agent application will periodically push updated data files to a pickup location, for example, a password-protected FTP server. Authorized clients will access the FTP server and download the data updates from there. This method frees the data-collecting host from any potential performance decrements that could occur due to excessive client loading and allows the support of far greater numbers of clients. As an added precaution, it is an option to have the data dissemination agent operate on a mirrored copy of the data collection host database, located on a second computer, thus completely freeing the host from data retrieval response issues.
>
> The agent could also respond to client requests for specific data returns. For example, when a client first logs in, it may request an historical period of data to bring it up to date, having not logged in for 24 hours or more.

The three-tiered approach standardizes the inter-networked connectivity of clients to their data sources. It also moves those activities outside the host network firewall, thus providing fewer security problems for the host network. Clients can connect via cost-effective ISPs rather than having to dial in to a modem bank maintained at the host. A number of agencies are already connected via office LANs to the Internet, and thus access is already incorporated in their current organization. If necessary, high-priority client links can be implemented as dedicated high-speed WAN links for additional cost. Finally, client applications that are currently LAN- or WAN-connected in a two-tiered architecture can make immediate use of this architecture with improved performance and robustness.

Regional data concentration and dissemination

Some pieces of the proposed architecture are similar to that being implemented in Ohio. For example, the regional hubs are analogous to the Ohio's FTP host and will likely be able to reuse software developed for Ohio to a large extent.

Other aspects of the NWS regional system aren't addressed by the Ohio system. The central hub processing must be developed to concentrate data received at regional hubs into a database covering the entire IFLOWS area. The data dissemination agent process will periodically sweep the central database and put the data into geographically sorted packets. These packets will be placed on the FTP servers for access by client applications via the Internet.

The Internet-based architecture offers numerous benefits over the current proprietary networking or traditional direct server dial-up methods:

- Internet protocols provide mature, standard, inexpensive and reliable technologies by which hosts can serve data and clients can log in and transfer data.
- These standards are ubiquitous today and are not linked to any proprietary software or hardware platforms.
- The chosen methods deploy across diverse telecommunications infrastructures, including point-to-point or multi-point RF modem networks, the public switched telephone network, dedicated land-based data links and satellite links.
- Links that go down can be backed up by links on redundant transport media that are switched in dynamically.

- The Internet offers most remote users redundant paths to their data, with the weakest links being the last link, either at the server or at the client. Redundancy can be added at both ends to meet high-availability requirements.
- The client link will be cost efficient, as most remote users will use local telephone numbers, RF modems or existing LAN connections for their primary Internet access.
- Removing client data access activities from the host platform onto an agent and FTP server eliminates the potential for loading and interference from high client-usage on data collection and concentration activities.
- Eliminating direct dial-in access provides greater security to any LAN-connected computers. The use of a firewall behind the FTP servers completes the security picture.
- The agent-produced files are encoded as plain text, making it possible for a variety of client types to ingest them, including humans.
- The FTP activities themselves are username-password protected, not anonymous, thus preventing unauthorized data transfer.
- Increased future loads can be managed by simply hosting additional servers and adding bandwidth; the system is built to scale up.
- Server-side modem hardware will be deployed in a few sites as backup only, and the hardware and functional maintenance savings will be significant.

Initial data collection in the NWS regional network

Thirteen primary sites, most of them NWS offices, have been identified that together will receive all the raw ALERT-formatted RF data reports throughout the IFLOWS area. These will function as the regional data hubs. The sites are:

1. Louisville, KY (Kentucky Dept. of Military Affairs at Frankfort as backup)
2. Cleveland, OH
3. Charleston, WV
4. Greer, NC
5. Richmond, VA
6. Sterling, VA
7. Connecticut Department of Inland Water, Hartford, CT
8. Taunton, MA
9. Mt. Holly, NJ
10. Albany, NY
11. Binghamton, NY
12. Pittsburg, PA
13. State College, PA

The data collection base stations at the regional hubs will be networked via TCP/IP links to the central hub. The central hub location remains to be chosen. Those regional hubs can be implemented with additional modems to support dial-up networking clients in the case of Internet-access failures. They will also support any LAN-connected network clients within their organizations.

The data files available for transfer on the FTP servers will be geo-coded, and STORM Watch client applications will transfer only those files selected by them as being of local interest. Each regional hub and client will have the ability in principle to retrieve a full data representation of the system from the FTP server, but only a few select sites will do so.

One or two sites should be selected as backup mirrors of the central files. These sites will be configured to download all the data files on the FTP servers, thus replicating all the data in the system. These sites should be equipped with multiple modem access, permitting clients to dial in if there is an Internet communications failure. The modems should be accessible via 800 numbers, allowing clients toll-free access. These sites need not be regional hubs, but rather can be receive-only client sites. Candidate sites may include Louisville, Albany, and Cleveland.

Bandwidth requirements for data concentration

The relevant data traffic for calculating bandwidth required for data concentration is the real-time sensor information. Other products from the NWS can be received directly at the central hub and disseminated from there, and thus will not have an impact on the incoming traffic. The transmissions being concentrated consist of validated data records.

Validated data records are small by contemporary data standards. A very rough estimate of bandwidth requirements can be approached in the following way. We’ll use a 40-byte STORM Watch validated data record size for these calculations.

Most days

Assume a state (e.g., Kentucky) has 200 working rain sensors. On a given day when it isn't raining, 400 data reports should be received (each sensor sends two 12-hour timer reports). Let's also assume there are 50 stream sensors that report both event and hourly time series data. On a quiet day, 1200 reports might be received. The sum of these is 1600 per day, or 64 kilobytes (KB) per day of data sent by the Kentucky regional hub to the central hub.

Big rain events

A big storm moving through might produce the equivalent of a one-inch per hour rain for an hour over the entire state. At 25 tipping bucket tips per inch, that translates to 25 reports for 200 sensors, or 5000 reports per hour. During and after this event, all the stream gages report every five minutes for two hours, producing an additional 1200 reports. That's a peak activity of about 6000 reports per hour, or 240 KB for the event.

Big months

A big rain month might have brought 30 inches of rain. That translates to 150,000 reports for the month. Let's add 4,000 reports per day for active stage sensors, summing to 270,000 reports per month. This means the monthly traffic from the hypothetical Kentucky regional hub to the central hub is 10.8 MB.

These numbers are rough estimates. Adding weather stations, which may report wind data every few minutes, and other types of time series measurements will increase the traffic, as will adding more sensors. Nevertheless, this gives a ballpark starting point from which to calculate requirements.

Bandwidth requirements for data retrieval

The traffic outbound from the central hub will be more significant. Many clients will be connected to the Internet via LAN and WAN connections, but some may be restricted to dial-up access.

Initially, clients will download only validated data and associated products. Padding figures to include overhead, STORM Watch central hub products (not including gridded rainfall data) and maybe some other NWS products, let's assume that a client will transfer data collections as large as 150 KB every five minutes during an active rain event. The clients may actually collect data more often, but only the five- or ten-minute interval data transfers are significantly large – the other minutes are just a few KB each. The following estimates cover a variety of connection schemes.

Worst case – dial up scenario

Modems today generally connect at 33.3 or 56 kilobits per second (kbps). Data are sent as eight bits per byte plus one start and one stop bit. At 33.3 kbps that will take 45 seconds, and at 56 kbps it will take about 27 seconds. STORM Watch clients are automated to dial in to receive updates and log out in between, thus minimizing time spent on metered ISP connections.

Medium case – WAN and ISDN type connections

At 64 kbps the above transfer will take 23 seconds, 128 kbps will take 12 seconds, and at 256 kbps the transfer will finish in six seconds.

Best case – LAN-connected speeds

Uncongested LAN throughput can be assumed to be about six mbps. In this case, the transfer will take 0.25 second.

The number of bytes transferred will increase when gridded products (e.g., radar) are added to the outgoing data stream. Also, clients may have the option to collect data going back in time. If the NWS decides this is valid, an initial session to catch up with a longer period will require more time at the session start. For now and the near future, however, this data stream is manageable given current network connection bandwidths.

Satellite implementation

An extremely efficient and reliable implementation is enabled by judicious use of satellite communications. In this scenario, the regional hubs concentrate their validated data via a TCP/IP connection on a very small aperture terminal (VSAT) over satellite to an earth station. A number of providers offer such service. This project used NovaNet, an Englewood, CO, company with extensive remote monitoring experience, as the provider for design and cost purposes.

The central hub application is running either at the earth station network management center, a 7 X 24 facility, or at some location that is reliably linked to the earth station via redundant data channels. All incoming data arrive over satellite, and the agent process running at the central hub pushes the data out to the FTP servers. The FTP servers are outside the firewall with respect to the central hub application and its satellite-networked sites. During normal operations, the regional data collection hubs and the central hub mirror sites retrieve centrally processed data back across the Internet.

The satellite channels selected use native internet protocol (IP) and will support two-way traffic. This means the data are transferred as IP packets and not additionally encapsulated in some other packet type. The service contract and channels implemented will include the opportunity to increase traffic on an exceptional basis.

In the event of an Internet backbone or regional access point failure, the mirror sites will access the FTP servers via their satellite links from inside the firewall. During the failure period, the centrally processed data are back-hauled through the satellite to the mirror sites, and possibly also to the regional data collection hubs.

Any client applications affected by the failure will then access their data from a mirror site or a regional hub via dial-up or other network connection. In this way, regional data exchange can continue without regard to the status of the public Internet.

Mirror sites and targeted regional hubs should be implemented with a watchdog process that tracks the success or failure of data retrieval from the FTP servers via the Internet connections. If a user-configured timeout period is surpassed without successful data retrieval, the mirror or hub application will automatically switch over to collecting the central data via its satellite link.

Fault tolerance and redundancy

The inherently redundant nature of Internet connections, plus the use of satellite connections, primary and backup central hubs and redundantly connected FTP servers produce a highly available data resource.

The primary and secondary central hub computers will independently perform watchdog functions. If the backup agent process is unable to contact the primary agent, or if new data records do not regularly appear in the dissemination database, the backup will initiate its own central processing tasks and FTP file production. Notification of the fail-over will be initiated by each of the new agent hosts. The data outage can be constrained to a few minutes and no data should be lost.

The NWS system could be designed to have no single point of failure. Single points of failure include the regional data collection hubs. Each data collection hub should be equipped with uninterruptible power supplies and redundant power resources. Where possible, the NWS could identify a networked second site for raw data collection for each hub. In some cases, the second site could be another hub(s) that has a large degree of data reception overlap with the primary.

Data products

In addition to supporting hydrometeorological data from real-time sensor systems, there are other NWS products that could be supported by the system.

- Flash flood guidance (FFG). In Ohio, STORM Watch will ingest FFG products, produce a summary display and reset local sensor alarm thresholds automatically to appropriate levels.
- SHEF-encoded data from other acquisition systems.
- Messages, watches and warnings.

Because STORM Watch uses an open database design, it is easy to link to it other hydrometeorologic applications that use the data, some of them in real time. Other chosen data collection applications should meet the same criteria. Some current options and future directions include:

Hydrologic forecast models

One of the most useful aspects of having real-time local rainfall and stream flow data is that flood forecast models can be used. This type of model computes a predicted time and peak amplitude stream flow based in part on estimates of the rainfall runoff from catchment areas that drain to the forecast point on the stream. In a real-time setting, the forecasted flow can be recomputed as often as there are new catchment rainfall estimates available, and the projected flow can be adjusted using the real-time observed flow.

There are a variety of models that are heavily used today. For example, two companion software suites that integrate with the STORM Watch database to produce runoff forecasts from real-time data are specific implementations of two models in widespread general use. FLOOD Watch^{TM}, provided by Riverside Technology inc., uses the NWS Sacramento RFC soil moisture accounting model, while the Catchment Forecast-modeling System

(CFS^{TM}), developed by David Ford Consulting Engineers, makes available a full suite of COE HEC-1F tools. Each of these products is available directly through their respective companies and can also be run with other databases and products.

Other models exist and can be implemented as well, although strong advantages exist in choosing widely-used and supported tools. Please note that the use of hydrologic models requires appropriate human expertise in the user organization to interpret correctly the actual flood risk.

Radar data

Dissemination and display of weather radar products should be required of the software applications. This opens doors to a wider variety of tools. For example, David Curtis, NEXRAIN, Inc., and Don Van Wie, DIAD Inc., are developing a real-time process to combine radar-estimated 15-minute rainfall accumulation with actual rainfall as measured by local rain sensors (Van Wie and Curtis, 1999, and see also Hartzell et al., 1998). In this way, the wide coverage of the radar estimate can be calibrated using ground truth data to create a more accurate estimate of rainfall accumulation for catchment areas and thus create higher quality input data for hydrologic forecast models. In particular, this approach will enable the future use of distributed rather than lumped models because the variables estimated are spatially distributed, as are the actual weather conditions, rather than estimated for single points (McLaughlin, 1995).

Network Deployment Plan

The system can be built in a staged fashion. There is some advance preparation required. Stage I entails installing the base station software at the regional hub sites and completing RF network connections to bring all the raw data to those sites. Stage II is the installation and startup of the data concentration into the central hub site, with geo-coded reprocessing and dissemination of validated data via the Internet. Stage III incorporates other products into the real-time data dissemination. Finally, ongoing support issues must be planned in advance.

Preparation

Software development – regional hubs

- Development of regional hub software from existing base stations
    - Addition of Greenwich Mean Time processing
    - Local-to-global Sensor ID translation processing
    - Documentation and help files development
    - Messages, watches and warnings ingest and display

Stage I

Implementation activities – regional hubs

- RF network backbone build-out
- Regional hub computer hardware acquisition
- Initial base station software installation at regional hub sites
- Training for regional hub users

- PC/IFLOWS still running at regional hub sites
- Testing of satellite links at prototype site

Software development – central hub

- Regional hub FTP host development
  - Minor changes to OEMA/NWS FTP host software
- Development of central hub software
  - Concentration process opens and files incoming validated data from regional hubs
  - Dissemination process produces geo-coded validated data output files
- Development of FTP client software
  - Minor updates to OEMA/NWS FTP client software

Stage II

Implementation activities – regional and central hubs

- Satellite hardware acquisition and installation at regional hubs
- Mirror site setup – satellite hardware and telecommunications hardware/software deployment
- Central hub hardware acquisition and installation at central site
- Central site telecommunications facilities acquisition and testing
- FTP server setup and startup
- Central site software deployment
- Regional hub FTP host software deployment
- Training for regional hub and end users

- Removal of PC/IFLOWS as deployment is completed

Software development – regional and central

- Central hub and client software expansion
  - Gridded products addition (rainfall products, forecast products, radar)

Stage III

Implementation activities – all remote sites

- Deploy new software, all sites
- Add sites as necessary/desirable

Ongoing support requirements

The tasks required to support this system are as follows:

RF network support

- Maintenance of and enhancements to the raw data collection network
- Support of those sites that use spread-spectrum or other RF networking links for validated data exchange

Central site maintenance

- Database maintenance and backup activities
- Software update installation
- 7 X 24 trouble-shooting and technical support
- Ongoing coordination with satellite staff, ISPs and telecommunications vendors

Regional hub and mirror site maintenance

- Trouble-shooting hardware, modems and data collection issues

- Facilitating software update installations

Client site maintenance

- Ongoing technical and software update support

The people required to fill these roles can be supplied either from within the NWS or by contract resources. The RF network and central site maintenance are particularly strong candidates for outsourcing, but the other two categories must also be covered very effectively.

Estimated project costs

Table 1 on the following page shows the cost estimates for the system as described in this document. To pay for this project will require two years' worth of the NWS budget designated for the IFLOWS program, and that makes the untrue assumption that all of the program's ongoing expenses fall inside the table. In fact, many sites will be still be using the IFLOWS network during the staged deployment, necessitating the maintenance of the old system as well. In addition, this does not include the hardware maintenance expenses for sensor systems in the field, expenses that today take up a large proportion of the IFLOWS budget.

Despite its high cost, today's system is not up to the demands of today's users, nor does it fulfill the promise it made, let alone the requirements set forth earlier in this paper.

NWS real-time weather monitoring network: provisional numbers

Initial purchase	unit cost	quantity	quantity discount	cost
FTP server computer	$ 5,000	2	1	$ 10,000
regional hub computer	$ 3,500	16	1	$ 56,000
central hub computer	$ 7,000	2	1	$ 14,000
mirror site hardware - modems etc.	$ 8,000	1	1	$ 8,000
regional hub software	$ 5,000	16	0.8	$ 64,000
central hub software	$ 75,000	1	1	$ 75,000
watchdogs	$ 500	6	0.8	$ 2,400
STORM Watch FTP host	$ 8,000	15	0.8	$ 96,000
STORM Watch FTP client	$ 1,200	250	0.6	$ 180,000
software installation	$ 1,200	10	N/A	$ 12,000
configuration and training	$ 1,200	30	N/A	$ 36,000
1-time VSAT network engineering charge	$ 10,000	1	N/A	$ 10,000
VSAT IPV, 2 serial ports, 1.8 m antenna	$ 5,950	17	1	$ 101,150
VSAT training - install and configuration	$ 2,000	3	N/A	$ 6,000
VSAT installation (1.8 m -> 2 people)	$ 2,500	16	N/A	$ 40,000
RF network updates: WV	$ 80,000	N/A	N/A	$ 80,000
VA	$ 20,000	N/A	N/A	$ 20,000
PA	$100,000	N/A	N/A	$ 100,000
NJ	$ 50,000	N/A	N/A	$ 50,000
TN	$ 50,000	N/A	N/A	$ 50,000
NY	$ 80,000	N/A	N/A	$ 80,000
NC	$ 40,000	N/A	N/A	$ 40,000
KY	$ -	N/A	N/A	$ -
OH	$ -	N/A	N/A	$ -
NE states	$ -	N/A	N/A	$ -
TCP/IP RF hardware	$ 20,000	1	1	$ 20,000
TCP/IP RF installation	$ 2,000	8	N/A	$ 16,000
router	$ 5,000	18	1	$ 90,000
T1 install	$ 1,500	6	1	$ 9,000
project management costs	$150,000	N/A	N/A	$ 150,000
totals				**$1,415,550**

Annual costs	unit cost	quantity	discount	cost
program user support position(s)	$150,000	N/A	N/A	$ 150,000
software maintenance (after 1st year)	$ -	N/A	1	$ -
central site 7 X 24 support, maintenance	$150,000	N/A	N/A	$ 150,000
hub base station maintenance	$ 4,000	16	N/A	$ 64,000
TCP/IP RF hardware maintenance	$ 1,000	8	N/A	$ 8,000
VSAT charges	$ 2,400	16	1	$ 38,400
co-location charges	$ 12,000	N/A	1	$ 12,000
T1 access	$ 4,800	6	1	$ 28,800
ISP access	$ 4,800	4	1	$ 19,200
totals				**$ 470,400**

Table 1. Cost estimate for project implementation and maintenance

Economic Design

This section outlines in brief an economic approach that leverages the usefulness of the data in this system to non-mission critical users, thus splitting the cost among primary and secondary user markets. In addition, it offers motivated vendors a new and fertile market for their products.

In a recent report commissioned by the USBR, Eve Gruntfest and Phillipe Waterincks reviewed a rapid evolution that is occurring in the United States and elsewhere in the uses of real-time environmental data. They defined "primary" uses as those essential to emergency management, and they stated that, "by encouraging alternative applications, other public and private organizations are stimulated to cooperate by funding equipment and assisting in maintenance operations" (Gruntfest and Waterincks, 1998, p. 5).

The example offered in this thesis is based on the NWS's need and requirement to serve their IFLOWS users. It is not a viable alternative for the NWS to approach Congress and ask for additional funds so they can also support other, secondary users and thus reap revenue in the future – this is not a capacity possessed by government agencies, it is not part of their mission, and to do so would entail having a government agency compete with the private sector. It is, however, a highly viable alternative for the NWS to make creative use of the funding they have.

It is also a viable business enterprise for the private sector to pursue. The serious, real-time weather information consumers do not end with public safety enterprises. There is no business concern that cannot be affected by severe weather, and for some types of enterprises, having information about even normal weather changes can enable them to make better use of their resources or to offer better service to their customers.

Transportation-oriented company operations are heavily affected by weather conditions. The utility companies would like to track actual rainfall or wind figures in as local a fashion as possible, being thus able to better predict where problems will arise during stormy weather. The operations staff at Coors Baseball Stadium in Denver would like to know whether it is raining a mile away from the stadium right now, and in which direction the wind is blowing that particular summer squall or thunderstorm. Wireless PCS operations using rain-affected spectrum bands would be better off to be able to pinpoint and predict potential outages as soon as possible in order to best manage their customer services.

This extremely timely, granular weather information is not currently available except to those few companies that have been given or have taken the opportunity to get access to their local ALERT or IFLOWS system. Until now it has not made economic sense for most of them to make the skill and time investment currently required to have the information directly, as the data are scattered across many sources and the tools required are esoteric.

Mission-critical customers such as the NWS and their cooperators will receive the maximum reliability and functionality from their required system if they choose to pay vendors from the private sector to create and maintain the system they require to fully support their mandated users with the following proviso: If the vendors are allowed to disseminate the data from this system to other paying users, they can in turn substantially reduce the cost of the data and services provided to the NWS and their users.

There are significant and substantial advantages to pursuing this public-private partnership approach. The approach enables the mission-critical users to have state-of-the-art tools that would be unaffordable by traditional funding mechanisms. It maximizes the usefulness to society of systems that have been hidden and ill-used in the past. It puts the pressures of the free market on the vendors to create and maintain a system that is efficient, scalable, interoperable, reliable and usable. This is in stark contrast with the model of government employees being required to support a few government agency clients, all the while maintaining a host of other required roles as part of their job. In such a case, if the very few people responsible either for providing or using the system aren't able to complete their jobs, then the system is useless and the mission is a failure.

The burden of finding a market for the data is on the vendor, not the mission-critical users. This means that, in order to succeed, the vendors must build business cases that give them a sturdy platform for providing the core, mission-critical functions and then build from that both the secondary market of subscribers and the tools available to all the users. Once such an enterprise is underway, the vagaries of government budgets and the cutbacks applied to in-house resources will have little impact on the NWS's ability to serve its users, for example.

There are a number of questions worth asking about this scenario. In particular, two of them include:

1) What entities should actually own and maintain the sensor systems that provide the data for this scenario?

If the sensors are owned by the government entities that are the mission-critical users, the agencies may still choose to outsource the installation and maintenance thereof, as some (including the NWS) have already opted to do. In existing cases this has been accomplished successfully and cost-effectively.

However, this will likely not be an adequate solution for the commercial side of the implementation. The locations and types of sensors chosen by the government users may not provide enough information to adequately support the secondary market. The vendors will want to make sure that they have coverage of areas that are of interest to a wider market segment, and if they do so, then the primary users will also benefit from the additional spread and density of available data. In these cases, the data vendors will want to place some of their own sensors.

Finally, other organizations may choose to add sensors of their own and gain access to a wider data set as well. This type of arrangement has emerged in the Overland Park, KS, area, where Allied Signal Corp. has installed their own ALERT sensors and receives data from those installed by Overland Park, just as the city can receive Allied Signal's sensor signals (Parent, 1998). The company's plant is surrounded by a flood wall to protect some hazardous substances stored on their large site. In the event of heavy rainfall and flooding, Allied Signal uses their system to help decide when to close the flood gates, thus preventing the potential release of these substances to the environment outside their perimeter. In this sort of case, the public and private entities cooperate closely in their parallel missions.

2) What aspects should the public clients pay for, and what should the commercial clients pay for?

From the starting point the mission critical customers will want to assure that the services they require are delivered as promised. They may choose to accomplish this by paying initially for highly specific products and tasks (e.g., a maintenance fee delivering a guaranteed level of system performance) from the vendors, while allowing the vendors to go forward with developing other product suites that may be of interest to multiple target user markets. At the point when a variety of products are deployable and when the subscription rate for them generates an adequate cash flow to assure functional continuity, the mission critical users can drop back to paying a data subscription cost. The price of this subscription would differ from the price paid by the other subscription users by some amount related only to the guarantee of good and timely data, a model that is not at all new in the telecommunications framework for selling bandwidth.

Conclusion

The present-day real-time weather monitoring systems described previously have significant functional and cost drawbacks. They serve a small group of mission-critical users relatively poorly with respect to what is possible.

The last chapter has described both the technological and economic aspects of a standardized approach that combines the strengths of the public and private sectors to serve both types of end user more effectively than ever before. It is this author's sincere hope that this approach or something like it will be realized in the very near future, rather than remain trapped in a dusty, bound master's thesis in the library. We can save more lives and dollars than ever before in a world where the weather is not about to calm down.

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