Service Assessment

Record Floods of Greater Nashville: Including Flooding in Middle Tennessee and Western Kentucky, May 1-4, 2010

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
National Weather Service
Silver Spring, Maryland

Cover Photographs: Unless noted, photos are courtesy of *The Tennessean* newspaper, Nashville, TN. Photos are from May 1-3, 2010. **Clockwise from top left:**

- Discharges out of Old Hickory Lock and Dam on the Cumberland River, courtesy of USACE
- Downtown Nashville flooded, Hard Rock Cafe
- LP Field, home of the NFL Tennessee Titans
- Teenagers trapped in flash flood, Hendersonville, TN, courtesy of Rick Murray
- Car submerged in Greater Nashville
- I-40 in Nashville flooded, courtesy of WSMV TV Nashville TN

Cover layout by Steven Vanderburg, NWS, WFO Reno

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January 2011

National Weather Service

John L. Hayes, Assistant Administrator

Preface

On May 1-2, 2010, record-breaking rains struck Kentucky and the Tennessee Valley region. Western and Middle Tennessee were hardest hit with local amounts of 18-20 inches to the south and west of Greater Nashville along the Interstate 40 corridor. Much of western and Middle Tennessee, including Greater Nashville, experienced widespread, devastating flash flooding, as well as unprecedented flooding along the Cumberland River and its tributaries. There were 26 flooding fatalities directly attributed to this event in Kentucky and Tennessee, 11 of which were in Greater Nashville. Preliminary estimates of property damage are in excess of $2 billion in Greater Nashville alone.

Due to the significant effects of the event, the National Oceanic and Atmospheric Administration's National Weather Service formed a service assessment team to evaluate the National Weather Service's performance before and during the catastrophic flooding. The findings and recommendations from this assessment will improve the quality of National Weather Service products and services, and enhance awareness relating to flash flooding and river flooding. The ultimate goal of this report is to help the National Weather Service perform its mission of protecting life and property and enhancing the national economy.

John L. Hayes
Assistant Administrator
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January 2011

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Executive Summary

Widespread record flooding occurred across the mid-Mississippi and Lower Ohio Valleys due to an unprecedented heavy rain event on May 1-2, 2010. This flooding prompted a major response by the National Weather Service (NWS), emergency managers and responders, state and local governments, the United States Army Corps of Engineers (USACE) and the United States Geological Survey (USGS).

Catastrophic flooding occurred in Greater Nashville, western Kentucky, and Middle Tennessee May 1-4, 2010. The event began with heavy rain on Saturday, May 1. There were numerous flash floods, and rivers quickly exceeded their banks. A second period of heavy rain occurred over much the same area on Sunday, May 2, resulting in a repeat of flash flooding and escalated river flooding to major and record flood levels.

Record levels were set at 11 NWS river forecast locations. River flooding covered parts of Kentucky, Tennessee, and Mississippi and involved operations at two NWS River Forecast Centers (RFCs) (Lower Mississippi RFC and Ohio RFC) and five NWS Weather Forecast Offices (WFOs) (Memphis, TN; Paducah, KY; Louisville, KY; Nashville, TN; and Jackson, KY).

Low pressure over the western United States and high pressure across the East allowed a plume of moisture from the Gulf of Mexico to push into portions of Kentucky and Tennessee. This deep moisture interacted with a stationary surface front, resulting in the development of severe storms with torrential rain over the weekend of May 1-2.

WFOs Paducah and Louisville issued flash flood watches the preceding Thursday, April 29, and WFO Nashville issued a Flash Flood Watch on Friday, April 30. The team concluded that the media and emergency managers were well informed of the potential for significant flooding. Nashville media began 24-hour coverage on Saturday, May 1, which continued through the weekend.

WFO Nashville issued several flash flood warnings Saturday morning, followed by widespread flood warnings that blanketed most of its county warning area; however, the wording of these products was such that many emergency managers and residents underestimated the catastrophic nature of the flooding.

Additional heavy rain on Sunday, May 2, resulted in river flooding that continued through Tuesday, May 4. The heaviest rain occurred in the uncontrolled basins[1] of the Cumberland River, which resulted in the unprecedented flooding.

[1] "Uncontrolled" river basins are those in which there are no dams or hydrologic projects designed to hold back or control flood waters, i.e., these basins have limited or no reservoir storage to reduce river flow. Rain falling into these basins runs directly into the rivers and tributaries, impacting their levels.

The extreme and widespread nature of this event caused NWS, USACE, and USGS staffs to be pushed to the limit in terms of workload. First responders, emergency managers, and local officials were thrown into the "flood fight" on Saturday, which continued through Tuesday. Personnel in every agency involved were in a reactive mode, making all effort to maintain operations and provide critical emergency support and services.

Sunday morning, May 2, the Ohio River Forecast Center (OHRFC) coordinated with WFO Nashville, which issued the first River Flood Warning for the Cumberland River at Nashville at 9:50 a.m. Central Daylight Time. This forecast called for a crest of 41.9 feet by evening. Flood stage is 40 feet, and major flood stage is 45 feet.

During a critical period Sunday afternoon and evening, the NWS and USACE did not communicate effectively regarding updated releases (outflows) from USACE reservoirs. This lack of critical information exchange and mutual understanding of each other's operations led to inaccurate river crest forecasts on the Cumberland River. USACE personnel were completely engaged in critical operations to prevent damage to structures or dam failures along the Cumberland River as the flooding intensified. With incorrect or untimely information from the USACE about their operations, as well as miscommunications and ineffective information exchanges between the USACE and NWS, NWS forecast crests were quickly exceeded on Sunday when the river stage at Nashville rose rapidly through moderate and major flood levels.

Many residents of Nashville who were interviewed stated that they "had no warning," despite numerous watches and warnings issued by WFO Nashville. The residents perceived that flood warnings did not directly affect them; they could not relate river levels to flooding at specific locations. The Nashville Mayor's Office of Emergency Management stated that NWS forecasts for the Cumberland River at Nashville were lagging behind observed river levels. One user told the team that his office lost confidence in river forecasts Sunday as forecast crests changed dramatically and frequently.

Through the weekend into Monday morning, the Cumberland River at Nashville rose more than 33 feet, cresting at 51.86 feet on Monday evening, May 3. This stage was approximately 4 feet higher than the previous flood control era peak (47.64 feet, March 1975), and 10 feet higher than the original forecast issued Sunday morning.

Many other record flood levels were set. Record discharges were made from USACE Lock and Dam projects in the Cumberland River Basin, including those at Cordell Hull, Old Hickory (upstream of Nashville), Cheatham, and Barkley.

The team found that everyone involved in this event, including federal, state and local staff members, were dedicated to their respective missions. In many cases, individuals went beyond the call of duty. For example, WFO Nashville employees risked their personal safety to supplement operational staffing on Sunday morning, when two of three roads into the WFO were impassable due to flooding. Tennessee USGS staff braved extreme elements to take manual river gage readings that were relayed to the NWS. USACE staff members at projects along the Cumberland River risked their own safety to ensure that the integrity of dam projects was not compromised.

In all, 26 people lost their lives due to flooding. There were 18 fatalities in Middle Tennessee with 11 occurring in Greater Nashville. Property damage estimates in Greater Nashville alone were over $2 billion.

This service assessment supports a number of key findings and recommendations for improved NWS services. The primary recommendation identifies the need for improved communication and collaboration between WFO Nashville, the OHRFC, USACE Nashville (LRN) and the Tennessee USGS.

Key Findings:

1. Coordination and effective communication between the NWS and primary federal water partners, the USACE and USGS, was lacking at critical times during the event, undermining key forecasts, particularly on the Cumberland River at Nashville.

2. Effective communication was hampered by a long-term working relationship deficient in a comprehensive understanding of each agency's operational procedures, forecast processes, and critical data needs, especially during non-routine events.

3. Pre-event coordination was proactive. Weather forecasts were sufficiently accurate to alert federal partners and other relevant organizations to the elevated risk for serious flooding in the region during the weekend. The NWS, along with many partners, responded by planning increased staffing levels.

4. Despite pre-event actions, the increased staffing during the event at the two NWS offices most impacted, WFO Nashville and OHRFC, was not sustained consistently at levels required to respond comprehensively to the extreme flooding.

5. Many people did not respond to NWS warnings because the products were not tone-alerted via the Emergency Alert System, were not worded in such a manner that adequately reflected the urgency of the situation, or because the warnings were not specific enough to cause listeners to believe the flooding would impact their location. Some people failed to receive warnings, or chose to disregard warnings that aired on television (for example, the tubing fatality on Mill Creek).

Key Recommendations:

1. The NWS should engage in additional interactions and exercises with USACE and USGS. Results of these efforts should be a clear understanding of the operating needs and procedures of each agency during routine and extreme events, the creation of quality long-term relationships, and ensuring open and effective communication.

2. The NWS should support field office staffing for potentially high impact events by implementing proven pre-event and event staffing models successfully employed by other field offices.

3. NWS, USACE, and USGS should expedite efforts to develop and implement Integrated Water Resources Science and Services. This effort should include expanding current inundation mapping initiatives in major populated and flood-prone areas.

Service Assessment Report

1. Introduction

1.1. NWS Mission

The National Weather Service (NWS) provides weather, hydrologic, and climate forecasts and warnings for the United States, its territories, adjacent waters and ocean areas, for the protection of life and property and the enhancement of the national economy. NWS data and products form a national information database and infrastructure, which can be used by other governmental agencies, the private sector, the public, and the global community.

1.2. Purpose of Assessment Report

This document presents findings and recommendations regarding NWS performance during the river flooding and flash flooding from May 1-4, 2010. The area most impacted was western and Middle Tennessee, including Greater Nashville, and western and central Kentucky. This Service Assessment focused on Greater Nashville and portions of Middle Tennessee due to the significant loss of life and the extreme amount of property loss in those areas.

The objectives of this assessment are to identify effective operations, significant findings and best practices, and to recommend remedial actions to address service deficiencies. This report focuses on the following key areas:

- Timeliness, quality, accuracy, and usefulness of NWS forecasts and warnings from the perspective of high impact services and decision support
- Effectiveness of NWS internal and external coordination/collaboration
- Effectiveness of NWS information dissemination and communication of uncertainty and flood risk
- Effectiveness of hydrologic forecasting and warning procedures at NWS offices
- Identification and evaluation of opportunities to improve collaboration among other federal, state, and local agencies

1.3. Methodology

The NWS formed an assessment team on May 20, 2010 (**page ix**). Team efforts included the following:

- Completed an onsite evaluation from May 20-27, 2010
- Interviewed staff from WFOs in Nashville, TN (OHX) and Louisville, KY (LMK), and the OHRFC in Wilmington, OH. These offices had primary responsibility for providing forecasts, warnings, and decision support to the residents and Emergency Managers (EM) of the most affected areas.
- Conducted phone interviews with the Meteorologist in Charge (MIC) and Service Hydrologist at WFO Paducah, KY and with the Lower Mississippi River Forecast Center (LMRFC)
- Met with representatives from the USACE Great Lakes and Ohio River Division Office in Cincinnati (USACE LRD), USACE Nashville District Office (LRN), and United States Geological Survey Tennessee Water Science Center (TN USGS)
- Interviewed EMs, the media, and the public, as well as other government agency representatives
- Conducted assessments of the damaged areas
- Interviewed representatives from the Nashville Mayor's office, U.S. Senator Lamar Alexander's office, and Representative Jim Cooper's office
- Interviewed representatives from Gaylord Entertainment, owners of Opryland Hotel and the Grand Ole Opry
- Evaluated products and services issued by the aforementioned WFOs and RFCs, as well as national guidance issued from the Hydrometeorological Prediction Center (HPC)
- Developed significant findings and recommendations to improve the effectiveness of NWS products and services

2. Event and Hydrometeorological Summary

Catastrophic flooding occurred across western and Middle Tennessee and western and central Kentucky from May 1-4, 2010. Flood damage was estimated at more than $2 billion and there were 26 flood-related fatalities. The worst flooding occurred in and around Greater Nashville.

At the time of this report, a paper under peer review entitled "*The Devastating Mid-Mississippi Valley Floods of 1-2 May 2010*", by Richard H. Grumm, National Weather Service, noted the following: "The event of 1-2 May 2010 had. . .key ingredients for a significant heavy rainfall event (Doswell et al. 1996), and for historic events (Bodner 2011). "This case is a classic case on the value of anomalies in identifying a potentially significant heavy rainfall event. . .clearly defined a threat of a Maddox Synoptic event type with a strong southerly jet and a surge of high PW [precipitable water] air into the region."

2.1. Antecedent and Event Conditions

Drier than normal conditions characterized the impacted area from February through late April. The May 1-2 heavy rain event increased precipitation to well above normal for the year to date at Nashville. This rainfall resulted in both the third highest and highest 24-hour amounts in 139 years of record at Nashville. The resultant 2-day rainfall total broke the record for the wettest May on record.

In late April, an upper level trough developed across the western United States, allowing southerly flow to push into the mid-Mississippi and Lower Ohio Valley region. This moist flow interacted with a stationary front oriented northeast-southwest across the Mississippi Valley (**Figure 1**).

Weather disturbances in the mid-levels of the atmosphere (**Figure 2**) helped trigger storms that produced heavy rainfall over the same areas May 1-2. In the lower levels of the atmosphere, a 65-knot (75 mph) jet was the key source of moisture transport into the region (**Figure 3**). Precipitable Water (PW) values, a measure of how much moisture is in the atmosphere (**Figure 4**), were up to 2 inches during the event. These values indicated an unusually high amount of available moisture.

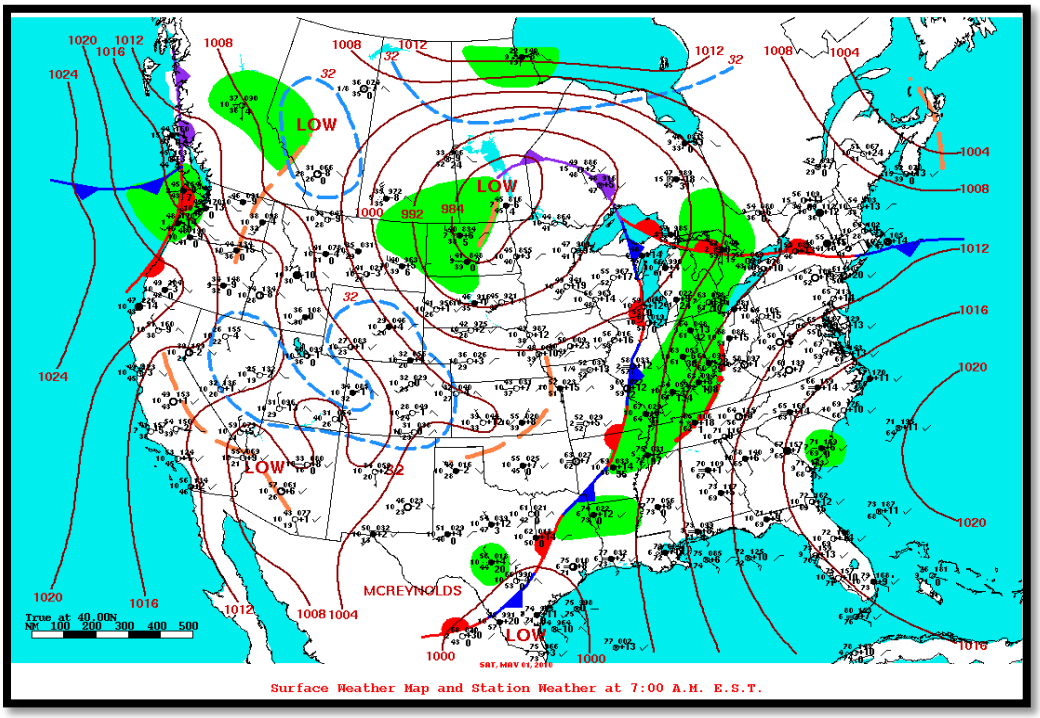

Figure 1: Surface Weather Map, May 1, 2010, 7:00 a.m. Central Daylight Time (CDT).

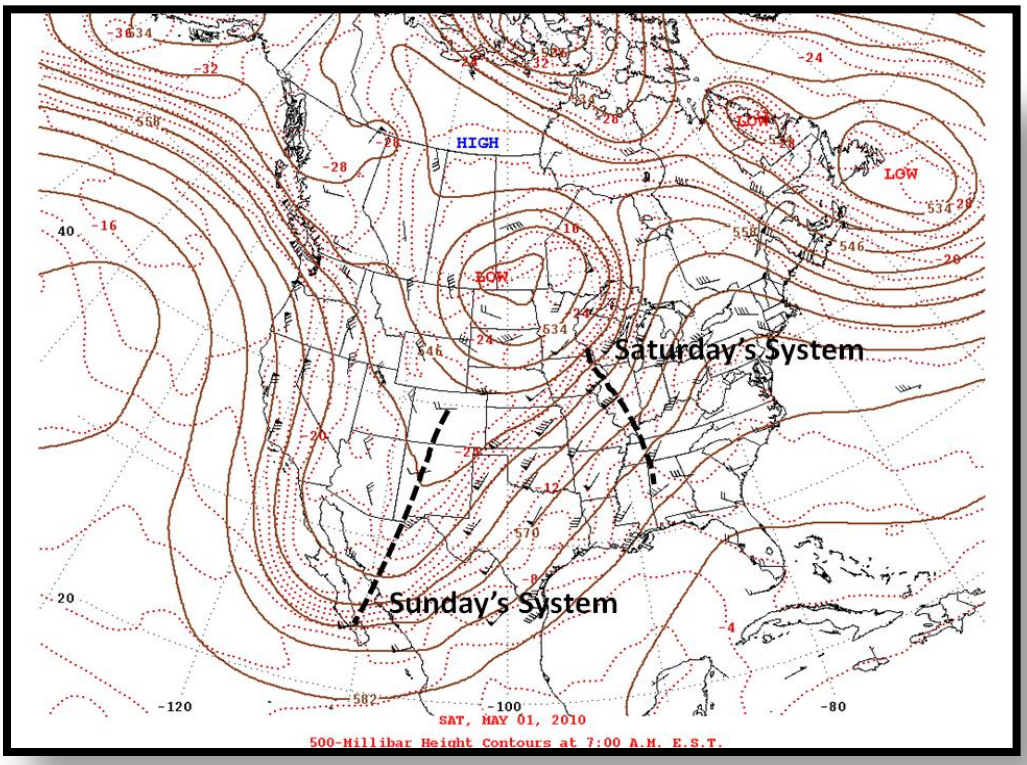

Figure 2: Upper air chart showing flow and disturbances at approximately 18,000 feet Above Ground Level (AGL), May 1, 7:00 a.m. CDT.

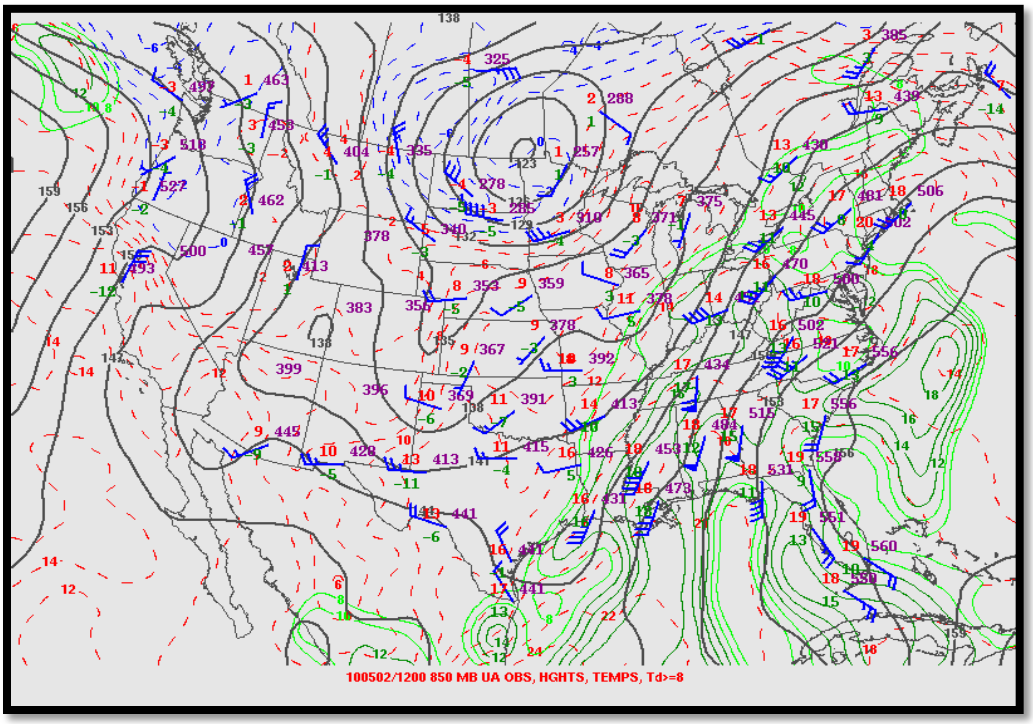

Figure 3: Lower levels of the atmosphere showing moisture transport (green lines) from the Gulf of Mexico into the Mid Mississippi and Tennessee Valleys, at approximately 5,000 feet AGL; May 1, 7:00 a.m. CDT.

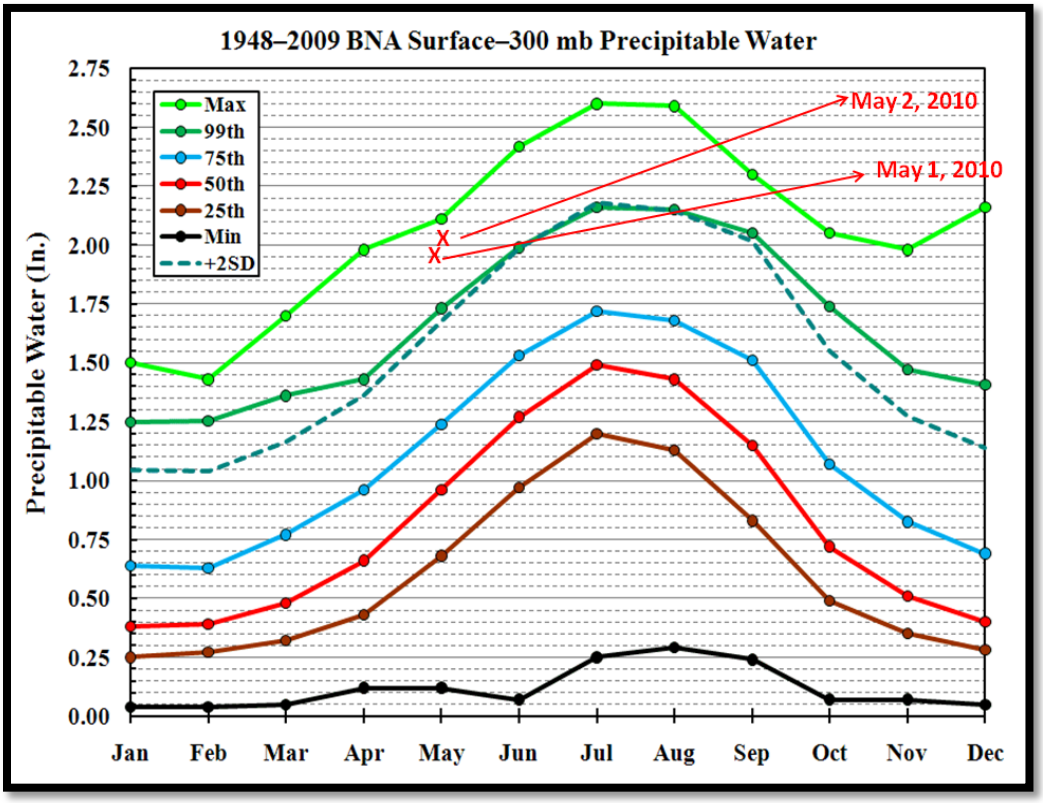

Figure 4: Climatological PW is a measure of available moisture in the atmosphere. Observed PW for Nashville at 7:00 a.m. and 7:00 p.m. May 1 is denoted by **X**s. The observed values are at nearly the maximum ever observed at Nashville for that time of year.

These ingredients combined to produce two episodes of heavy rain across the same areas in Kentucky, and western and Middle Tennessee. Between 10-20 inches of rain fell in 36 hours on May 1-2, causing a catastrophic flood event. The heaviest rains fell primarily in unregulated portions of the Cumberland River Basin, downstream of the reservoirs containing sufficient flood control storage to have helped contain the event's runoff and mitigated flood damages (**Figure 5**).

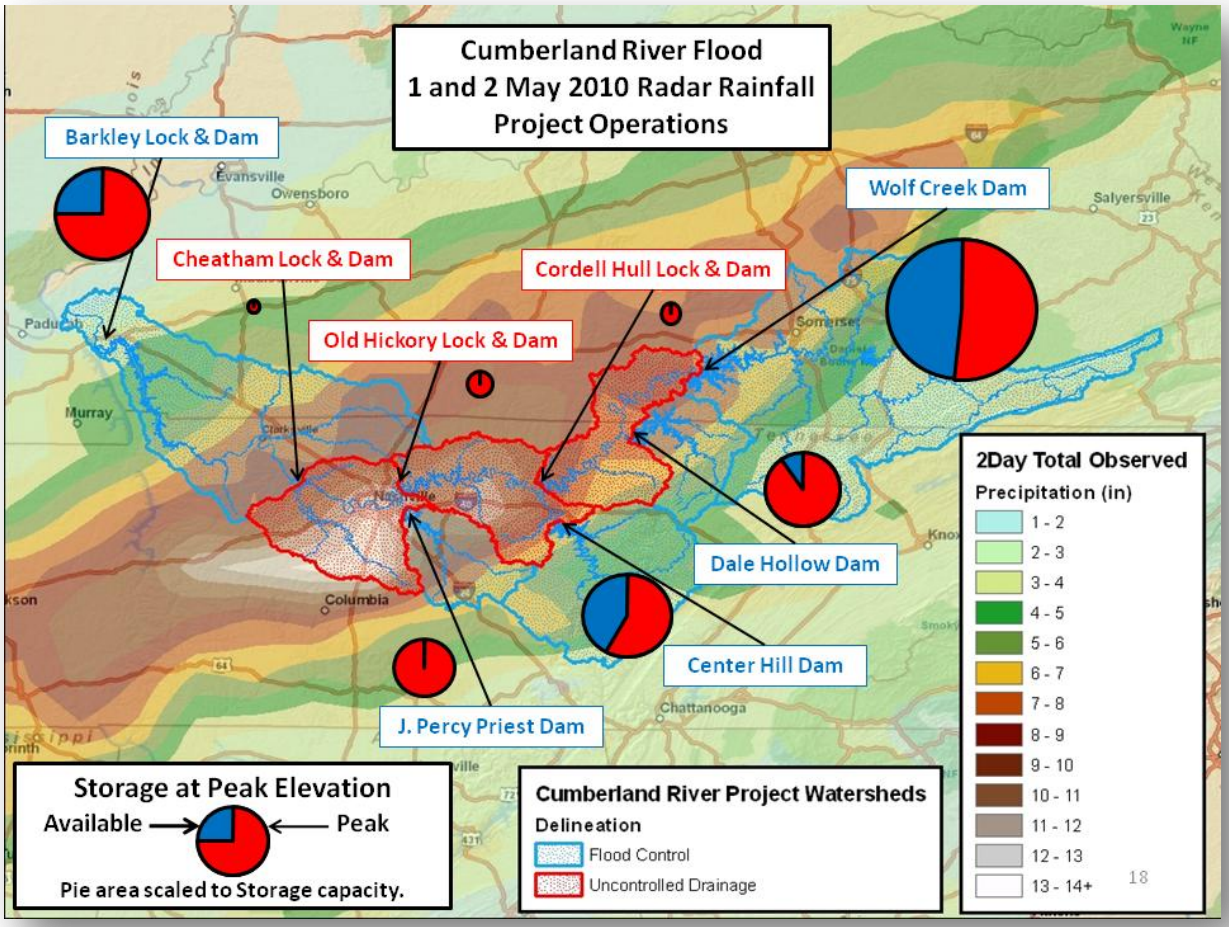

Figure 5: An overlay of precipitation data with drainage areas in the Cumberland River Basin. Red outline indicates uncontrolled drainage areas. Drainages outlined in blue flow directly into a USACE Flood Control Project. Pie charts show the relative capacity for each project and how much capacity was used during this event. The heaviest rain fell over uncontrolled basins of the Cumberland River resulting in record rises at Nashville and Clarksville. *Graphic courtesy USACE. May 2010 Nashville Flood Event After-Action Report, page 18.*

Hourly rainfall and rainfall accumulations at the Nashville International Airport (KBNA) are shown in **Figure 6.** At Nashville, 13.57 inches of rain was measured during a 36- hour period; 6.23 inches on May 1, the 3rd highest 24-hour total on record, and 7.25 inches on May 2, which broke the previous 24-hour rainfall record of 6.60 inches set in September 1979. The combined two-day rainfall total *doubled* the previous 48-hour rainfall record at Nashville for the 139 years recorded. The highest weekend rainfall total was reported by an NWS Cooperative Observer in

Camden, TN at 19.41 inches. **Figure 7** shows rainfall distribution over the affected area. **Figure 8** shows the extreme rainfall totals of 12 to 16 inches along Interstate 40 (I-40) in Tennessee.

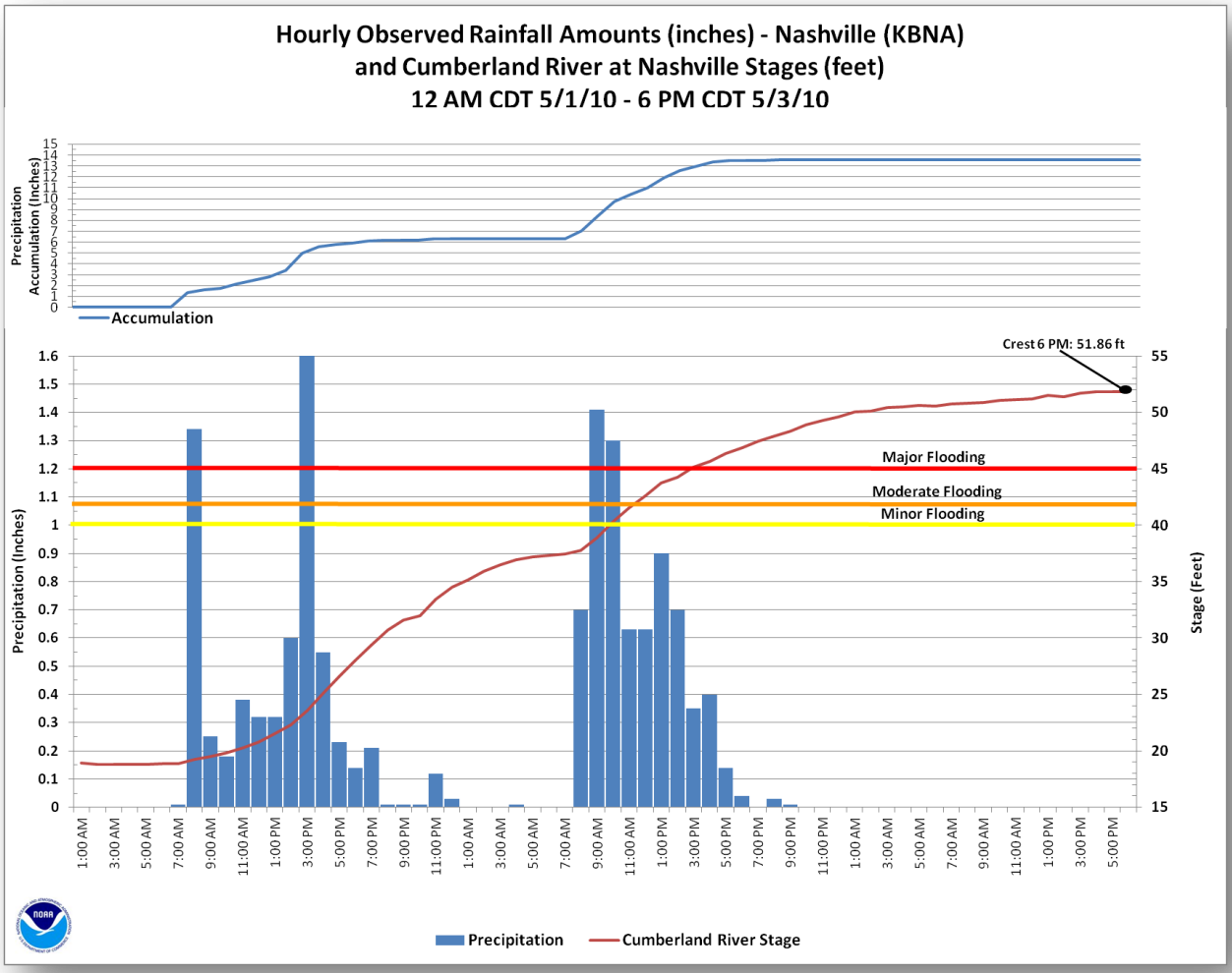

Figure 6: Hourly rainfall amounts (inches) and rainfall accumulation trace (top) at Nashville International Airport (KBNA) from 12:00 a.m., May 1 to 12:00 a.m., May 3. Brown line rising from bottom left to top right depicts the resultant river level rise on the Cumberland River at Nashville.

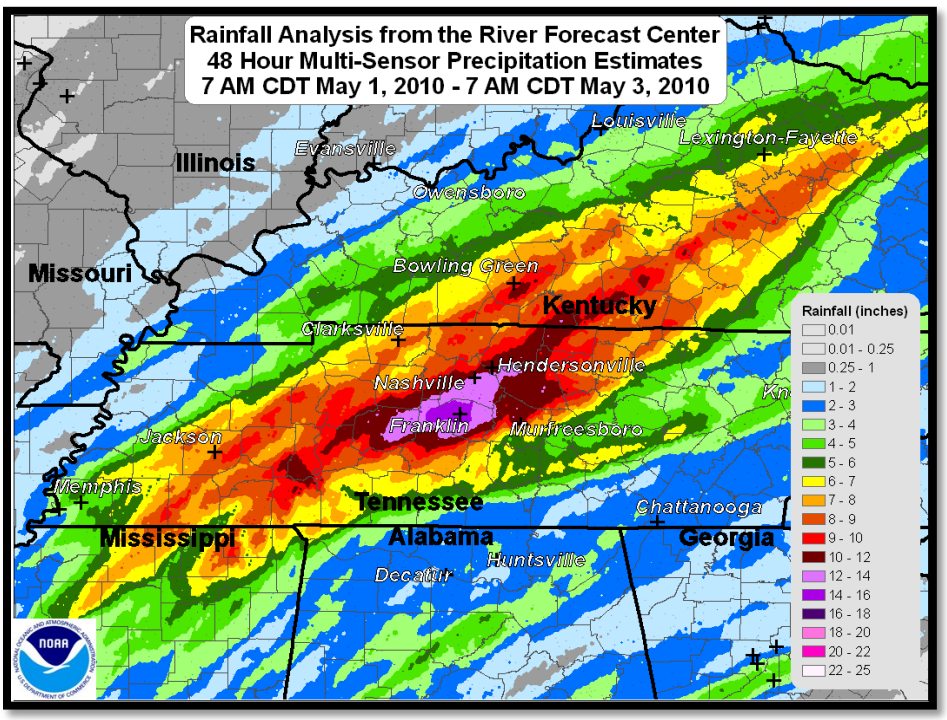

Figure 7: Multi-sensor 48-hour precipitation total for May 1–2 across the Mid-Mississippi and Tennessee Valleys.

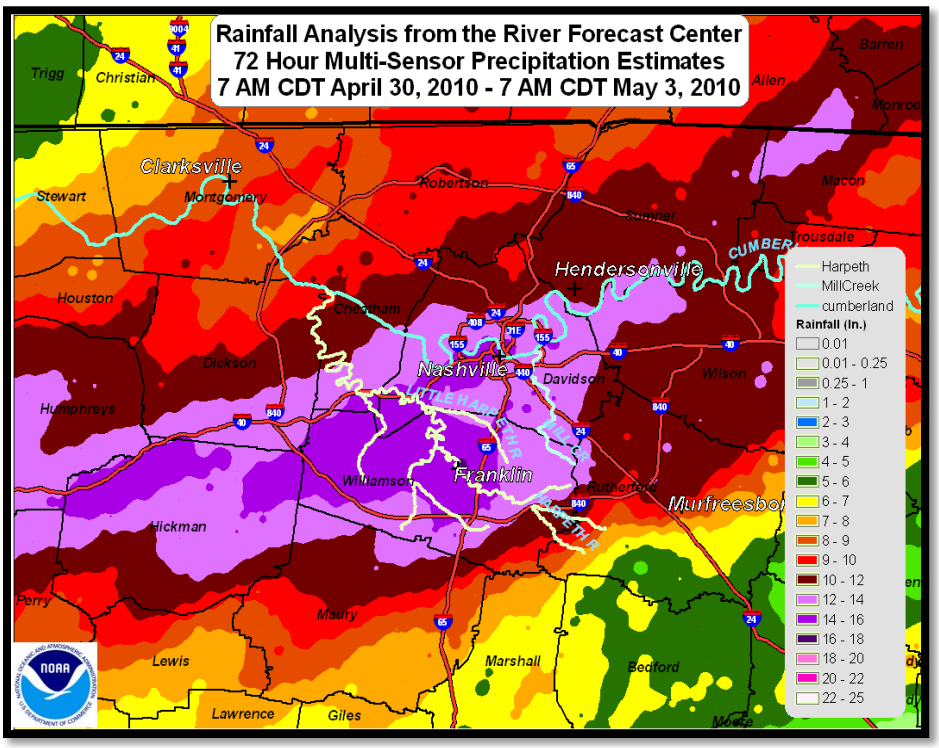

Figure 8: Multi-sensor precipitation totals for the May 1-2 weekend in and around Greater Nashville.

2.2. Impacts

Fatalities

Twenty-six confirmed fatalities resulted from the flooding in Tennessee and Kentucky, 11 in Greater Nashville (**Figures 9, 10, Tables 1, 2**). An additional death was tornado-related and is not included in these totals. Flooding deaths in Greater Nashville resulted from flash flooding of streams and tributaries of the Cumberland River, versus flooding of the mainstem Cumberland River. At least 14 of the flooding deaths were people over 60 years of age, which was a disproportionate number of fatalities (over 60 percent) for the senior citizen population. Much of the significant flooding in the Nashville area occurred in areas where a high percentage of senior citizens live, i.e., in older, established neighborhoods such as Delray, Bellevue, River Plantation, and Waterford. At least four of the residents who drowned were on their way to church Sunday morning.

The Nashville Council on Aging identified possible factors that may be associated with the weather-related fatalities in this age range:

- NWS staff and local media hold weather education classes and NOAA Weather Radio All Hazards (NWR) give-away events at night. Seniors often choose not to travel at night.
- Many seniors have computers but use them primarily for emailing family. Most carry cell phones, but many don't turn them on unless they need to make a call.
- Seniors do not typically use social media, and many find it difficult to navigate through web pages to obtain warning information.

It was not clear to the team whether these fatalities were a result of the location of the flooding or a lack of hazardous weather education within the senior population.

Flood Fatalities				
Date and Time	**Location**	**Sex**	**Age**	**Activity**
5/02 Evening	KY – Madison Co.	M	65	In home
5/02	KY – Barren Co	F	27	Vehicle
5/02	KY – Lincoln Co	M	48	Vehicle
5/02	KY – Allen Co	M	34	Vehicle
5/01	West TN – Carroll Co	M		Near hwy. 79
5/01	West TN – Gibson Co	M		Walking Gann Rd
5/01	West TN – Shelby Co	M		Vehicle
5/01	West TN – Tipton Co	M		Walking
5/01 1142 am	Middle TN – Stewart Co	F	62	Vehicle
5/01 1142 am	Middle TN – Stewart Co	M	64	Rescue attempt
5/01 130 pm	Middle TN – Williamson Co	M	70	Vehicle
5/02 900 am	Middle TN – Perry Co	M	44	Home evacuation
5/02 900 am	Middle TN – Perry Co	F	15	Home evacuation
5/02 1030 am	Middle TN – Hickman Co	F	70	Leaving home
5/03 900 pm	Middle TN – Montgomery Co	F	63	Vehicle

Table 1: Flood fatality details for western and central Kentucky and western and Middle Tennessee (does not include Greater Nashville).

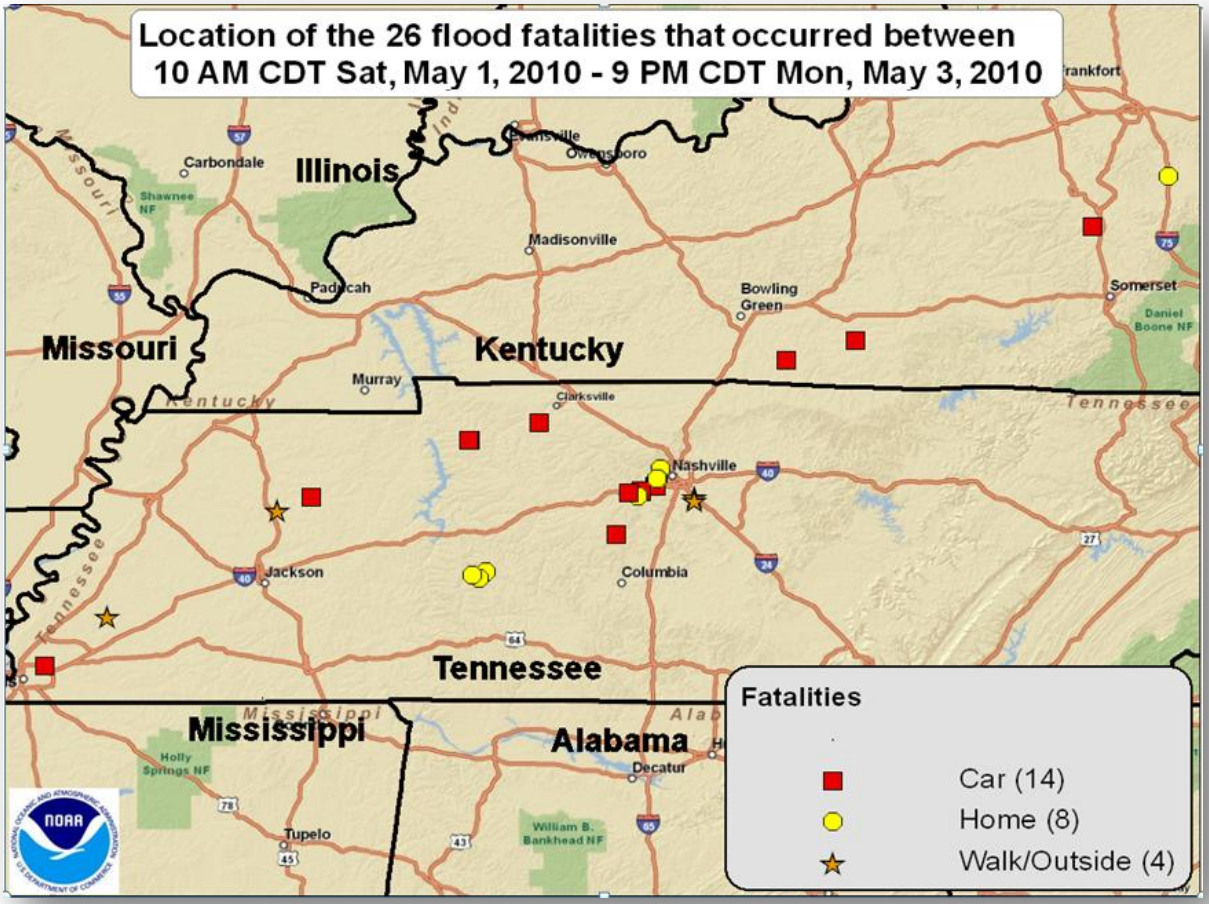

Figure 9: Flood fatalities in western and central Kentucky, western and Middle Tennessee; *not* including the Greater Nashville area (some fatalities were couples in vehicles, which are designated with only one red box).

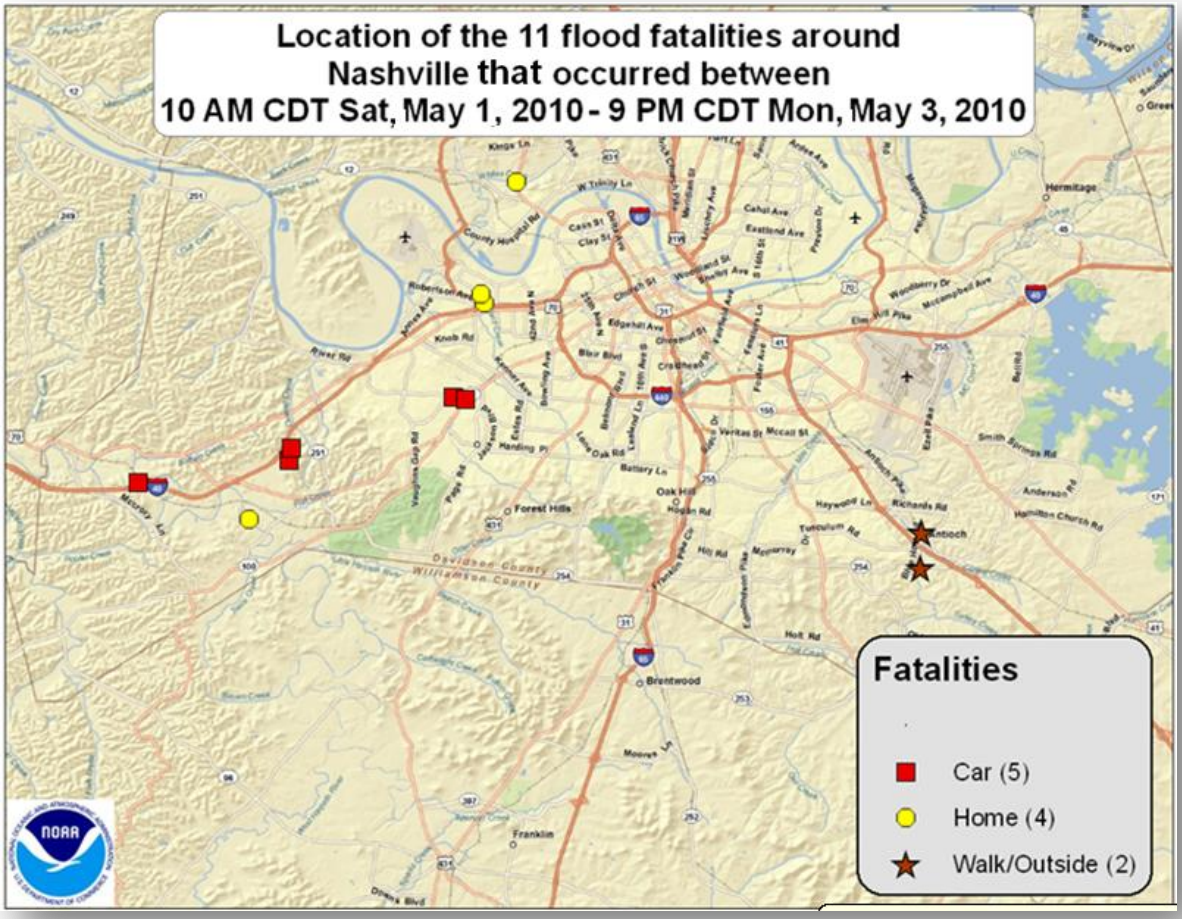

Figure 10: Flood fatalities in Greater Nashville, Davidson County. (One red box was used to designate two fatalities that occurred when fleeing a vehicle.) Flood fatalities in Nashville were a result of flash flood, stream and tributary flooding, versus flooding of the mainstem Cumberland River.

Flood Fatalities				
Date and Time	**Location**	**Sex**	**Age**	**Activity**
5/01 200 p.m.	Blue Hole Rd @ Bell Rd	M	21	In flood water
5/01 1000 p.m.	Harpeth River	M	39	Vehicle
5/02 930 a.m.	Near Richland Ck @ Harding	M	70	Fleeing vehicle
5/02 930 a.m.	Near Richland Ck @ Harding	F	65	Fleeing Vehicle
5/02 930 a.m.	Sawyer Brown Rd	M	88	Vehicle
5/02 930 a.m.	Sawyer Brown Rd	F	78	Vehicle
5/02 1000 a.m.	West Hamilton Ave.	M	75	yard at home
5/02 1000 a.m.	Mill Creek	M	18	Tubing
5/02 1030 a.m.	Sawyer Brown Rd	M	86	In home
5/02 1100 a.m.	Delray Rd.	M	78	In home
5/02 1100 a.m.	Delray Rd.	F	80	In home

Table 2: Flood fatality details in Greater Nashville, Davidson County.

Damage

Nashville

The Nashville area was severely impacted on three consecutive days, May 1-3. On May 1, there were record flood stages on many streams south of I-40 between Memphis and Nashville. Flash flooding occurred on I-24 and I-40. Heavier rain occurred on May 2 along and north of the I-40 corridor. On May 3, the Harpeth and Cumberland Rivers reached record flood stages, including a post-flood control era record of 51.86 feet on the Cumberland at Nashville. Flooding of the Cumberland River, including its tributaries and creeks, caused most of the damage, estimated at more than $2 billion. At least 11,000 structures were damaged. Below are estimated damages/impacts to some of the most significant structures:

- Metropolitan Transit Authority's Administration building: $3.1 million
- Bridgestone Arena: $3 million
- LP Field: $2.3 million
- Schermerhorn Symphony Center: $2.5 million
- Water treatment plant: $40 million
- Opryland Resort and Convention Center: $220 million
- Gaylord Entertainment: 1,700 workers temporarily laid off
- Opry Mills Mall: 7 feet of water inundated 1.2 million square feet.

Interstate 24

- Officials closed I-24 over Mill Creek Saturday afternoon, May 1 **(Figure 11).** Dozens of vehicles were trapped by floodwaters as water overtopped the 5-foot concrete median. Vehicles in westbound lanes heading into Nashville were floating in 6 feet of water.
- A portable school building floated down I-24 until it imploded.
- A road closed near LaVergne. City leaders shut down the town due to high water. After the water receded, more than 130 vehicles were towed.

Figure 11: Flooding on Interstate 24 Saturday afternoon, May 1.
Photo courtesy of WSMV Nashville, TN.

Interstate 40

- West of Nashville at mile marker 180 near Fairview, I-40 was under water the evening of May 1 (**Figure 12)**.
- Emergency staff conducted boat rescues Saturday night, May 1, between mile markers 153 and 154.
- A 65-mile portion of I-40 was closed due to high water for much of the period from May 1-3.

Figure 12: Flooding on Interstate 40 Saturday evening, May 1.
Photo courtesy of WSMV Nashville, TN.

Kentucky

- Emergency declarations were made in 83 counties. Roads and bridges were damaged; several water treatment and sewage plants flooded.
- At least 300 roads were blocked by high water, mud and rock slides, and debris.
- A record water release of almost 303,200 cfs on the Cumberland River below Barkley Dam caused nearly $1 million in damage to dozens of homes.

Nearly all counties in western and Middle Tennessee, along with numerous counties in Kentucky, fell under Major Disaster Declarations by the Federal Emergency Management Agency (FEMA) **(Figure 13)**.

COUNTIES UNDER MAJOR DISASTER DECLARATIONS

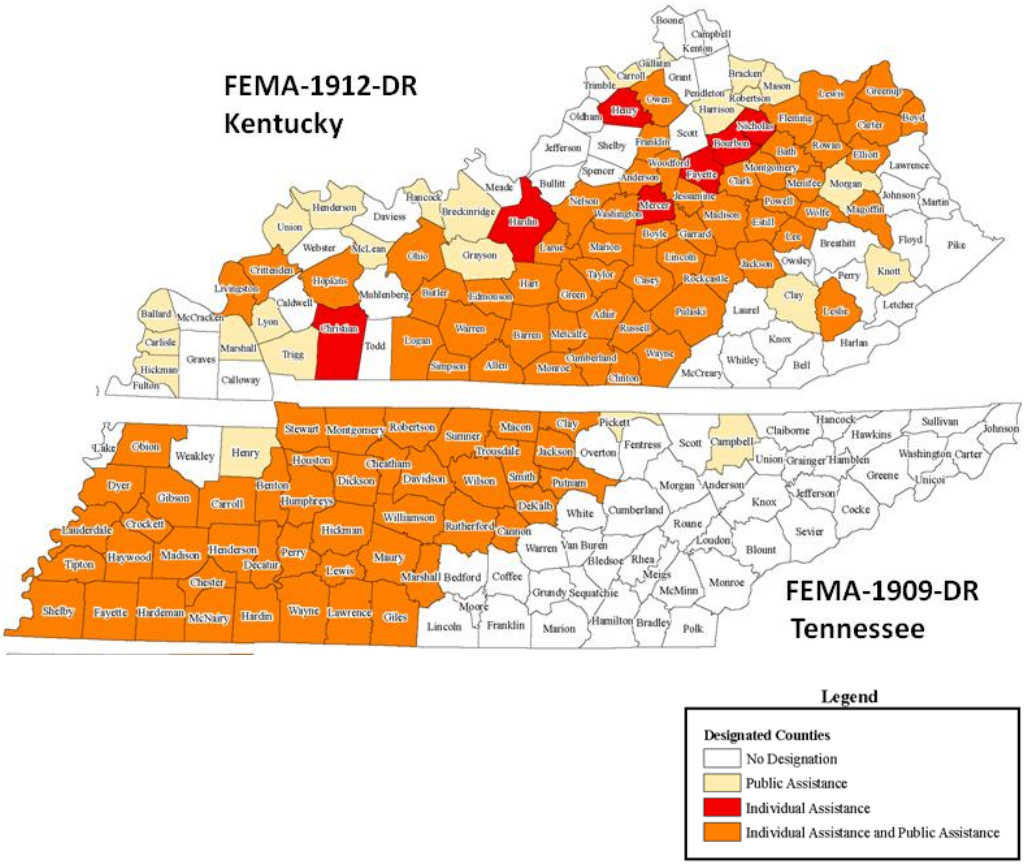

Figure 13: FEMA 1912-DR* Kentucky and FEMA 1909-DR Tennessee

*DR is a FEMA identifier for a Major Disaster Declaration

FEMA-1912-DR (Figure 13, Top)
Kentucky
Combined Public and Individual Assistance Costs: over $16 million

FEMA-1909-DR (Figure 13, Bottom)
Middle Tennessee (combined Public and Individual Assistance Costs – Flood related)
Over $660 million in Davidson County alone (Nashville)
Over $848 million all of Middle Tennessee (includes Davidson County)

2.3. River Flood Warnings/Forecasts for Major Flood Stage and Above

This event generated a combined total of 20 major and record river floods at NWS river forecast points, 9 within the LMRFC service area and 11 in the OHRFC service area. There were record levels at 12 locations in Tennessee. Major floods were distributed across three WFO areas, four forecast points in the Memphis Hydrologic Service Area (HSA), seven points in the Louisville HSA, and 10 points in the Nashville HSA **(Figure 14). Floods impacted t**he Kentucky, Green, Cumberland, Harpeth, Duck, and Red River Basins **(Table 3).**

Initial river forecasts were made early May 1. River flood warning lead times were 4-6 hours, but varied considerably based on river basin topography and response to extreme rainfall intensity.

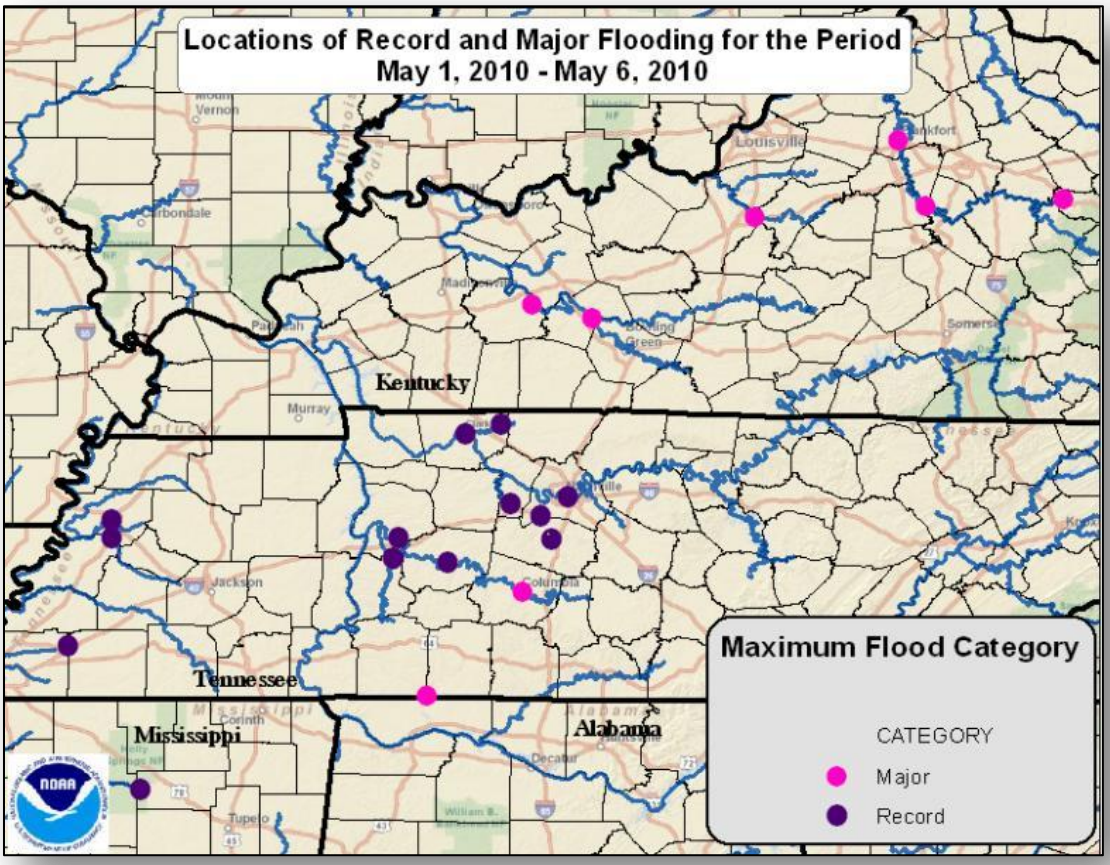

Figure 14: Locations of record and major flooding in the Lower Ohio and middle Mississippi Valley Region, May 1-6, 2010.

Table 3: Major and record flood locations. Red denotes major flooding and blue denotes record flooding.

NWS ID	Location	River Name	Major Flood Stage (ft)	Pre-May 2010 Record Stage (ft)	May 2010 Crest (ft)**
DYET1	Dyersburg, TN	North Fork Forked Dear	29	30.91	31.21
HLST1	Halls, TN	South Fork Forked Deer	16	15.21	16.14
ARLT1	Arlington, TN	Loosahatchie	24	25.27	25.58
ETAM6	Etta, MS	Little Tallahatchie	29	29.41	29.85
IRCT1	Iron City, TN	Shoal Creek	22	28.1	23.12
COLT1	Columbia, TN	Duck	41	51.75	44.91
CNVT1	Centerville, TN	Duck	32	37.58	47.5
LBVT1	Lobelville, TN	Buffalo	22	25.23	25.7
HMLT1	Hurricane Mills, TN	Duck	28	30.70	32.95
BELT1	Bellevue, TN	Harpeth	28	24.34	33.2
KINT1	Kingston Springs, TN	Harpeth	30	32.2	46
NAST1	Nashville, TN	Cumberland	45	56.2	51.86*[1]
CKVT1	Clarksville, TN	Cumberland	55	57.1	62.58
PORT1	Port Royal, TN	Red	40	48.26	49.48
FFTK2	Frankfort, KY	Kentucky	40	48.47	42.84
HIBK2	High Bridge, KY	Kentucky	38	53.1	42.6
BSNK2	Boston, KY	Rolling Fork	45	55.2	50.74
CYCK2	Clay City, KY	Red	23	26.75	23.3
WDBK2	Woodbury, KY	Green	48	58.9	49.52
PRDK2	Paradise, KY	Green	390	403.95	398.2

*[1] Cumberland River at Nashville Record crest in the post flood control reservoir era (the last Flood Control Project put into place along the Cumberland River was Percy Priest, circa 1968).

** Some crest values are "provisional" per the USGS.

3. Facts, Findings, Recommendations, and Best Practices

3.1. Hydrometeorological Prediction Center (HPC) Products and Services

HPC consistently forecast total rainfall amounts of 5 or more inches over Middle Tennessee for the weekend of May 1-2, beginning 7:00 a.m., Wednesday, April 28 (**Figures 15-18**). Wording in HPC discussions emphasized the significance of the impending rainfall event. Prior to the rainfall onset, forecast amounts for the weekend had increased to more than 8 inches, corresponding to record 24- and 48-hour events.

Rainfall maxima were initially forecast over Alabama and northern Mississippi, but pinpointed western and Middle Tennessee in later forecasts. By mid-day May 1, HPC forecasters identified Middle Tennessee to be at a high risk of an excessive rainfall event. HPC then issued an Excessive Rainfall Potential Outlook **(Figure 19)**, indicating a 15 percent chance of more than 5 inches of rain from 1:00 p.m., Saturday, through 7:00 p.m., Sunday. A probability of 15 percent is considered a high risk of the event happening. HPC forecasters expressed concern about much greater totals within this excessive rainfall event in discussion products, noting at 12:41 p.m., Saturday that:

> WIDESPREAD STORM TOTAL AMTS IN EXCESS OF 8.00 INCHES ARE LIKELY… SOME VERY LOCALIZED AREAS HAVE ALREADY EXCEEDED THAT AND WOULD NOT BE SURPRISED TO SEE STORM TOTAL AMTS APCH AND/OR EXCEED 12 - 15 INCHES OVER SOME SPOTS.

Forecasters were successful predicting storm totals near or exceeding record amounts in Tennessee and Kentucky. Consistency was maintained among forecasts and motivated NWS and partner agency pre-event planning and expanded operations; however, the Friday morning forecast **(Figure 17)** placed the rainfall core too far west and underestimated the magnitude by approximately half in places. The Saturday morning forecast **(Figure 18)** improved in predicted magnitude and location, but still underestimated amounts by up to 8 inches **(Figure 20)**.

The significant QPF underforecasts for certain locations point to an ongoing need for the NWS to invest resources toward increasing QPF accuracy, especially for rare, record hydrologic events. This recommendation has been made in previous Service Assessments **(C3, Appendix C)**.

Despite the errors in forecast location, timing, and magnitude, NWS forecasts did afford up to 5 days of lead time in predicting a rare and potentially disastrous event, providing actionable information to the affected agencies. HPC elevated the seriousness of the flood potential as the event approached, and it provided increasingly accurate rainfall locations and amounts for the weekend.

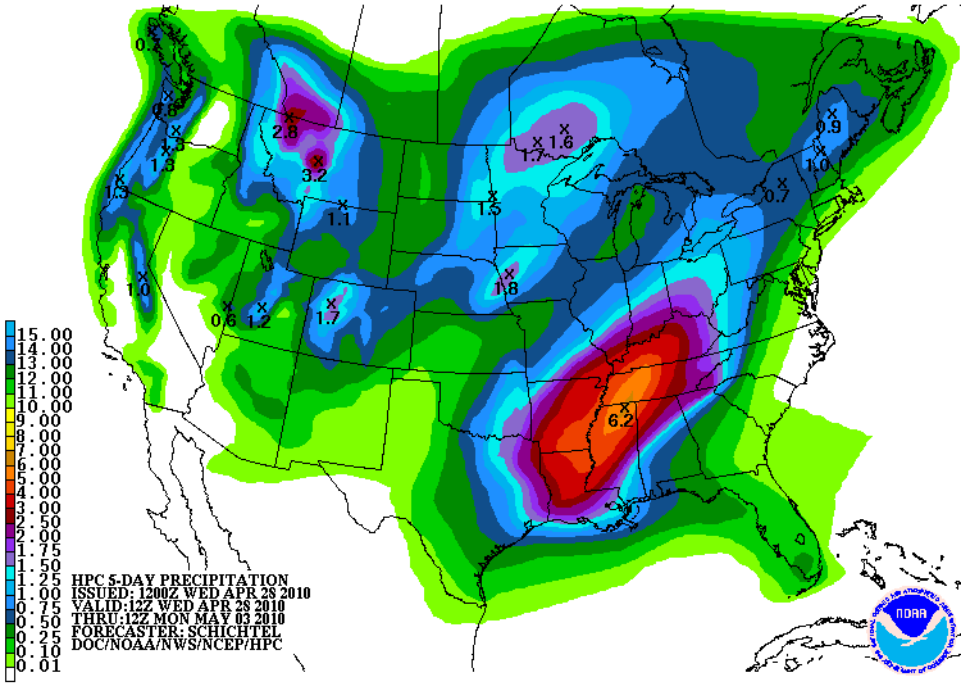

Figure 15: HPC 5-Day Precipitation issued 7:00 a.m., Wednesday, April 28; valid 7:00 a.m., April 28, to 7:00 a.m., May 3.

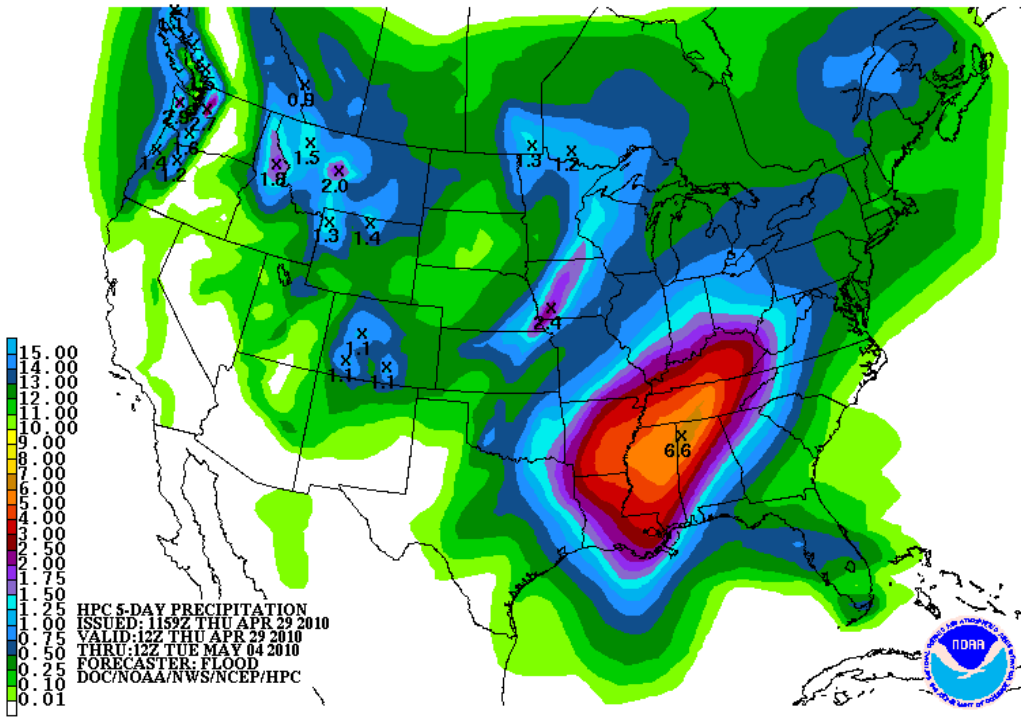

Figure 16: HPC 5-Day Precipitation issued 7:00 a.m., Thursday, April 29; valid 7:00 a.m., Thursday, April 29 to 7:00 a.m. Tuesday, May 4.

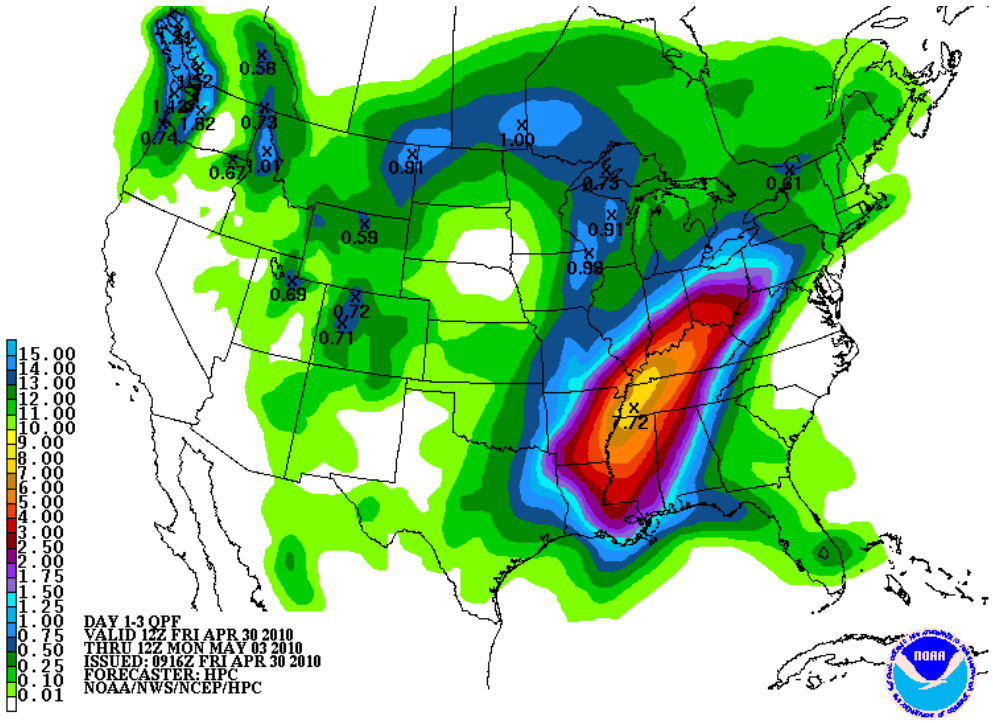

Figure 17: HPC 3-Day Quantitative Precipitation Forecasts (QPF) issued 4:16 a.m. Friday, April 30; valid 7:00 a.m., Friday, April 30 to 7:00 a.m., Monday, May 3.

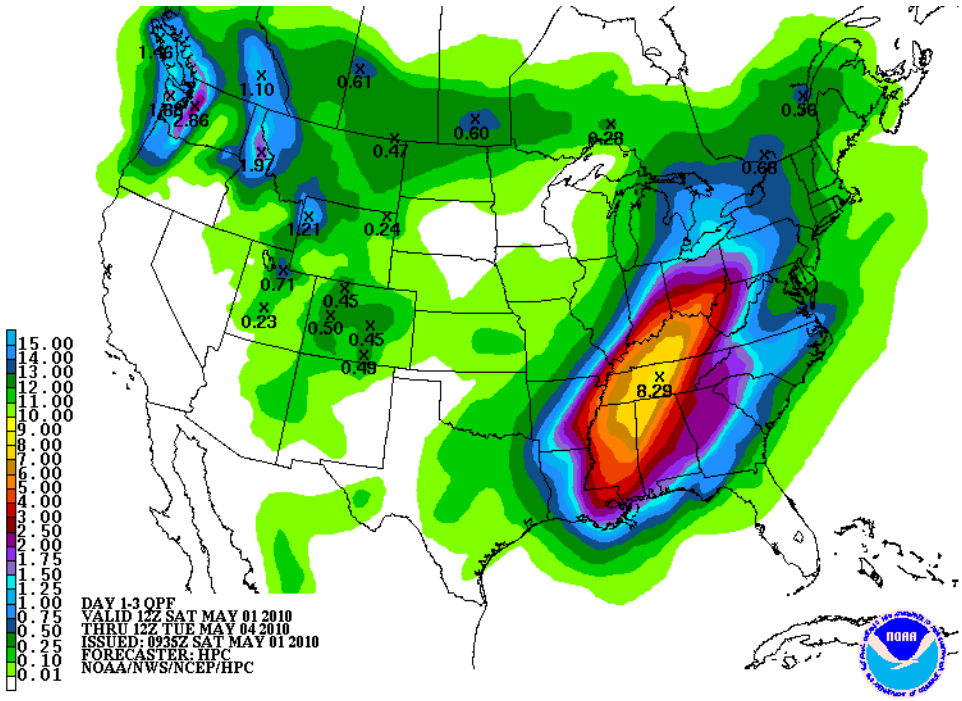

Figure 18: HPC 3-Day QPF issued 4:35 a.m. Saturday, May 1; valid 7:00 a.m., May 1 to 7:00 a.m., May 4. These amounts represent record breaking 2-day rainfall for Nashville and Middle Tennessee.

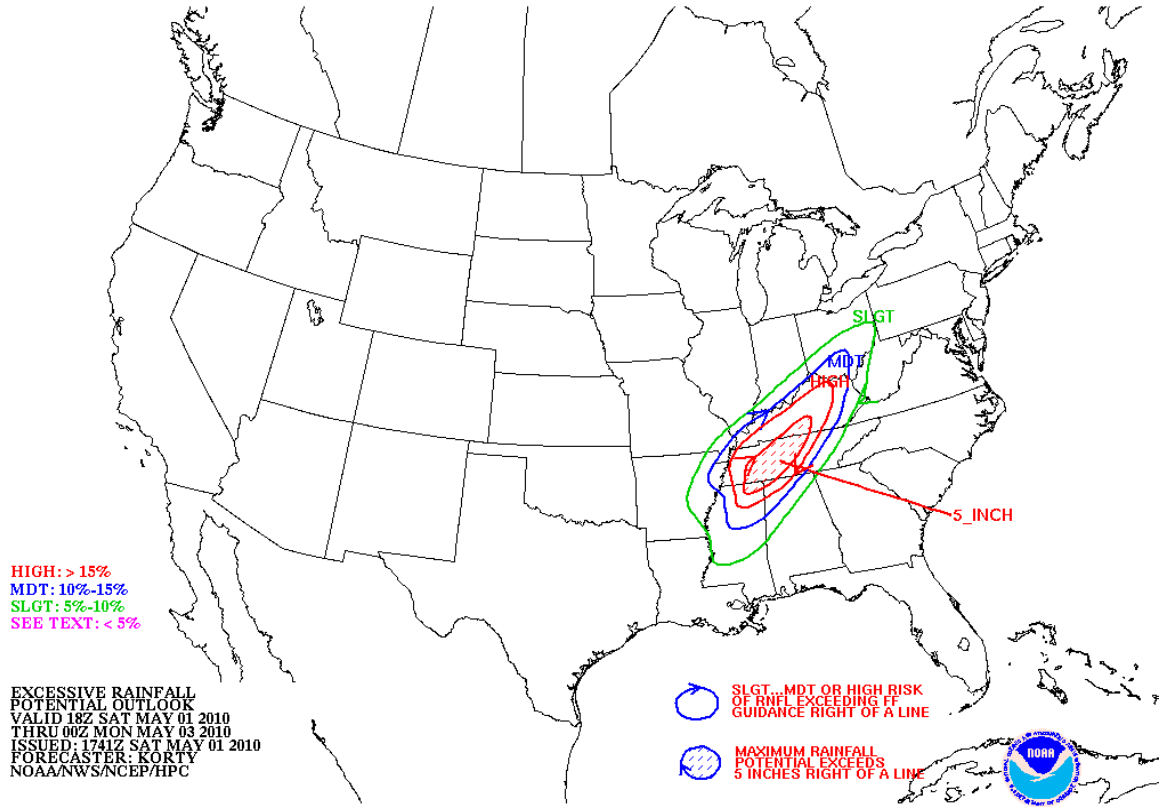

Figure 19: HPC Excessive Rainfall Potential Outlook issued 12:41 p.m., Saturday, May 1; valid 1:00 p.m., Saturday, May 1 to 7:00 p.m., Sunday, May 2.

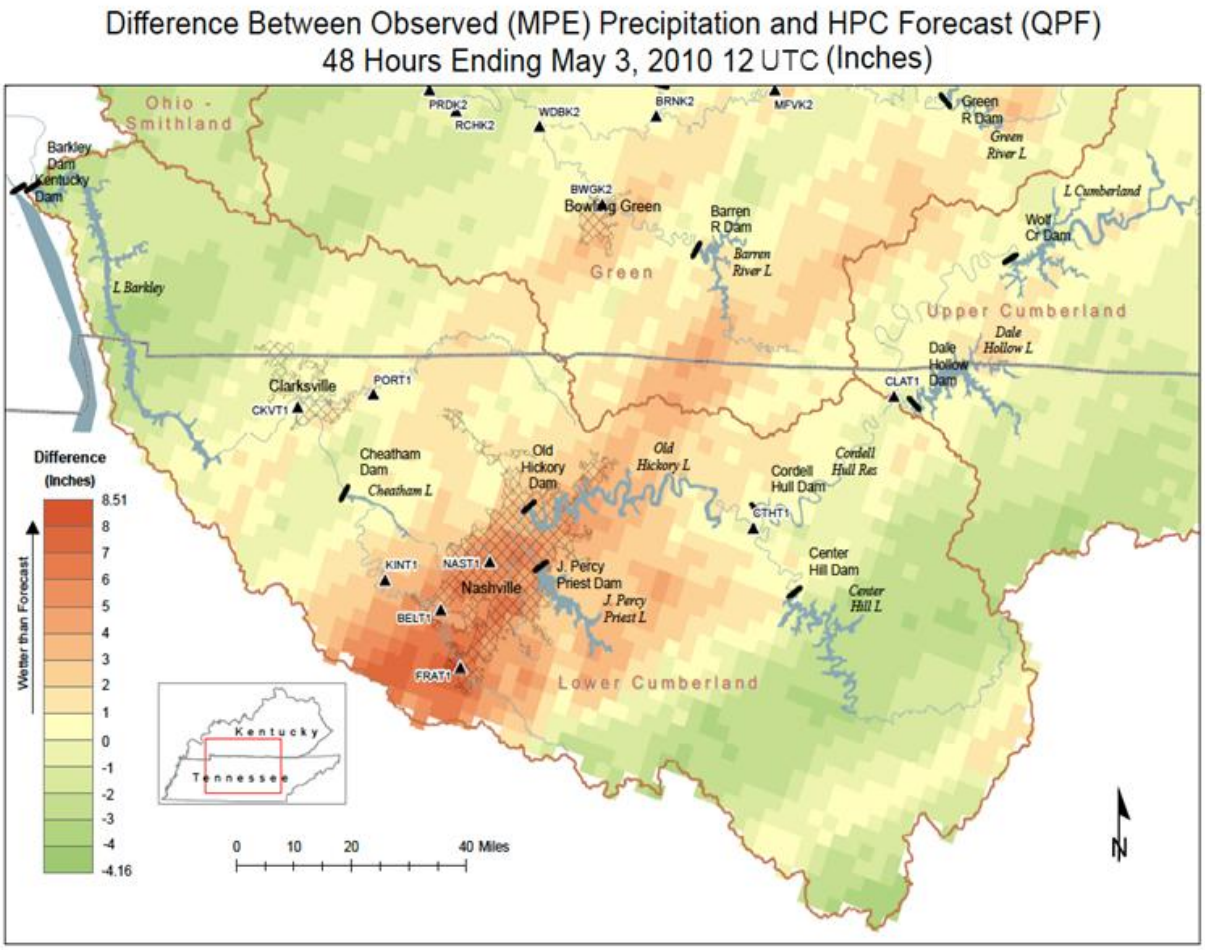

Figure 20: Error in the 48-hour HPC QPF. Storm totals in the Nashville region were under-predicted by 5-8 inches (red) but over-predicted elsewhere (green).

3.2. Communication/Collaboration with Partners

3.2.1. Interagency Communication (NWS – USACE – USGS)

The unprecedented flooding event in Nashville demanded an intensive interagency effort to forecast flooding and respond to the catastrophic impacts. The primary federal agency offices with responsibilities related to the Nashville flood event were the NWS OHRFC and WFO OHX offices, the USACE Great Lakes and Ohio River Division Office, Cincinnati (LRD), the USACE District Office, Nashville (LRN), and the TN USGS.

Based on a review of NWS interactions with partner agencies during this event, several primary themes emerged:

- NWS, USACE, and USGS staff exhibited dedication to their respective agency missions. All agency staffs were taxed with an extreme workload during this historic event.
- The working relationship between the OHRFC, OHX, USACE LRN, and TN USGS prior to this event was inadequate. Confusion over the current and projected operations of USACE Cumberland River projects, particularly at Old Hickory and Cordell Hull, compromised NWS forecasts. In addition, uncertainty in the ratings of Old Hickory and the USGS Nashville gages and in observed rainfall amounts further complicated the situation.

- There is no established, comprehensive framework for federal agencies involved with water forecasting to exchange data or leverage each agency's models/systems to allow for collaborative work.
- There is an urgent need to strengthen relationships between the agency partners, improve data sharing, and enhance coordination of operations and services.

The following provides historical context for the interagency relationship prior to this event:

- The Cumberland River at Nashville had not reached flood stage since 1984, in large part because of USACE reservoir operations throughout the Cumberland River Basin.
- There was limited participation, especially with respect to operational staff, between the OHRFC, USACE LRN, and TN USGS in tri-agency meetings over the past several years.
- USACE LRN left the Cooperative Stream Gage Program in May 2005, ending funding for the TN USGS to perform stream gage maintenance and support. Per post-event interviews, this action negatively impacted the USACE-USGS relationship in Tennessee and the overall tri-agency working relationship.

It should be noted that a successful ad hoc interagency collaborative effort between USACE LRD and the OHRFC was undertaken in the past couple of years, resulting in the Ohio River Community Model. These efforts were "grass roots" and required no additional agency funding to complete.

In the days leading up to the event, OHRFC communicated the potential for heavy rainfall and flooding. From Wednesday through Friday, April 28 – 30, OHRFC sent numerous emails to partners indicating the potential for heavy rainfall and flooding in the Lower Ohio, Cumberland and Tennessee Valleys through the weekend. USACE LRD acknowledged the emails, provided a specific point of contact for USACE LRN, and indicated they would forward emails on to USACE LRN. NWSChat was not used operationally by OHRFC prior to or during the flood event.

USACE LRN regularly produces daily reports detailing the latest observed and 5-day forecast releases for eight USACE Cumberland River projects. USACE release forecasts are based on observed 24-hour rainfall as of 6:00 a.m., but do not include forecast precipitation. This information is received daily at NWS offices via direct email and Standard Hydrologic Exchange Format (SHEF) encoded products. OHRFC's standard forecast practice uses data from these reports as the major input in determining flow and stage forecasts for Cumberland River locations (e.g., Carthage, Nashville, and Clarksville). The daily reports were updated and received by the OHRFC on the weekdays leading up to the event, including Thursday and Friday, April 29-30; however, the reports containing the 5-day release forecasts were not sent from the USACE to OHRFC on Saturday or Sunday. According to the USACE, this was due to two different communication outages.

On Saturday morning, OHRFC issued official forecasts for Cumberland River locations, including Nashville. These forecasts were based on observed and forecast releases for USACE-operated projects from Friday morning, April 30. As a result, official forecasts reflected minimal rises at Cumberland River locations during the weekend. Around noon Saturday, May 1, spillway releases from Old Hickory were initiated in response to heavy rains and runoff from unregulated watersheds in the Cumberland River Basin.

Spillway gate changes at Old Hickory continued throughout Saturday as total discharges increased from 24,300 cfs at noon to 74,500 cfs by midnight. Spillway releases also began Saturday at Cordell Hull dam. None of the updated releases were communicated from the USACE LRN to OHRFC. Throughout the day and night Saturday, observed rises at Nashville and other Cumberland River locations far outpaced OHRFC forecasts. Since OHRFC utilized outdated USACE forecast releases as the main input to their forecast models, official forecasts did not reflect the rapidly changing conditions on the Cumberland River Saturday **(Figures 21-22).**

A break in the heavy rainfall occurred Saturday evening into early Sunday morning. During this time, staff at both the OHRFC and USACE LRN noted the possibility for significant flooding at Nashville. Saturday evening, USACE LRN sent an internal email discussing the potential flood threat for Nashville. The email stated, "*If we get the rain on Sunday that is being forecast by the NWS, the current event could exceed what was observed in 1984*" (i.e., 45.3 foot stage, the last time flooding occurred in Nashville). That email was not forwarded to the OHRFC by USACE LRD until 4:16 a.m., Sunday, May 2.

Late Saturday night into Sunday morning, OHRFC attempted to contact the USACE LRN several times to obtain updated information on Cumberland River projects. Phone calls were unanswered because USACE LRN was not staffed overnight. USACE stated that no phone messages were left on USACE LRN answering machines. OHRFC staff had phone numbers for USACE LRD Water Management staff but did not attempt to contact them so that USACE LRD could use other means to contact USACE LRN. OHRFC staff completed forecast model simulations without incorporating USACE release data. These model simulations indicated major flooding levels at Nashville **(see Figure 29 Section 3.3.2, *Event Operations, Products, and Services*)**.

OHRFC called USACE LRD on Sunday, May 2, at 7:15 a.m. to ask for updated project release projections for the Cumberland River and to ask how to contact USACE LRN. The OHRFC was told that USACE LRN staff would be in around 7:30 am. At 8:30 a.m., USACE LRD facilitated a conference call with OHRFC and USACE LRN. Discussion on the call covered QPF, current and forecast releases from the USACE Cumberland projects, and the OHRFC model simulations. Participants, however, *did not successfully resolve crucial discrepancies between divergent OHRFC outlooks for the Cumberland River at Nashville. These discrepancies are depicted in* ***Figures 29*** *and* ***30 in section 3.3.2.***

Figure 29 shows a forecast run that *relied on the NWS River Forecast System (NWSRFS), which includes the Joint Reservoir Regulation (RES-J) operation, to determine the releases* from Old Hickory Dam, rather than USACE-projected releases. The RES-J model recognized surcharged pool conditions during the event and essentially passed project inflows through Old Hickory. The predicted flow showed a *potential for major flooding levels at Nashville and was an accurate simulation of the flows that would occur.* This forecast accuracy argues that the OHRFC models (hydrologic and reservoir) combined with the rainfall forecasts were functioning properly.

In contrast, **Figure 30** shows the forecast *that incorporated the much lower USACE LRN* release projections *(100,000 cfs from Old Hickory)* that were conveyed during the 8:30 a.m. Sunday conference call. This forecast indicated that only moderate flood levels would be reached at Nashville, a significantly different outlook than that depicted in **Figure 29**.

During the 8:30 a.m. conference call, OHRFC and USACE LRN discussed the simulation (**Figure 29**) that predicted a river stage of approximately 54 feet. The discussion did not conclude with an understanding that operations essentially passing flow at Old Hickory at the core of the simulation were more realistic than using USACE LRN projected outflows. Ultimately, OHRFC used the simulations based on USACE LRN projected outflows, which adheres to their standard operating procedure.

At 9:39 a.m. Sunday, May 2, using the USACE release projections described above, OHRFC issued an updated forecast for Nashville. The forecast was for a crest of 41.9 feet to occur at 7:00 p.m. Sunday evening, just below "moderate" flooding and 3.1 feet below "major" flooding. Heavy rainfall had already begun on Sunday morning, and at the time of the forecast the Cumberland River level at Nashville was nearly 40 feet. At 10:00 a.m. the USACE began increasing spillway releases at Old Hickory Dam due to rapidly rising lake levels. Releases from Old Hickory increased from 80,300 cfs at 10:00 a.m. to 123,600 cfs by 1:00 pm. As a result of the rainfall and dam releases, observed rises at Nashville far outpaced the stage forecast, and the forecast crest of 41.9 feet was exceeded by 11:30 a.m., less than 2 hours after it was issued.

Between the 8:30 a.m. Sunday conference call and the next planned call at 1:30 p.m., no communication occurred between the USACE and NWS. In addition, a communication line break caused a network outage at USACE LRN from 9:50 a.m. to 8:05 p.m. on Sunday. This outage cut off transmission of project data, which impaired the ability of USACE LRN to quickly analyze and respond to changing conditions during a critical part of this flood event.

At 1:30 p.m. on Sunday, USACE LRD facilitated a second conference call with OHRFC and USACE LRN. USACE LRN indicated that current releases from Old Hickory at 124,000 cfs would be rising to 130,000 cfs immediately and possibly to 140,000 cfs by 2:00 p.m. As in the earlier teleconference, the interaction was limited, especially with regard to the uncertainty in project inflows/USACE operations and the resulting impacts on OHRFC forecasts and flood stages at Nashville. Specifically, the conference call did not conclude with a mutual understanding that Old Hickory reservoir operations would essentially pass inflows later in the day to prevent lake levels from overtopping dam structures. In addition, no plan was made to elevate the frequency of communication between the NWS and the USACE as the flooding impacts increased.

Shortly after the 1:30 p.m. conference call, the USACE initiated more aggressive gate changes at Old Hickory to keep the lake level from overtopping the project lock wall. Over the next few hours, releases at Old Hickory were increased from 123,600 cfs at 1:00 p.m. to 212,260 cfs by 6:00 p.m. (**Figure 21**); however, there was no update to the stage forecast at Nashville until 3:37 p.m., at which point the observed stage had surpassed "moderate flooding" and was only 0.4 feet below "major flooding." Note that releases of over 212,000 cfs had never occurred at Old Hickory, and that value well exceeded the previous release record of 165,500 cfs set in March 1975. The 212,260 cfs release value was off the rating table. Record releases were set at the Cumberland River lock and dam projects of Cordell Hull, Cheatham, and Barkley as well.

At 4:43 p.m., Sunday, May 2, the first communication since 1:30 p.m. occurred between the USACE and NWS when WFO OHX phoned USACE LRN to inquire about updated releases. WFO OHX was given release data of 150,000 cfs; however, actual releases had topped 200,000 cfs by this time. OHX phoned USACE LRN again at 7:50 pm. The update provided to OHX was based on an *estimate* of the dam release at Old Hickory at the time the gate rating curve was exceeded (several hours earlier), and was not clearly conveyed to OHX by USACE LRN, or

clearly understood by OHX. This misunderstanding resulted in inaccurate release data (150,000 cfs) being passed from OHX to OHRFC around 8:00 p.m. These data were used in OHRFC forecasts until the next communication with USACE LRN, around 11:00 pm. As a result, by 8:15 p.m., Sunday, observed rises at Nashville were again outpacing the latest official forecast; the river exceeded the forecast crest of 48.0 feet.

Beginning very late Sunday night, the OHRFC and USACE LRN initiated a more timely and effective coordination of flow conditions and release forecasts for USACE projects on the Cumberland River. This improved coordination continued through the next week and resulted in more accurate forecasts as Cumberland River locations approached their crests.

An example of the impacts of inadequate interagency communications is evident in a comparison of the OHRFC forecasts at *regulated* (controlled) versus *unregulated* (uncontrolled*)* river locations during this event. The forecasts at *regulated* locations (where USACE project release data were used) were notably *less accurate* than the forecasts at *unregulated* locations (where USACE release data was not required). A comparison of an unregulated forecast location, the Red River at Port Royal, TN (**Figure 23**), with the regulated Nashville, TN location (**Figure 21**), and another regulated location upstream, Carthage, TN (downstream of Cordell Hull dam (**Figure 24**), illustrates the challenge faced by OHRFC forecasters in trying to incorporate project release information from USACE during this event.

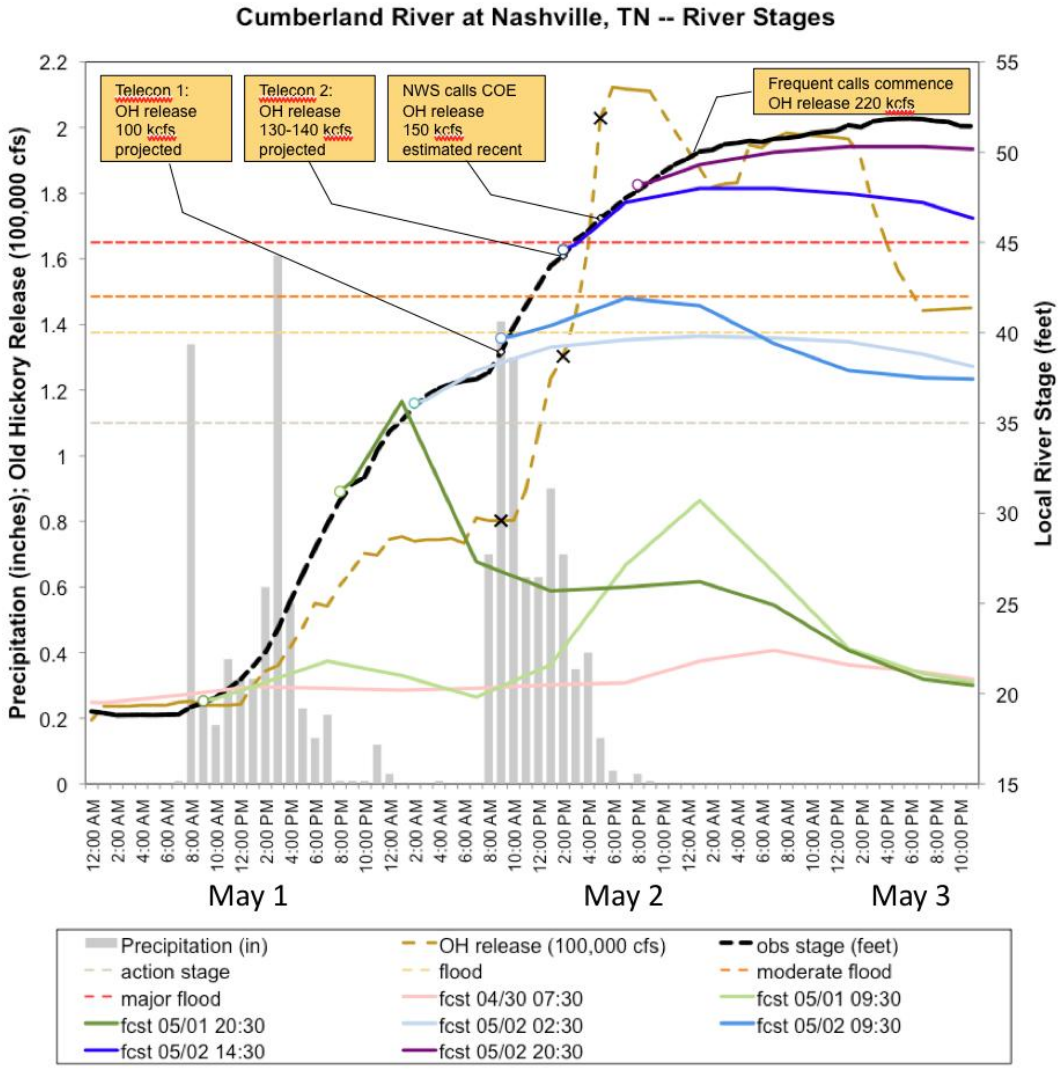

Figure 21: Cumberland River at Nashville; a comparison of river forecasts, observed river stages, Old Hickory releases, and *communicated* Old Hickory releases. Black **X** symbols denote actual Old Hickory releases at the approximate times of communication between USACE LRN and OHRFC on Sunday, May 2.

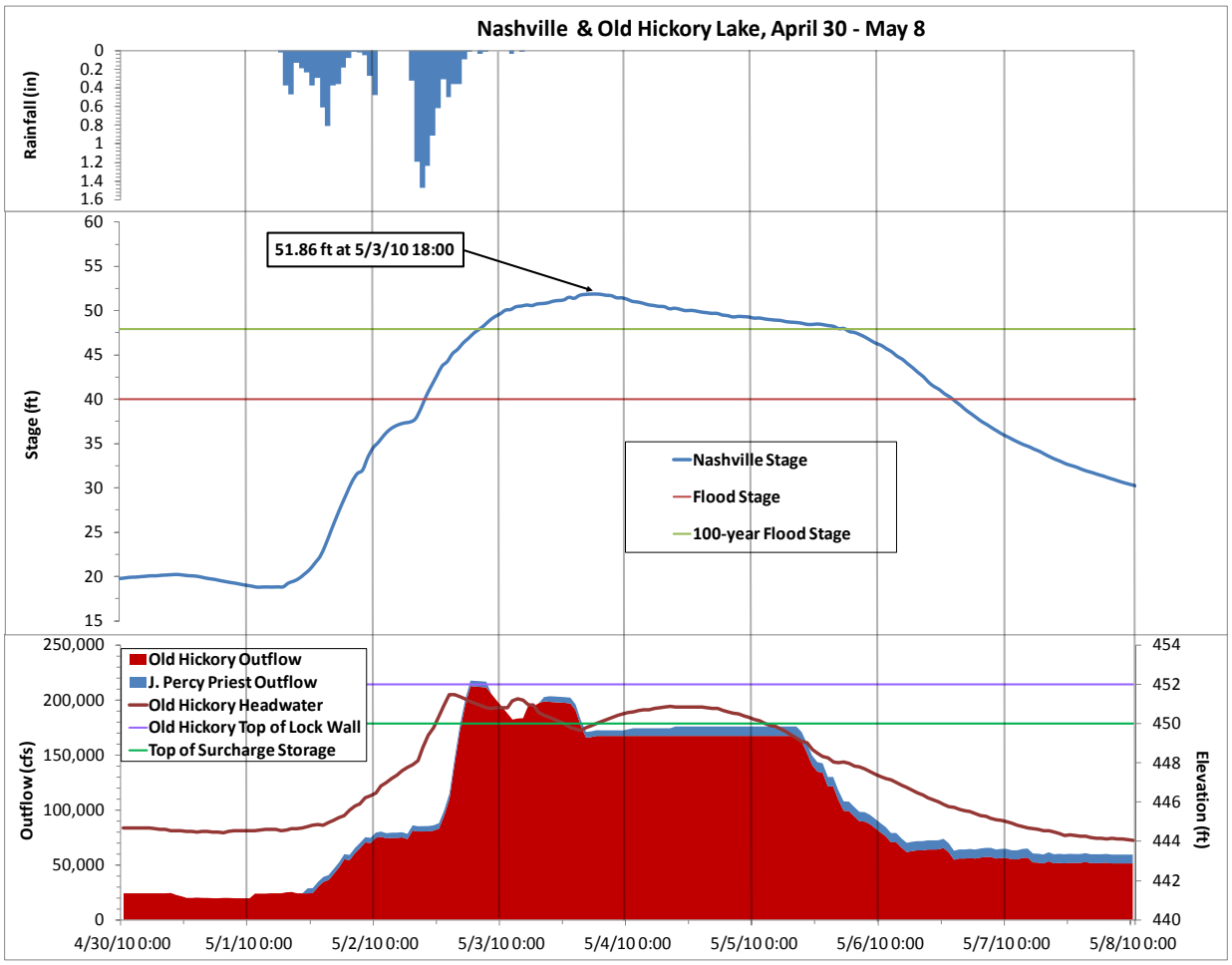

Figure 22: Cumberland River at Nashville observed river levels, Old Hickory and Percy Priest Outflow, and rainfall at Nashville. Graphic used with permission from USACE (2010). *May 2010 Nashville Flood Event After-Action Report, page 129.*

Table 4: Timeline of Critical Communications between OHRFC – WFO OHX – USACE
May 1 - 3, 2010

	CDT	From	To	Description
1-May	10:00pm	OHRFC	LRN	No Answer
2-May	midnight	OHRFC	OHX	Cumberland at Nashville will probably make Flood Stage
2-May	2:16am	OHX		Nashville forecast "27.3"; current stage "35.4"
2-May	4:16am	LRD	OHRFC	relays the 1-May, 7:08pm LRN email (read @ 7am)
2-May	6:36am	OHX		Flood Advisory: Nashville fcst 39.8 ft (used 110 kcfs; actual est 78 kcfs)
2-May	7:10am	OHRFC	LRN	Called but no answer
2-May	7:15am	OHRFC	LRD	told OHRFC that LRN in ~ 730am, OHRFC said Nashville could go to 54'
2-May	8:12am	OHX	OHRFC	Coordination
2-May	8:30am	LRD	OHRFC	Also LRN; OHRFC reiterated 54 ft at Nashville using reservoir simulation
2-May	9:00am	OHRFC	OHX	41.9 ft forecast at Nashville
2-May	9:50am	OHX		Flood Warning: Nashville fcst 41.9' (used 104 kcfs; actual est 80 kcfs)
2-May	10:43am	OHX	OHRFC	Coordination
2-May	10:46am	OHX	OHRFC	USGS flow measurement at Kingston/Bellevue gage OTS
2-May	11:18am	OHX		Nashville forecast 41.9' (used 104 kcfs; actual est 95 kcfs)
2-May	1:30pm	LRD	OHRFC	Conference Call; LRN said 124 kcfs, possibly to 130-140 kcfs
2-May	2:30pm	LRD	PAH	high releases from Barkley Dam
2-May	4:19pm	OHX		Nashville forecast 48' (used 141 kcfs; actual est 176 kcfs)
2-May	4:43pm	OHX	LRN	relayed 4:19pm fcst of 48'; LRN "fairly confident they can hold 150 kcfs"
2-May	6:00pm	OHX	OHRFC	USGS Bellevue manual observation 33.23 ft and steady
2-May	6:28pm	OHX		Nashville forecast 48' (used 141 kcfs; actual est 212 kcfs)
2-May	7:43pm	OHX	LRN	OEM had question about 2-3' rises on Cumberland
2-May	7:50pm	LRN	OHX	Percy Priest 5-10 kcfs; O.H. @ 150 kcfs
2-May	8:04pm	OHX	OHRFC	passed along info about Percy and O.H.
2-May	10:00pm	OHX		Nashville forecast 50.3' (used 151 kcfs; actual 205 kcfs)
2-May	10:59pm	OHRFC	OHX	called SH - told no updates from LRN; Nashville sandbagging not working
2-May	11:00pm	OHRFC	LRN	"sitn from bad to very serious";was told to estimate O.H. At 222 kcfs
3-May	12:20am	LRN	OHRFC	Conf O.H. At 220 kcfs; going no lower than 175 kcfs; lowered by 5 kcfs/hr
3-May	1:00am	OHRFC	OHX	Coordinated update Carthage from 43 ft. to 39 ft.
3-May	2:45am	OHRFC	OHX	Coordinated 51.5 ft at Nashville
3-May	4:02am	OHX		Nashville forecast 51.5' (used 181 kcfs; actual est 184 kcfs)
3-May	7:25am	OHX		Nashville forecast 51.5' (used 181 kcfs; actual est 197 kcfs)
3-May	8:30am	LRD	OHRFC	Conf Call also w/LRN & OHX; 51.5 ft at Nashville
3-May	12:20pm	LRN	OHRFC	Old Hickory releases lowered
3-May	12:30pm	OHRFC	LRN	Conference Call w/ OHX and OEM
3-May	1:30pm	LRD	OHRFC	Conf Call with OHX and LRN – 52 ft at Nashville
3-May	1:45pm	OHRFC	OEM	Conf call with TEMA, OEM, LRD, OHX re: 52 ft
3-May	2:30pm	OHRFC	LRN	Can you use Percy Priest to hold 52 ft at Nashville?
3-May	3:42pm	OHX		Nashville forecast 52' (used 190 kcfs; actual est 169 kcfs)
3-May	6:00pm			Cumberland at Nashville crests at 51.86 feet (est 150 kcfs)
3-May	6:30pm	OHRFC	LRN	Conference Call
3-May	8:19pm	OHX	OHRFC	Coordination
3-May	8:25pm	OHX	LRN	Coordination

"at Nashville" refers to Cumberland River Forecast; ### kcfs refers to Old Hickory Dam releases

*Communications extracted from logs and information provided by NWS offices and USACE timeline

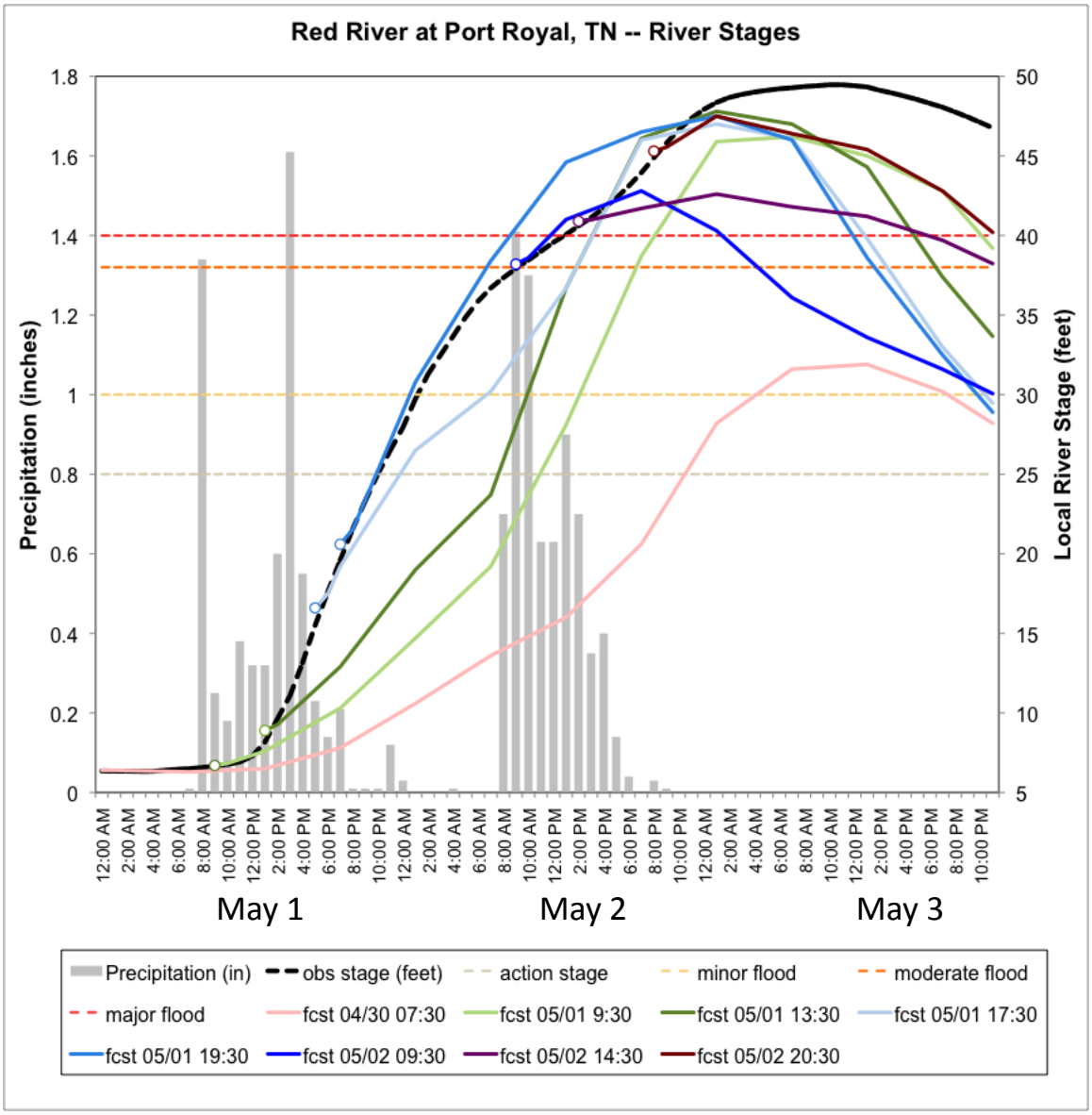

Figure 23: Observed and forecast stages at Red River at Port Royal, TN, an *unregulated* (uncontrolled) drainage basin near Nashville. Precipitation at Nashville, TN, is also shown. *Note the comparative accuracy of this forecast versus those at regulated locations.*

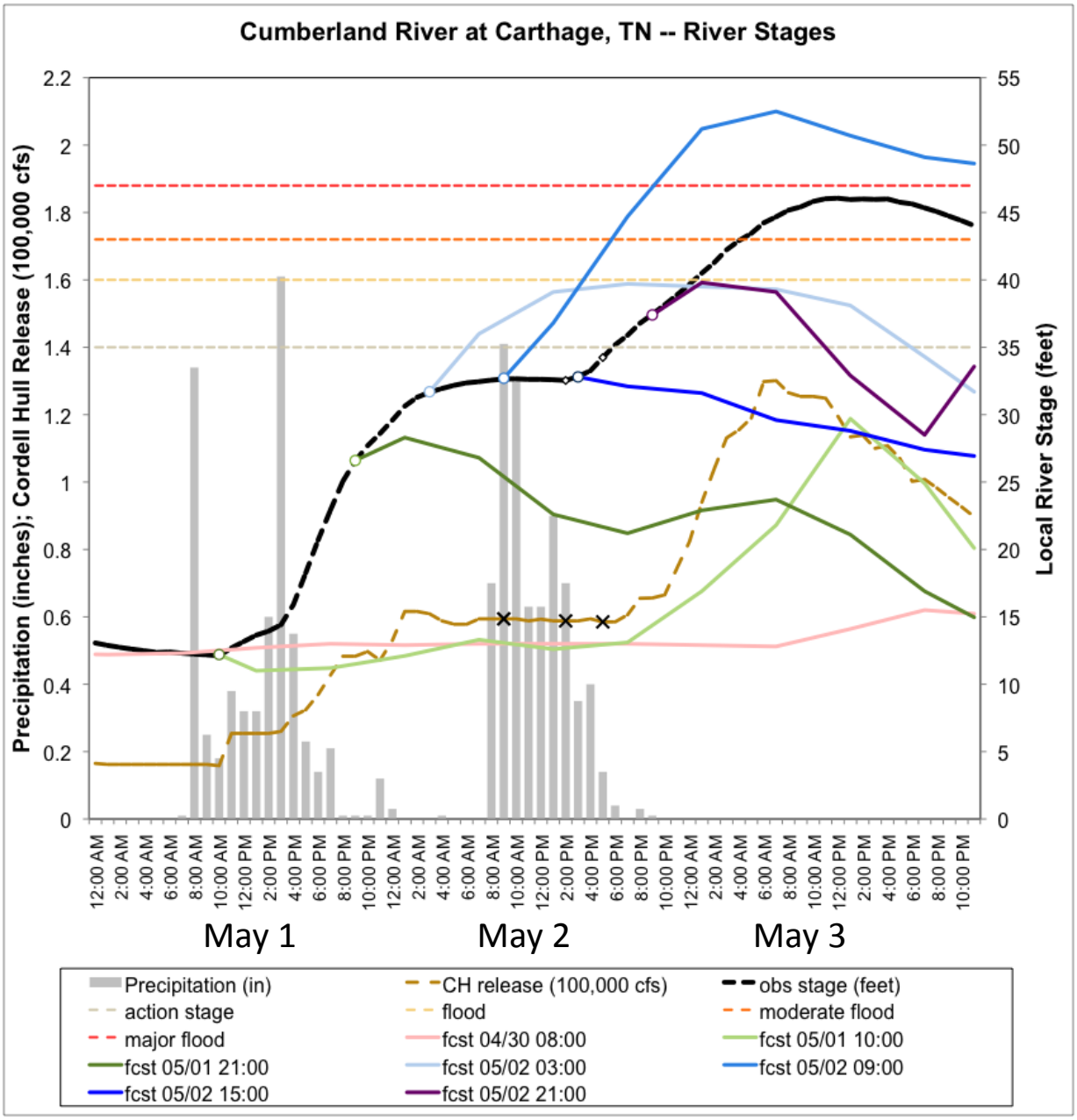

Figure 24: Observed and forecast stages at the Cumberland River at Carthage, TN, a regulated (controlled) drainage basin upstream of Nashville (and downstream of Cordell Hull dam). Precipitation at Nashville, TN, and project releases from Cordell Hull (black **X**) are shown. **X**s denote communicated releases between the NWS and USACE on Sunday. *Note the comparative inaccuracy of this forecast versus those at unregulated locations.*

Fact: A tri-agency (NWS, USACE, USGS) consortium, "Fusion Team" (**Appendix B**), was formed in response to the 2008 upper Mississippi River flood. The consortium's goal is to increase collaboration among the three agencies during "flood fights." The Fusion Team was expanded to address collaboration issues uncovered during the Kentucky and Tennessee floods of May 1-2, 2010, the subject of this Service Assessment. The USACE LRD (already a member of

the Fusion Team), NWS Eastern Region, and the USGS are represented on the expanded Tri-Agency Fusion Team.

Fact: The USACE began increasing spillway releases at Old Hickory Dam at 10:00 a.m., Sunday due to rapidly rising lake levels. Releases from Old Hickory increased from 80,300 cfs at 10:00 a.m., to 123,600 cfs at 1:00 p.m. During this time, none of the dam release updates were communicated between the USACE and NWS.

Fact: Immediately after the 1:30 p.m., Sunday, conference call, the USACE began more aggressive gate changes at Old Hickory to keep the lake level from overtopping the project lock wall. Over the next few hours, releases at Old Hickory were increased from 123,600 cfs at 1:00 p.m. to 212,260 cfs at 6:00 p.m. No communication occurred between USACE and NWS until nearly 5:00 p.m. when releases topped 200,000 cfs.

Finding 1: Limited interactions among OHRFC, USACE LRN, and TN USGS prior to this historic flood contributed to a lack of understanding of each agency's operational procedures, forecast processes, and critical data needs. This led to a breakdown in effective interagency communication, especially on Sunday, May 2.

Recommendation 1: OHRFC management and operational staff should increase regular interactions and table-top exercises with USACE LRN and the TN USGS. These management and operational staff interactions should include defining interagency procedures and mutual data needs to optimize collaboration and effective operations/forecasting services during routine and extreme events.

Finding 2: Real-time exchange of critical data among agencies during this event was insufficient and limited. In the short term, additional automation of this critical data exchange would have enhanced the forecast process at OHRFC.

Recommendation 2: OHRFC should develop a list of data exchange processes that can be automated. The list should be provided to USACE and USGS. Candidates for automation should include updated headwater/tailwater conditions and real-time water release data for USACE projects.

Finding 3: There is no framework for the federal agencies involved with water forecasting to seamlessly exchange data, leverage each agency's models/systems, and work from a common operating picture.

Recommendation 3: Federal water agencies should accelerate efforts to develop and implement technological advances and a framework that enables seamless data exchange and a common operating picture. The interagency Integrated Water Resources Science and Services (IWRSS) initiative is an appropriate framework to promote such enhanced collaboration.

3.2.2. Communication with Local Partners, Customers, and Public

WFO Nashville communicated with its partners, including EMs, media, and local officials, before, during, and after the event. In the days leading up to the event, information was passed through emails, webinar briefings, and phone calls. OHX sent email briefings to EMAs, FEMA Region IV, and the Tennessee Emergency Management Agency (TEMA) on April 30 and May 2. They conducted web briefings May 1 and May 3. As the event unfolded, communication expanded to include NWSChat, which proved valuable; a Channel 2 meteorologist said, "*It's been very helpful, we're pro-NWSChat*."

The team intervewed many residents of the Greater Nashville area. Regardless of their situations, they had similar stories and comments:

- All were watching television for information
- All understood that extreme amounts of rain had fallen
- All knew there was severe flooding on local streams and knew lives had been lost
- None related forecast stages on the Cumberland River to the threat at their homes
- None felt unsafe until local law enforcement announced the need to evacuate
- All stated that they had "no warning" despite NWS flood warnings that were scrolling continuously on TV

Fact: Residents interviewed in the neighborhoods of Greater Nashville impacted by flooding said that they could not relate forecast stages on the Cumberland River to the threat at their homes, and all perceived that they had "no warning."

Customers, including the Nashville Mayor's office, were trying to get a sense of the level of certainty the NWS had in its stage forecast for the Cumberland River at Nashville, especially on Sunday afternoon, May 2, when the river was at major flood stage and forecast to rise to 48 feet. The Service Hydrologist and the Nashville Mayor's office discussed the possibility of the river rising to 50 feet. The SH had included impacts in Nashville for the 50-foot level in flood statements for Sunday afternoon. Nashville Office of Emergency Management (OEM) and the Mayor's office discussed the 48-foot forecast with Gaylord Entertainment officials, owners of Opryland Hotel, who perceived that there was relatively high confidence that the river would not rise above 48 feet.

Fact: OHX briefed the Nashville Mayor's office and OEM Saturday evening, May 1, on the potential for much more rain Sunday. They briefed OEM on a 41.9 ft forecast for the Cumberland River at Nashville for Sunday morning, and coordinated on forecast changes throughout Sunday.

The NWS is limited to "impact statements" in flood-related text products, including warnings, for defining areas that will be impacted by flooding. These statements provide some useful information, but do not give the level of geographic detail needed by emergency management, local officials, or the public to take necessary actions to protect life and property. Nashville OEM stated, "*The forecast river level 'number' was meaningless to homeowners.*" TEMA stated, "*We need better flood maps and inundation maps.*"

The deficiency in geographically-relevant warning information is being addressed to show flood inundation levels at the neighborhood level. For a small number of locations, only a few dozen at present, inundation maps are generated for different river stage levels and displayed on

an interactive webpage, allowing users to query inundation maps by river stage (**Figure 25**). These maps can be used during a flood to link forecasted river levels to areas that are expected to be flooded, making forecasted river levels geographically relevant.

To meet this need, tri-agency collaboration on dynamic GIS-based flood inundation mapping should be expedited. Representative Cooper's staff said, "*We need…inundation maps showing what would be flooded at every height [water level] so a homeowner could go online and see if they were going to be flooded*."

Fact: TEMA officials stated that there was an urgent need for better flood maps and inundation mapping. Staff from Representative Cooper's and Senator Alexander's offices echoed that need. Business owners could not determine if their structures would be flooded, and the public did not know if their residences would be impacted. Emergency responders could not determine which roads were flooded and which could be safely used.

Finding 4: There is an urgent need for dynamic GIS-based flood inundation mapping that can be integrated into NWS watch and warning operations and made available to the public, partners and emergency management entities.

Recommendation 4: Tri-agency collaboration on development and implementation of dynamic GIS-based flood inundation mapping should be expedited as part of the interagency Integrated Water Resources Science and Services (IWRSS) initiative.

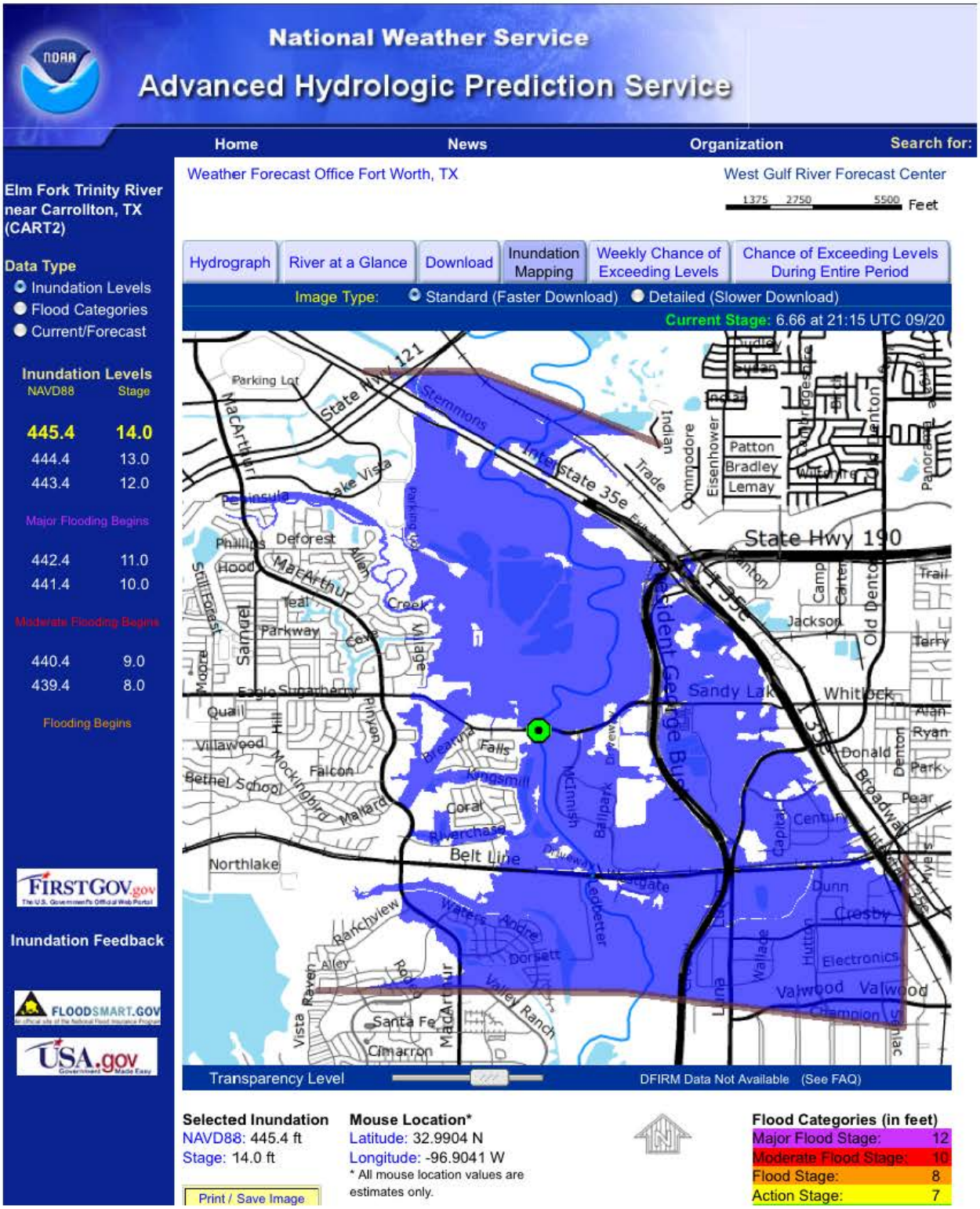

Figure 25: Example of an AHPS interactive flood inundation mapping display: http://water.weather.gov/ahps2/inundation/inundation.php?wfo=fwd&gage=cart2

3.3. Ohio River Forecast Center (OHRFC)

3.3.1. Pre-Event (OHRFC)

During the week before the event, OHRFC identified a significant flood threat for the upcoming weekend. Beginning April 28, OHRFC communicated with key partners using conference calls, internal and external web pages, emails, alert messages, and phone calls. The OHRFC used direct phone calls to the USACE, to the TN USGS (via WFO OHX), and to affected WFOs throughout this event. The conference calls, however, did not include LRN, the TN USGS, and affected WFOs. OHRFC used an internal chat room for communicating with WFOs. On Thursday, April 29, the OHRFC adopted an expanded staffing plan, including 24-hour coverage for the upcoming weekend. The office was proactive in releasing guidance products containing forecasts of the heaviest rainfall and associated stream flow predictions.

An example of pre-event communication was the issuance of Hydrometeorological Discussions (HMDs), which were available to partners and visitors to the OHRFC website. The April 28 HMD indicated, "…lofty rainfall totals through the weekend, particularly along and south of the Ohio River" and described an increasing flood threat at several locations. The next day, the HMD stated that "On Friday night and through the weekend…strong storms and heavy rains are expected with the greatest rainfall amounts along and south of the Ohio River" and that "flooding is expected into the weekend."

To quantify and provide hydrologic forecast uncertainty information to key partners, the OHRFC implemented the Meteorological Model-Based Ensemble Forecast System (MMEFS). This initiative responded to specific recommendations made in the Service Assessment of the June 2008 Central United States Flooding, as well as to the overarching recommendations of the 2006 National Research Council report entitled, "Completing the Forecast."

MMEFS incorporates all the models and procedures, including the RES-J operation, which the NWSRFS uses to produce operational forecasts. Two primary differences distinguish MMEFS from the official operational OHRFC forecast process: first, it does not use real-time forecaster modifications to models and data, e.g., manual input of reservoir outflows; and, second, it uses numerical weather prediction ensemble forecasts rather than deterministic weather forecasts. Specifically, MMEFS uses the precipitation and temperature fields from the Global Ensemble Forecast System (GEFS) and Short Range Ensemble Forecast (SREF) systems.

Although the MMEFS forecasts were considered experimental at the time of the flood, OHRFC provided the probabilistic forecast information to NWS field offices and external partners before and during the event. The probabilistic information from MMEFS also was used in the Significant River Flood Outlook product (**Figure 26**) and the Hydrologic Alert Message (HAM), an email service initiated for the first time during the May 2010 flood event by the OHRFC. The HAM was implemented as a result of a Best Practice from the 2009 NWS Southeast Floods Service Assessment.

HAM emails highlighting the risk of flooding were sent to the OHRFC Customer Advisory Board, composed of 19 key partners, including TEMA and the USACE LRD. HAM emails can be auto-generated with standard text phrasing, or manually generated with free-form text. Several recipients were asked about their usefulness. Most appreciated getting these reminders, but some

critized what appeared to be standard text phrasing telling them to be alert for a future flood risk when impacts were already occurring.

Fact: Friday, April 30, the OHRFC issued a Significant River Flood Outlook indicating a possibility of moderate to major flooding beginning Saturday, May 1, in Middle Tennessee, including Greater Nashville **(Figure 26).**

Fact: Friday, April 30, at 12:39 p.m., a HAM indicating that "at least moderate flooding was likely in Kentucky and Tennessee" was sent to all OHRFC partners via email.

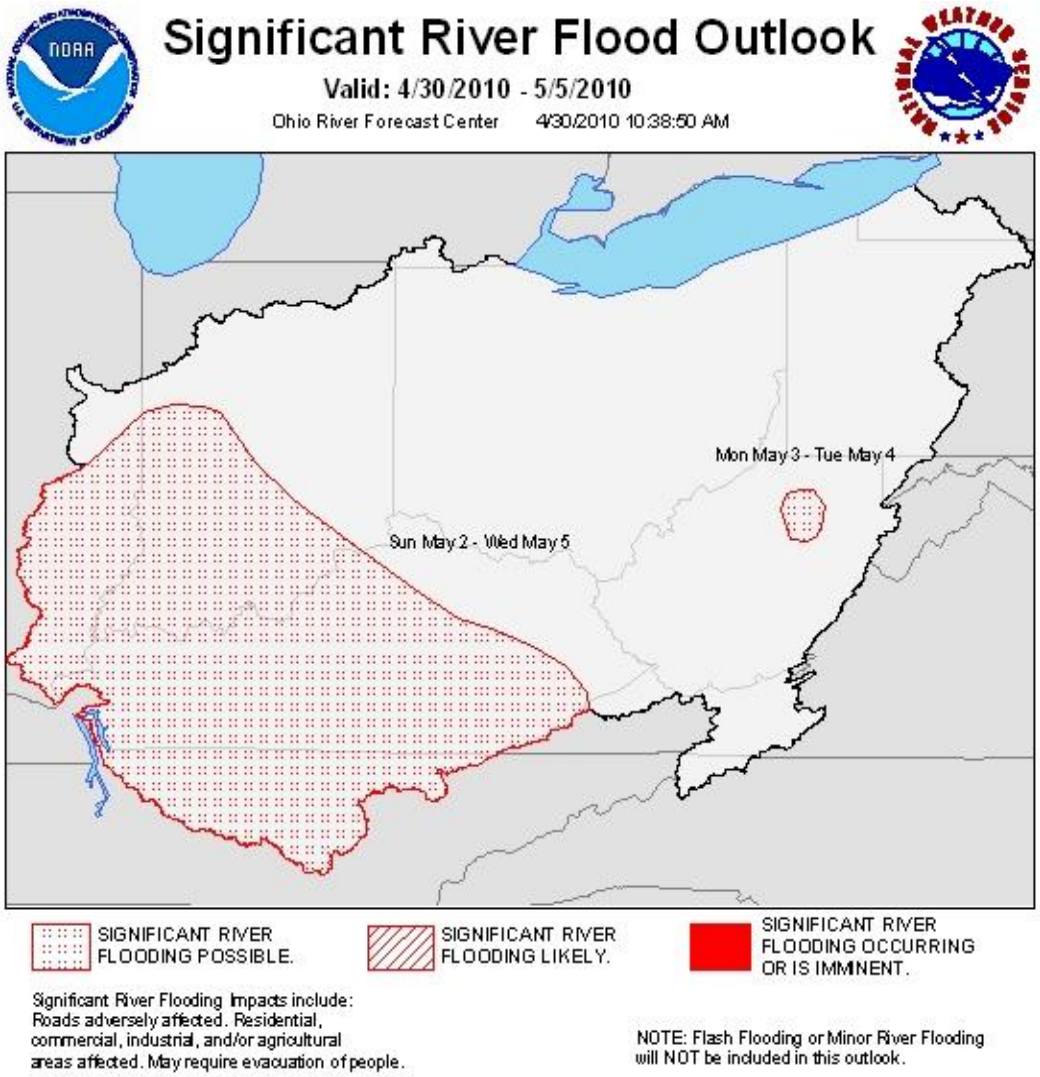

Figure 26: OHRFC Significant River Flood Outlook issued at 10:38 a.m., Friday, April 30; valid through Wednesday, May 5. Hatched area outlines significant river flooding possible.

Fact: On Friday afternoon, April 30, when the official OHRFC forecast indicated no flooding at Nashville (forecast was 17 feet below flood stage), the MMEFS predicted an approximate 50 percent risk of flooding and 15 percent risk of major flooding at Nashville **(Figure 27)**.

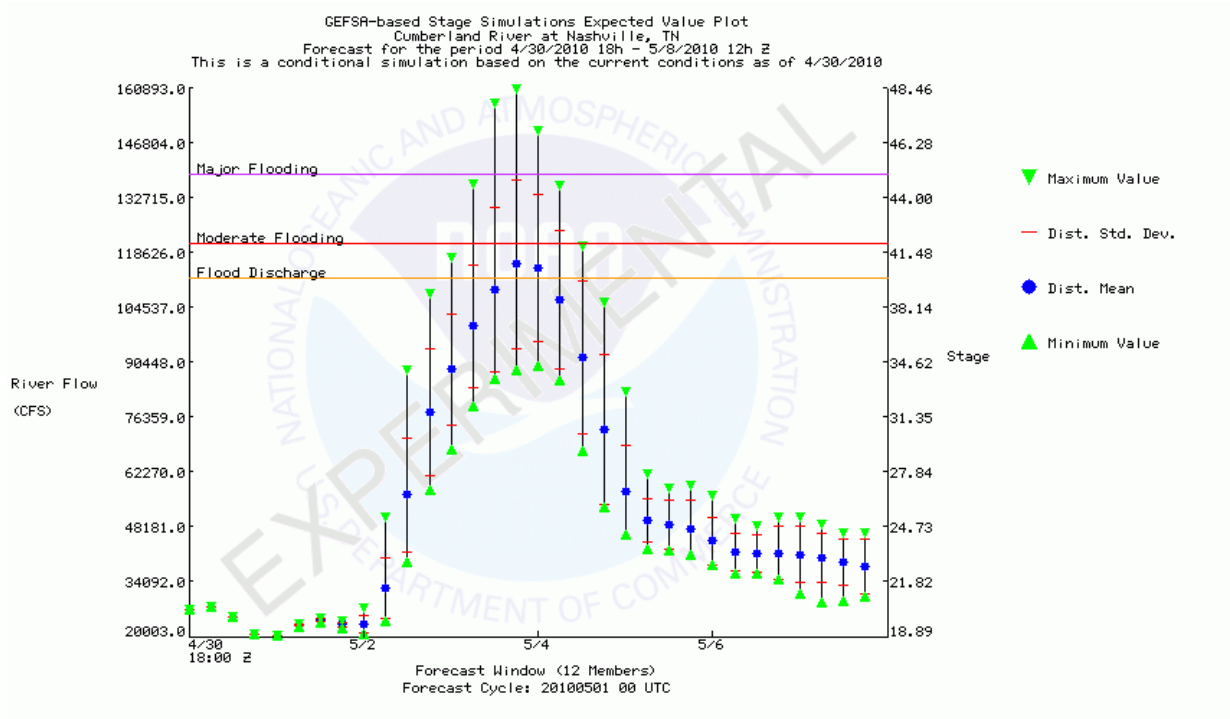

Figure 27: Friday afternoon, April 30, MMEFS GEFS run, predicting an approximate 50 percent risk of flooding and 15 percent risk of major flooding at Nashville.

On Saturday morning, May 1, MMEFS results continued to show a significant risk of flooding at Cumberland River locations, including Nashville. The MMEFS forecasts on Friday and Saturday showed a high risk of flooding for two reasons: first, incorporation of QPF from the SREF and GEFS models; and second, an internal reservoir operations model that did not rely on USACE reservoir release projections. Email from the OHRFC to affected WFOs and USACE LRD on Saturday morning regarding these forecasts stated the following:

> *Please take the attached (MMEFS) results seriously. The model trends have been consistent. We are looking at significant potential for Major Flooding. The OHRFC will be staffed 24-hrs from now through Monday morning, with increased weekend day and evening staffing as well.*

Before and during the event, the OHRFC shared the experimental probabilistic analyses of flood risk to help alert WFOs and the USACE of significant potential for major flooding in their service areas. The OHRFC extended the lead time and gravity of its hydrologic alert messages by placing greater emphasis on QPF and including the results of experimental forecast tools. After Saturday morning, MMEFS results graphics continued to be sent via automatic emailing to the WFOs and partners, but without additional forecaster comment.

Best Practice 1: The MMEFS results, HAMs, and the Significant River Flood Outlook products were used by OHRFC as a way to alert partners such as USACE, USGS, and FEMA that significant flooding was possible.

Finding 5: USACE district offices in Huntington, WV and Pittsburgh, PA and LRD had taken the necessary training to allow them access to the MMEFS results. USACE district offices in Louisville (LRL) and LRN and TEMA, had not taken the training and therefore had no access to

the MMEFS forecasts during this flood event.

Recommendation 5: The OHRFC should provide onsite MMEFS training to relevant partners including the USACE, USGS, and other appropriate state and local agencies.

Standard operating procedure at the OHRFC is to use only 24 hours of QPF in operational river forecasting due to concerns about uncertainty in location, timing, and magnitude of forecasted precipitation and effects in hydrologic forecasts. On Friday morning, April 30, OHRFC forecasters were concerned about potential river flooding across the Lower Ohio Valley. In this case, use of the standard QPF duration (24 hours) in operational river forecasts would have underestimated potential flood risks.

To address use of QPF beyond the standard period, OHRFC polled 12 WFOs via 12Planet, an NWS internal chat forum. Three options were proposed for operational QPF during this event. OHRFC subsequently ran river forecast operations using 72-hours of QPF, with a 50 percent reduction to the HPC QPF for the latter 36 hours. River forecast guidance was issued based on this QPF configuration. In this case, the reduced 72-hour QPF lowered storm event totals in the Nashville area relative to the original totals forecasted by HPC.

As of Saturday morning, HPC QPF continued to underestimate weekend rainfall totals in areas *downstream* of the major USACE flood control projects and *upstream* of Nashville. Reductions applied to HPC QPF by RFC Hydrometeorological Analysis and Support (HAS) forecasters compounded this forecast error, leading to an underestimation of up to 10 inches in critical areas **(Figure 28)**.

Other issues in the application of QPF occurred. Standard operating procedures at OHRFC and many other RFCs dictate that the QPF model input is prepared at 12 UTC and 00 UTC. QPF input can be updated at 18 UTC and 06 UTC, although several OHRFC staff did not know QPF updates could be made at these interim times. By noon (17 UTC) Saturday, half of the 2-day QPF total for the weekend storms at Nashville had already been observed. The QPF model input could have been updated at 18 UTC to reflect incoming precipitation observations and forecasts.

Finding 6: Several OHRFC staff did not understand that river model updates could be made with 6 UTC and 18 UTC QPF data.

Recommendation 6: RFCs should update QPF input during 06 and 18 UTC model runs when river forecasts need to be updated to ensure the latest QPF is used in NWS hydrologic river modeling.

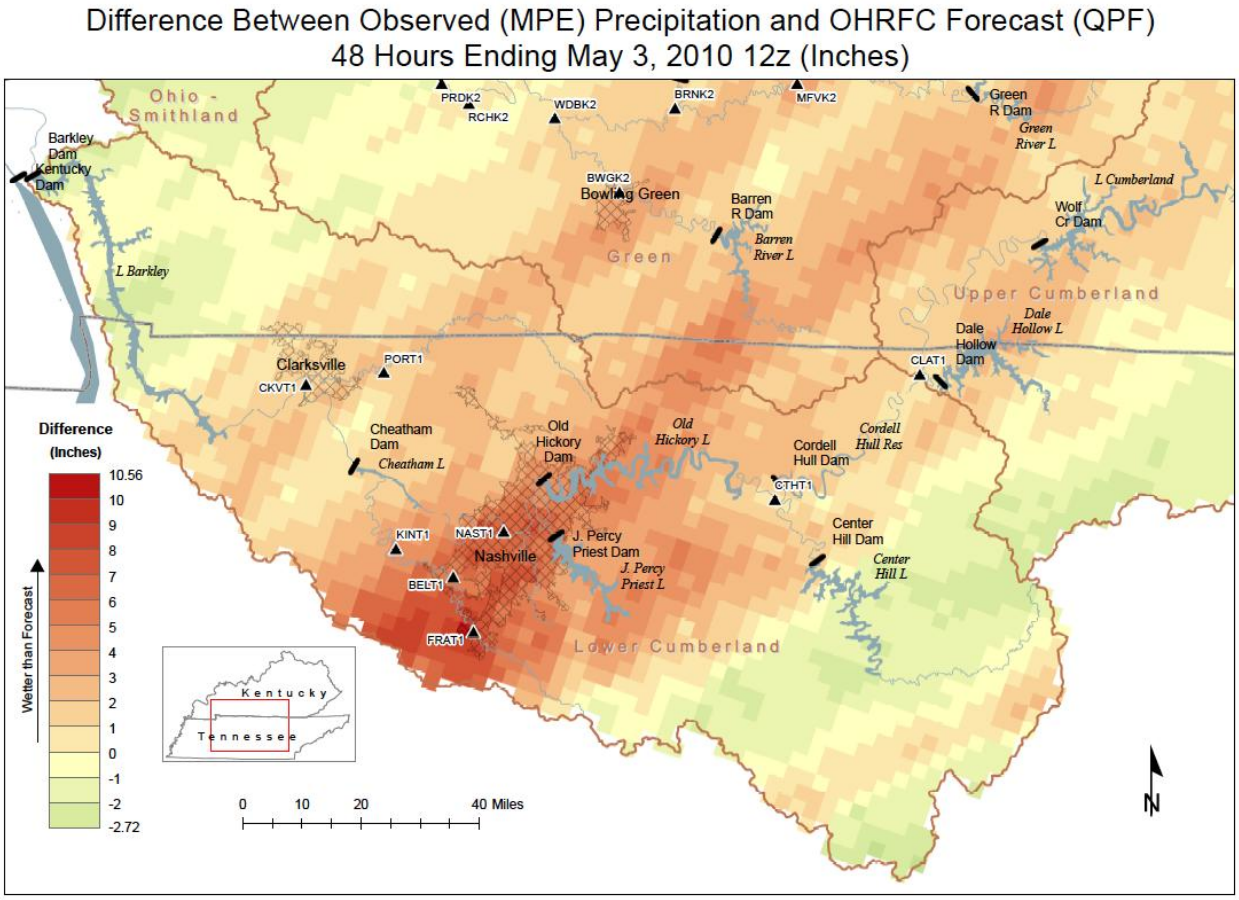

Figure 28: Errors in OHRFC 48-hour QPF from Saturday morning. Positive differences represent forecast underestimation.

OHRFC creates a HAS precipitation forecast using local forecaster expertise. This OHRFC operational QPF and the HPC QPF are both available on the OHRFC website. However, several customers and partners, including USACE, access rainfall graphics and text products directly from the HPC website versus the OHRFC website.

Fact: OHRFC reduced the 72-hr and 48-hr HPC QPF (issued Friday and Saturday, respectively), but increased the 24-hr HPC QPF issued Sunday. In this event, the reduced 72-hour HPC QPF lowered storm event totals in the Nashville area relative to the original totals forecasted by HPC, but increasing the QPF on Sunday improved the forecast at Nashville.

Finding 7: OHRFC consistently reduced the HPC QPF used in river forecast operations before the event on Friday and during this event on Saturday. Reducing QPF beyond 24 hours is a common practice at RFCs, due to uncertainty in extended periods. However, there was no coordination with HPC on these changes.

Recommendation 7: To increase communication between field offices and HPC before and during significant hydrological events, field offices should request, or HPC should initiate, HPC hosted conference calls with affected WFOs and RFCs. These calls should be modeled after those successfully used by NWS's Storm Prediction Center.

Fact: USACE LRN reviewed QPF for the Cumberland River Basin directly from the HPC website.

Fact: The OHRFC did not communicate details regarding its modified use of HPC QPF in river forecast models to external partners such as USACE.

Fact: Based on post-event interviews, USACE thought the forecast rainfall used in river forecast products issued by the WFOs and RFCs was the HPC QPF, when in fact, it was the modified OHRFC QPF.

Finding 8: Not all RFCs communicate how they are using QPF and observed rainfall, or Quantitative Precipitation Estimation (QPE), in their river forecast models with critical external partners such as the USACE and USGS.

Recommendation 8: RFCs should communicate in detail their use of QPF and QPE in generating river forecasts to the USACE and USGS and other critical partners. One possibility would be to provide this information on the Advanced Hydrological Prediction Service (AHPS) webpage.

3.3.2. Event Operations, Products, and Services (OHRFC)

During the flood event, the OHRFC produced many river forecasts to support WFO hydrologic operations. Forecasters also performed an analysis for a potential dam failure situation in southern Kentucky for WFO Louisville. River forecasting for flood conditions in southern portions of the Ohio River basin and in the Cumberland River Basin escalated on Saturday, May 1, and continued around the clock through the first week of May.

The rapidly evolving hydrometeorological situation of May 1-3 strained resources at the OHRFC, despite increased staffing for 24-hour operations. Forecast updates increased to several times per day as new information was received and rainfall observations exceeded expectations.

OHRFC was in a reactive mode over the weekend with respect to flooding on the Cumberland River at Nashville. Record-breaking rains over largely unregulated (uncontrolled) basins of the Cumberland River, inadequate communication with USACE LRN concerning releases from Old Hickory Dam, less than optimum staffing at critical times and an overall lack of heightened situational awareness resulted in operational staff not staying abreast of record and catastrophic flooding. As a result, the flood warnings for the Cumberland River at Nashville had negative lead times in initial forecasts for Flood Stage, Moderate Flood Stage, and Major Flood Stage.

Three primary conclusions emerged during the assessment of OHRFC operations:

- OHRFC staff exhibited dedication to the NWS mission. This historic event generated an extreme workload for an extended period of time. The staff worked diligently to meet the demands of river forecast operations.
- Inadequate staffing at times, specifically on Sunday, contributed to difficulties with Cumberland River forecasts. Additional staff was needed to maintain situational awareness and enhanced coordination and communication with WFOs and external partners. Staff augmentation would also have allowed for more frequent updates of river forecasts and critical, in-depth evaluation of observational data and assessment of

hydrologic model results.

- During a critical period, significant discrepancies were not resolved between OHRFC reservoir simulations and the standard OHRFC model forecasts (that incorporated USACE projected dam releases). These discrepancies were not thoroughly discussed with or understood by the USACE.

By extending its operations to 24-hour coverage, the OHRFC demonstrated awareness that a serious flood event could develop over the weekend. Despite this increase, several operational decisions/actions over the weekend indicated inadequate staffing, especially during a critical period on Sunday, and left staff unprepared to deal effectively with a rapidly changing and catastrophic flood scenario:

- The lead forecaster from the Sunday, May 2, 5:00 a.m.–1:00 p.m. CDT shift who ran the Cumberland River model that morning and was most familiar with the hydrologic situation, did not stay to participate in, or act as the OHRFC lead on the 1:30 p.m. coordination conference call with USACE regarding Cumberland River reservoir operations. OHRFC staff that did participate on the call had relatively little knowledge of what was occurring with respect to the Cumberland River, hampering effective communication with the USACE. Interviews with OHRFC staff indicated there was confusion about who the OHRFC lead was during the conference call and on the critical afternoon and evening shifts Sunday when conditions were changing rapidly.
- Although this rainfall event was rapidly evolving into a record breaker, a HAS specialist was not working shift during some critical periods of the event. All RFCs have three HAS specialists and these forecasters, versus "HAS qualified" forecasters, should be staffing the dedicated HAS shifts during extreme events.
- During the Sunday afternoon shift, despite the fact that the Cumberland River was rising rapidly through successive flood categories, analysis of a potential dam break at Dunham Lake Dam in Kentucky diverted the attention of the lead forecaster responsible for the Cumberland River for about a 30-minute period. This duty should have been assigned to another staff member. In addition, due to the serious of the situation, two forecasters assigned to the Cumberland River would have been optimum.
- As the Cumberland River stage at Nashville rose rapidly through flood level categories on Sunday, more than one forecast was quickly exceeded. One forecast, in particular, did not get updated for over 3 hours. The Sunday 9:39 a.m. crest forecast of 41.9 feet (just below moderate flooding) was exceeded within an hour and a half, more than 9 hours before the forecasted crest arrival. No update to the stage forecast was provided until 3:37 p.m. Sunday, at which time the observed stage had surpassed "moderate flooding" and was only 0.4 feet below "major flooding" (45 feet).
- Early Sunday morning, the USGS river gage at Bellevue, TN on the Harpeth River went out of service. OHRFC requested and received a manual observation (via OHX) of the river level from the TN USGS. The river level reading received was substantially above the highest point on the USGS rating curve, close to the 1948 flood of record stage, indicating the river was likely at record stage and flow levels. The reading did not relate stage and flow and OHRFC deemed that it did not make sense in their hydrologic model. The OHRFC and OHX should have made additional attempts to get measurements from the TN USGS.
- OHRFC staff did not incorporate feedback from WFO Louisville (LMK) concerning data quality at a river forecast point on two occasions after the gage failed to report accurate

data. The OHRFC staff should have recognized that the data were bad and made the necessary adjustments at those points. The OHRFC, however, worked closely with WFO LMK to derive a stage at that river point for the Monday, May 3, forecast.

Due to a rapidly escalating flooding event on the Cumberland River, additional staffing Sunday could have assisted with forecasting, communication, obtaining real-time rainfall reports and critically assessing model results. The OHRFC Station Duty Manual (SDM) states*:*

In addition, while it won't be possible in every case (especially for situations which arise during the evening hours), the Senior Duty Hydrologist (SDH) should make every attempt to ensure that any additional coverage is arranged before leaving for the day.

OHRFC shift leaders should have arranged for augmented shift coverage on Sunday in response to the increasing flood risk. Additional personnel were needed to maintain situational awareness, for timely updates to river forecasts as needed, and for forecast diagnosis to reduce the significant uncertainty of river projections, especially with respect to the Cumberland River.

Fact: Operations at the OHRFC were hampered by absence of a HAS specialist during critical hours on Saturday and Sunday.

Fact: The attention of the Cumberland River forecaster, even if for a relatively short period of time, was diverted during the critical Sunday afternoon period to analyze a potential dam break in Kentucky.

Fact: The Cumberland River at Nashville rose through minor and moderate flood stages without forecast updates as stipulated by NWS directive.

Finding 9: Leadership on operational shifts is critical for an office to function effectively and efficiently during a rapidly changing, non-routine, extreme event. Additional staff on Sunday would have allowed for in-depth review of data and critical forecast processes and procedures by senior operational forecasters, enhanced communication with WFOs and partners, including obtaining real-time rainfall observations, and more frequent updates of river crest forecasts that had been exceeded.

Recommendation 9: RFCs should implement proven staffing models that other RFCs have employed prior to and during high impact events.

The OHRFC uses the NWSRFS, which includes the RES-J operation, to produce its official operational river forecasts. As part of the AHPS program, the RES-J reservoir model was calibrated for nine dams in the Cumberland River Basin. The calibrated models were delivered to OHRFC in 2005, along with a report detailing pertinent information about each calibration. The report gave a satisfactory evaluation of the RES-J routine. The models were placed into OHRFC's operational forecast process in the same year. In every run of NWSRFS, the RES-J routine calculates reservoir operational variables, including pool elevations and flow releases for each project.

In OHRFC's standard operational forecast process, these RES-J *calculated* dam releases are replaced with *planned* dam releases provided by the reservoir operator, USACE LRN, in this case. OHRFC's standard operating procedure has been to overwrite RES-J calculated dam releases with

USACE-provided release data to produce the river forecast for the Cumberland River at Nashville. Such data improve forecasts *during normal flow regimes*.

In the absence of updated USACE dam releases late Saturday through early Sunday morning, OHRFC ran reservoir simulations with NWSRFS. Such exploratory runs are not uncommon in RFC operations. Although the OHRFC's standard forecast process uses observed and forecasted dam releases from the USACE as the major input for its Cumberland River forecasts, these reservoir simulations runs did not incorporate the releases.

Large discrepancies existed between the OHRFC reservoir simulations, using RES-J modeled outflows (releases) from Old Hickory Dam and the standard OHRFC model forecasts that incorporated USACE-provided releases. The reservoir simulations indicated Nashville river stages *exceeding* major flood levels **(Figure 29)**, while the standard OHRFC forecast process (overwriting reservoir simulated releases/outflows with USACE-provided releases) indicated Nashville river stages *well below* major flooding levels **(Figure 30)**. As noted previously, the MMEFS runs (that also used RES-J rather than USACE releases at the reservoirs) also showed large risks of extreme flooding at Nashville.

Thus, two very different pictures of the flood risk at Nashville emerged from OHRFC analyses. The discrepancies between the three model scenarios: standard forecast process results; reservoir simulations; and MMEFS results were never fully resolved during conference calls with the USACE on Sunday. As a result, OHRFC forecasters deferred to USACE projections of Old Hickory releases as the main input for its official river forecasts at Nashville, as is their standard operating practice.

Note: **Figures 29 and 30** illustrate the discrepancies that arose in reservoir model simulations during the weekend of May 1 and 2 between forecast runs that *relied on the RES-J to determine releases* from Old Hickory **(Figure 29)**, and forecast runs *that incorporated the USACE LRN release projections* for Old Hickory Dam **(Figure 30)**.

Figure 29 also illustrates that the RES-J model releases and subsequent routing downstream to Nashville, TN produced an *accurate simulation* of future flow, indicating that major flooding would occur at Nashville, TN. Much lower flows (not reaching moderate flood levels; **Figure 30**) resulted when the RES-J *model outflows* from Old Hickory were replaced by *USACE LRN projections* for Old Hickory (the projections conveyed during the 8:30 a.m. Sunday conference call between OHRFC and USACE).

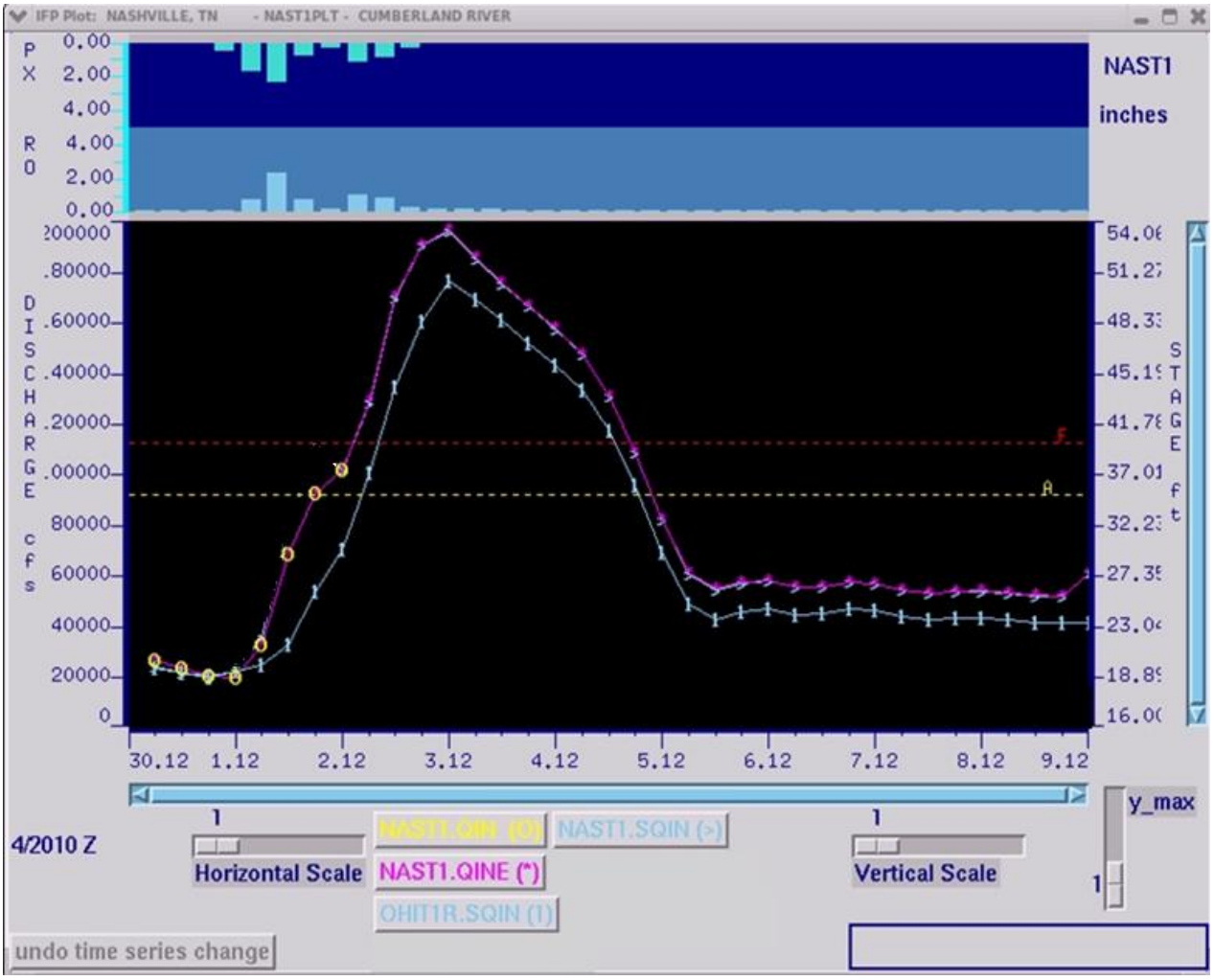

Figure 29: OHRFC Cumberland River model forecasts from Sunday morning. In this figure, release projections provided by USACE LRN for Old Hickory Dam *were not* incorporated into the reservoir model simulation. Observed Old Hickory flows are shown by yellow "O" symbols and extend to 05/02/2010, 1200Z. The blue line with a "1" symbol is the model simulated Old Hickory outflow; the purple line with plotting symbol "*" represents the resulting alternative forecast of river stage at Nashville (using model- simulated, Old Hickory releases).

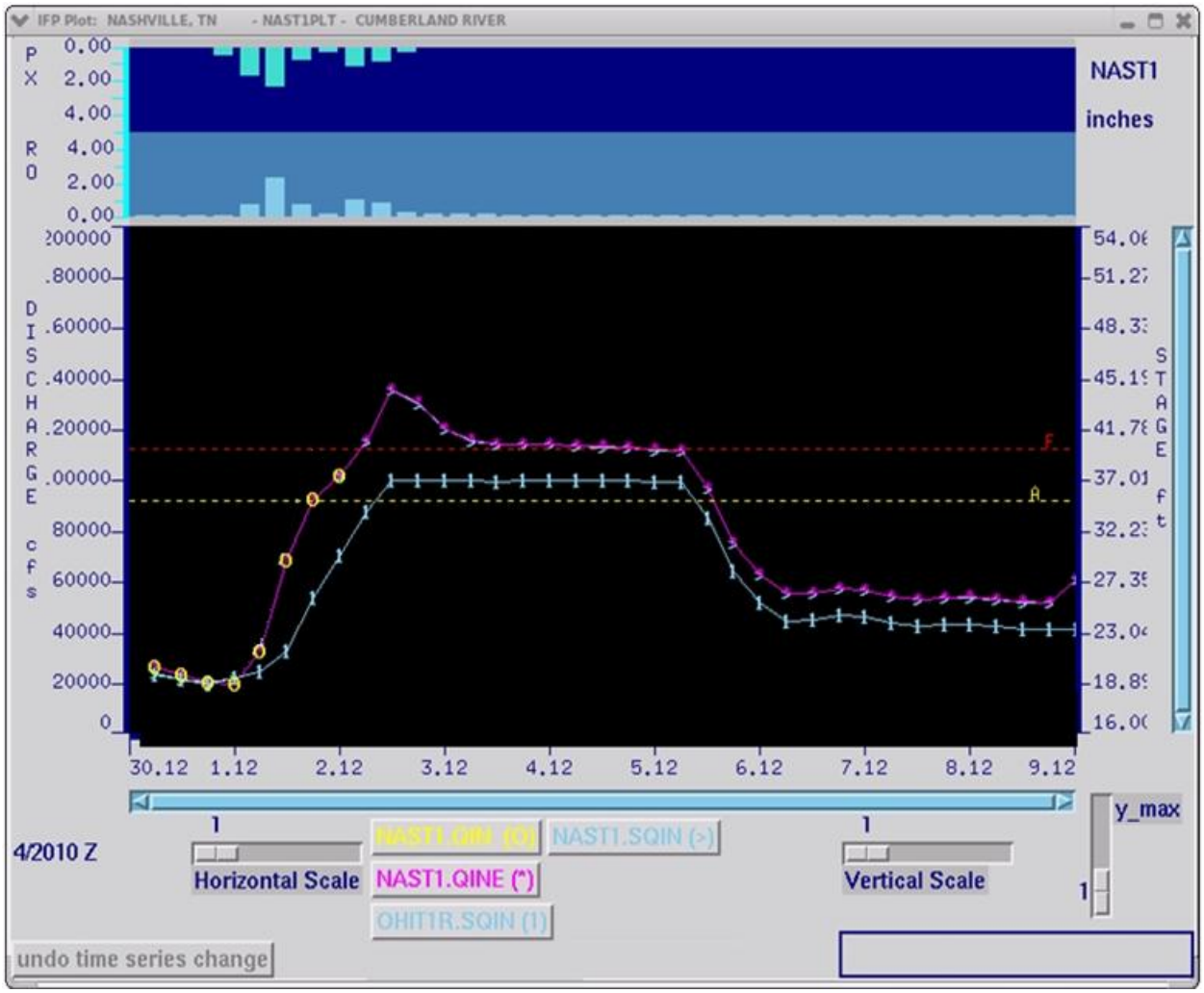

Figure 30: OHRFC Cumberland River model forecasts from Sunday morning. In this figure, release projections provided by USACE LRN for Old Hickory Dam *were* incorporated into the reservoir model simulation. Observed Old Hickory flows are shown by yellow "O" symbols and extend to 05/02/2010, 1200Z. The blue line with a "1" symbol is the model simulated Old Hickory outflow; the purple line with plotting symbol "*" represents the resulting alternative forecast of river stage at Nashville (using model- simulated, Old Hickory releases).

Fact: Between the Saturday, 7:00 p.m. and the Sunday, 7:00 a.m. (**Figure 31**) experimental MMEFS model runs, results showed the risk of major flooding at Nashville increasing from at least 80 percent to 100 percent.

Fact: OHRFC's standard forecast practice uses the latest available USACE observed and forecasted releases at Cumberland River projects as the major input in determining flow and stage forecasts for Cumberland River locations including Carthage, Nashville, and Clarksville. OHRFC receives automated daily reports from the USACE containing this information.

Fact: OHRFC interviews revealed there is no written policy dictating that USACE releases be used in river forecasts. Rather, culturally this is what staff always did as it was standard procedure.

Fact: The OHRFC and USACE never successfully resolved discrepancies between USACE LRN dam release projections and OHRFC's reservoir simulations on Sunday. The two Sunday conferences calls with USACE LRN/LRD did not conclude with a mutual understanding that Old Hickory reservoir operations would essentially pass inflows later in the day to prevent lake levels from overtopping dam structures, rather than adhere to the much lower projected releases estimated by the USACE LRN.

Finding 10: OHRFC staff members did not deviate from the established Cumberland River forecast process of incorporating USACE projections, even when faced with a rapidly deteriorating meteorological/hydrological situation and a lack of real-time information and projections from USACE LRN. OHRFC did not use the RES-J model for Old Hickory appropriately, negatively affecting the forecast for the Cumberland River at Nashville. A staff member at OHRFC stated, "We would never overwrite information from the USACE." Another said, "…felt that was a lot of water at Nashville, but felt the USACE would hold it as they always had."

Recommendation 10: RFCs should evaluate their forecast processes for "standard" dependencies on forecast data from partners (e.g., release data from USACE projects), and develop procedures to recognize and address situations in which such standard forecast processes are no longer valid.

Finding 11: There is no comprehensive training tool available to RFC forecasters to build confidence in working extreme hydrologic events and to assess the reliability of alternative forecast processes and methodologies if standard operating procedures become invalid as an event unfolds.

Recommendation 11: NWS should develop the ability for RFC forecasters to conduct training sessions using archived operational data from historic flood events, allowing forecasters to experiment with alternatives to standard forecasting procedures. This 'simulator program' should use operational hydrologic tools, providing a capability analogous to that of the Weather Event Simulator (WES), which WFO forecasters use to train on meteorological events.

Fact: USACE LRD conference calls included OHRFC and LMRFC, but did not include WFOs over the weekend. RFCs did not invite affected WFOs to participate in these calls.

Fact: Many OHRFC operational staff members had never been, or had not been in a number of years, on familiarization visits to WFOs within their HSA. Likewise, many WFO operational staff had not participated in a familiarization visit to the OHRFC. The OHX SH visited the OHRFC just once in the past several years. OHRFC staff had not visited OHX or USACE LRN since the Wolf Creek Dam exercise in August 2007.

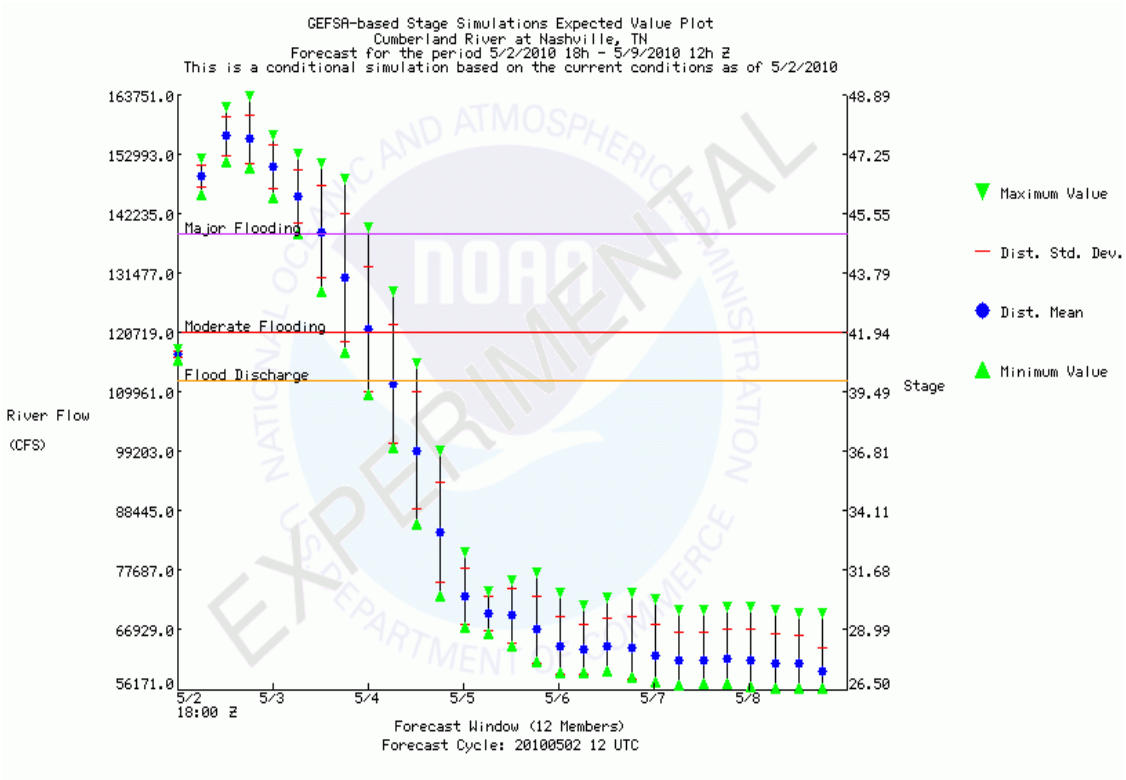

Figure 31: Ensemble-based forecast product from MMEFS produced by automated procedures on Sunday morning. For each future 6-hour period, the two green triangles show the maximum and minimum of the range of forecasted flow, and the blue circle shows the mean forecast.

3.4. WFO Nashville (OHX)

The rapidly evolving hydrological and meteorological event on May 1-2 stressed the operations at WFO OHX. Workload anticipated days earlier was greatly exceeded. Initially, the heaviest rain was anticipated for Sunday, May 2, so the extreme rainfall that occurred on Saturday put OHX in a reactive operational mode. In addition, OHX dealt with widespread severe weather Saturday and Saturday night.

At the time of this report, a paper under peer review entitled "*The Devastating Mid-Mississippi Valley Floods of 1-2 May 2010*", by Richard H. Grumm, National Weather Service, noted the following: "The event of 1-2 May 2010 had …key ingredients for a significant heavy rainfall event (Doswell 1996), and for historic events (Bodner 2011); This case is a classic case on the value of anomalies in identifying a potentially significant heavy rainfall event... [which] clearly defined a threat of a Maddox Synoptic event type with a strong southerly jet and a surge of high PW [precipitable water] air into the region."

As the NWS focuses increasingly on Decision Support Services, offices and operational staff at all levels should place more attention on anomalies and pattern recognition in advance of potentially significant events.

Fact: The NWS is increasingly focusing on Decision Support Services for customers and partners, particularly with respect to high impact meteorological and hydrologic events.

Finding 12: Many forecasters do not have the tools or experience to incorporate pattern recognition routinely, and use information from anomalies and short range ensemble data, in the forecast process.

Recommendation 12: The NWS should enhance training for operational forecasters on pattern recognition for extreme events and use of anomaly data in the forecast process in an effort to better predict rare or record events.

3.4.1. Pre-Event (OHX)

During the week prior to the event, OHX provided consistent notification that heavy rain was expected over the weekend. Customers and partners in the OHX service area, including local officials, EMs, private entities, and the public, were aware of the significant storm potential over the weekend, but did not perceive the attendant risk of extreme flooding.

OHX conducts hydrologic drills and seminars annually; a flash flood case was included in their WES training during the fall of 2009. The Warning Coordination Meteorologist (WCM) attended a FEMA weeklong disaster exercise in August 2009, which simulated significant flooding in Nashville. This exercise and the WCM's extensive participation strengthened relationships with partners and aided in Nashville's response to the extreme flooding. During the spring of 2010, OHX took part in tours of Percy Priest and Old Hickory Dams, and provided a safety briefing to the security team at Opry Mills Mall.

On Tuesday, April 27, OHX first mentioned the threat of heavy rain for the upcoming weekend. A Flash Flood Watch for the OHX County Warning Area (CWA) was issued Friday, mentioning 2 – 4 inches of rainfall over the weekend. For this same period, HPC rainfall predictions were 4 – 5 inches for Nashville and 4 – 6 inches across Middle Tennessee. OHX reduced HPC forecast rainfall guidance in their official products and noted this in Area Forecast Discussions (AFDs), yet did not contact HPC for further discussion.

On Friday, the MIC coordinated with the TEMA Regional Director and emailed local and state Emergency Management Agencies (EMA) regarding the heavy rain/flood/severe weather threat. The MIC also conducted a webinar for these agencies Saturday. By Saturday, HPC advertised a precipitation "bulls-eye" of 8.3 inches over the Nashville area. OHX again reduced HPC predicted rainfall amounts in its official products and noted such in AFDs.

Fact: AFDs mentioned flooding risks and increasing confidence in heavy rain beginning Thursday, April 29, but a ".HYDROLOGY…" section was not added to these discussions until Saturday. Friday afternoon, the AFD mentioned rainfall with "locally up to 8 inches possible."

> Example: AFD 935 AM CDT SAT MAY 1 2010
> &&
> **.HYDROLOGY...**
> **UP TO FIVE INCHES RAINFALL IN W MID TN THIS MORNING. POTENTIAL UP TO EIGHT INCHES THIS WEEKEND.**

Finding 13: AFDs are widely used by media and EMs to assess severity of events. Despite mention of possible flooding in AFDs, there was no discussion of potential severe impacts and consequences from the heavy rain or flooding. In this case, "up to 8 inches" of rain and the potential for record rainfall amounts implied serious hydrologic consequences.

Recommendation 13: Include a hydrology section in AFDs, including possible impacts, when there is a potential for significant rainfall and flooding.

3.4.2. Event Operations (OHX)

The events of May 1-2, 2010 were unprecedented in Middle Tennessee. Several primary themes emerged upon a review of OHX operations during the event:

- OHX staff exhibited dedication to the NWS mission. The staff was taxed with an extreme workload during this historic event. Hundreds of watches, warnings, statements, updates, and graphicasts were issued over the weekend.
- OHX operations were more focused on the severe weather threat, which was indeed significant, versus the flooding threat, which became catastrophic and resulted in numerous fatalities.
- Staffing resources were not adequately allocated to assist with hydrologic warning services given the magnitude of this event. Staffing was not adequate on the overnight shifts during the event.

Note: Times concerning issuance of river flood warnings in this section relate to the WFO product issuance time, rather than the OHRFC guidance issuance times noted in Section 3.3.

Since 1999, Tennessee has led the Nation in tornado fatalities with 113. The OHX CWA has experienced 52 tornado fatalities since 1999. Major tornado outbreaks occurred in 2003, 2006, and 2008. As a result of the high incidence of tornados in Middle Tennessee, OHX was properly focused on severe weather during this event and was confident and competent in doing so.

The distinct focus on severe weather during this event, however, diminished situational awareness with respect to the extreme flooding. Operational staff deferred to the SH with respect to handling nearly all hydrology-related duties, including product issuance and communication with federal water partners, TEMA, Nashville OEM, and the OHRFC. This is not unique to OHX.

OHX issued 22 graphicasts on Saturday and 40 on Sunday. Many of the graphicasts focused on severe weather. Ongoing and widespread flooding was mentioned as a separate text box on several of the images. Some of the flood-focused images issued on Saturday showed the latest radar image with rainfall contours **(Figure 32)**; however, at no time on Sunday did any of the graphicasts include river flood information. The resources used to issue such frequent updates of these graphicasts may have been better utilized for enhanced communication with the OHRFC and closer monitoring of the rapidly changing crests on the Cumberland River.

On Sunday, around 30 significant NWSChat messages were sent to OHX (**Appendix D**). These included reports of torrential rain, severe flooding, and swift water rescues across Middle Tennessee and for Nashville, in particular. During that same period, only five reports of severe weather came across NWSChat. A review of AFDs indicated an emphasis on severe weather.

As previously mentioned, OHX operational staff did not change the focus of situational awareness from severe weather to catastrophic flooding -- the immediate threat to life and property. OHX did not shift staffing resources to assist the SH with hydrologic warning services. In fact, a flash flood warning or other EAS-activated hydrologic warning was never in effect for Greater Nashville throughout the weekend. Less than optimum resource allocation contributed to a reactive operational mode. *This fact further validates Recommendation 11 from the Southeast United States Floods, September 18-23, 2009, Service Assessment* **(C15, Appendix C)**.

The OHX Station Duty Manual (SDM), updated March 15, 2010, includes a policy on staffing procedures for severe weather but not for hydrological warning duties. The staffing profile for severe weather recommended in the SDM was not consistently followed during the event, particularly for the overnight periods. WFO OHX also has laminated quick reference duty lists to define roles and responsibilities, but none of the lists discuss hydrologic duties.

OHX staffing was adequately augmented during the day and evening hours of Saturday and Sunday, including using the Information Technology Officer (ITO) and a Student Career Employment Program (SCEP) student to assist in operations; however, the overnight shift lacked additional operational staff. From midnight to noon Saturday, no additional forecasters were on duty; however, the WFO OHX SDM recommended additional staffing due to tornado watches and a flash flood watch in effect, numerous warnings issued and heavy rainfall forecast for Saturday. From midnight to 6:00 a.m. Sunday, staffing included only one additional forecaster, although there was a Particularly Dangerous Situation (PDS) Tornado Watch in effect, there had been severe flash flooding with fatalities Saturday and more heavy rain was forecast for Sunday. By Monday night there was no additional staffing, although the Cumberland River at Nashville had crested earlier that evening, many rivers were still in flood, and officials had evacuated the Waterford subdivision in Old Hickory (northeast of Nashville along the Cumberland River.

Saturday night into Sunday morning OHX dealt with widespread severe weather, although no Local Storm Reports (LSR) were issued during that period. A forecaster on the midnight shift stated that he felt all flood related products "were in good shape…we would not have to worry about county [based] warnings, just watch the rivers. I felt like going in [to the midnight shift] hydro was in good shape." An OHRFC forecaster called OHX shortly after midnight, stating that he thought the Cumberland River at Nashville would go to flood stage. The OHX forecaster responded that the SH would be in around 6:00 a.m. and that the SH would handle any flooding issues. The official forecast, which indicated the river would rise *to just below flood stage*, was issued at 6:36 a.m., and flood stage was reached about 3 hours later.

In two instances, OHX revised the Deterministic Hydrologic Forecast (RVF) guidance provided by OHRFC for river forecasts without coordinating with OHRFC. A forecast for the Harpeth River at Bellevue was modified on Saturday without initiating coordination with OHRFC. In the 11:18 a.m., Sunday forecast for the Cumberland River at Nashville, OHX added the statement that the river could "possibly" rise to 45 feet (which is major flood level) without speaking with OHRFC forecasters. OHX could have communicated more with the OHRFC concerning changes to river forecasts and necessary updates. RFCs and WFOs should ensure, through appropriate meetings and interactions, that they fully understand each other's data needs, forecast processes, and product suites.

By Sunday morning it was difficult, and in some instances considered unsafe, for staff to travel to the WFO because two of the three roads into the office were flooded. OHX staff members were reluctant to put coworkers in a potentially dangerous situation by calling them into

the office. It took one dedicated employee 2 ½ hours to get to the office Sunday morning to supplement staffing. At the same time, on both Saturday morning and Sunday morning, the midnight shift forecasters were allowed to leave at the end of their regularly scheduled times.

Fact: From 8:00 am-4:00 p.m., Saturday, the SH was assigned to one of the routine meteorology forecast shifts, was the designated shift Lead Forecaster, and was also responsible for hydrological duties. Operational staff deferred to the SH with respect to handling nearly all hydrology-related duties and critical communication concerning flooding.

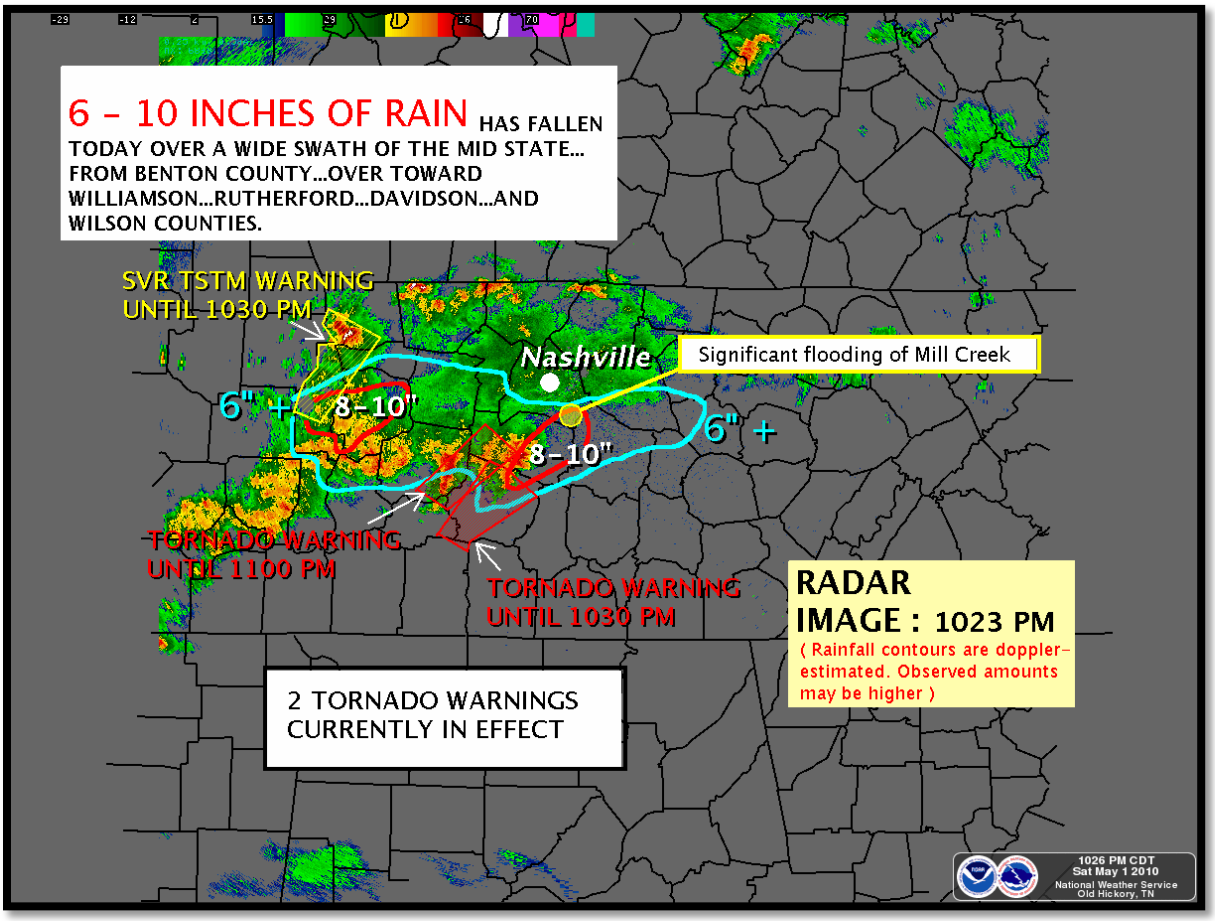

Figure 32: Graphicast issued by OHX at 10:23 p.m., Saturday.

Fact: From midnight to 6:00 a.m., Sunday, only one additional forecaster was on duty to augment standard staffing. A PDS Tornado Watch was in effect, there had been significant flooding and fatalities on Saturday, active weather had moved across the OHX CWA **(Figure 33),** and heavy rainfall was forecasted again for Sunday. From late Sunday night to Monday morning, standard staffing was not augmented despite flood warnings in effect and the fact that the Cumberland River was continuing to rise toward its highest crest in the post-flood control era **(Figure 34)**.

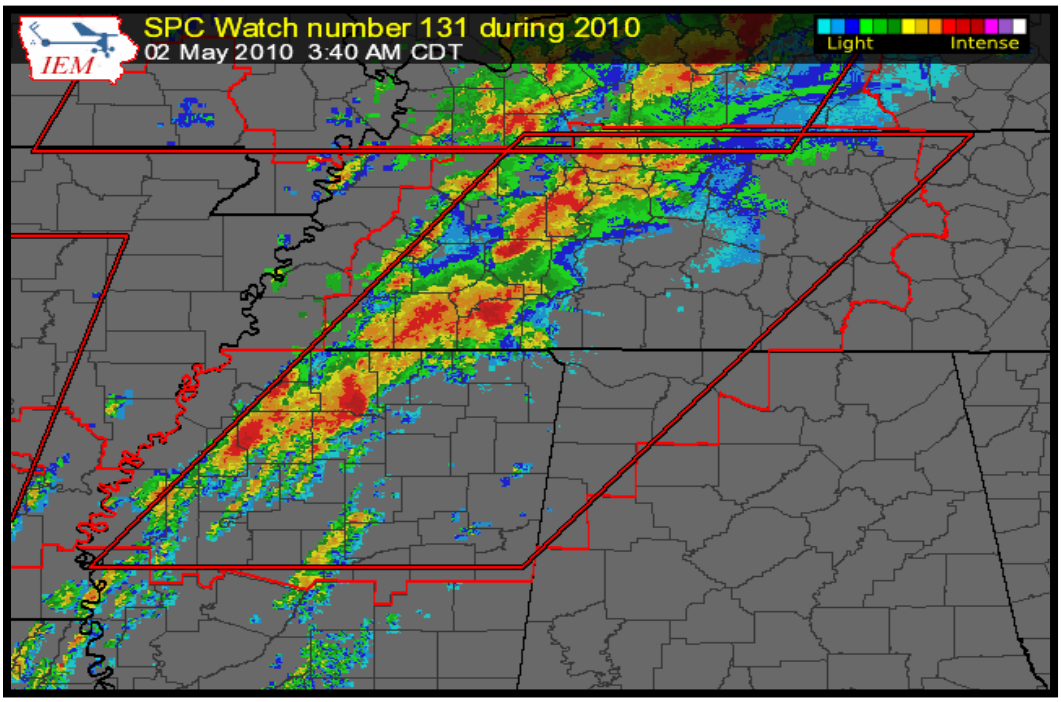

Figure 33: Radar display early Sunday morning, May 2, 2010.

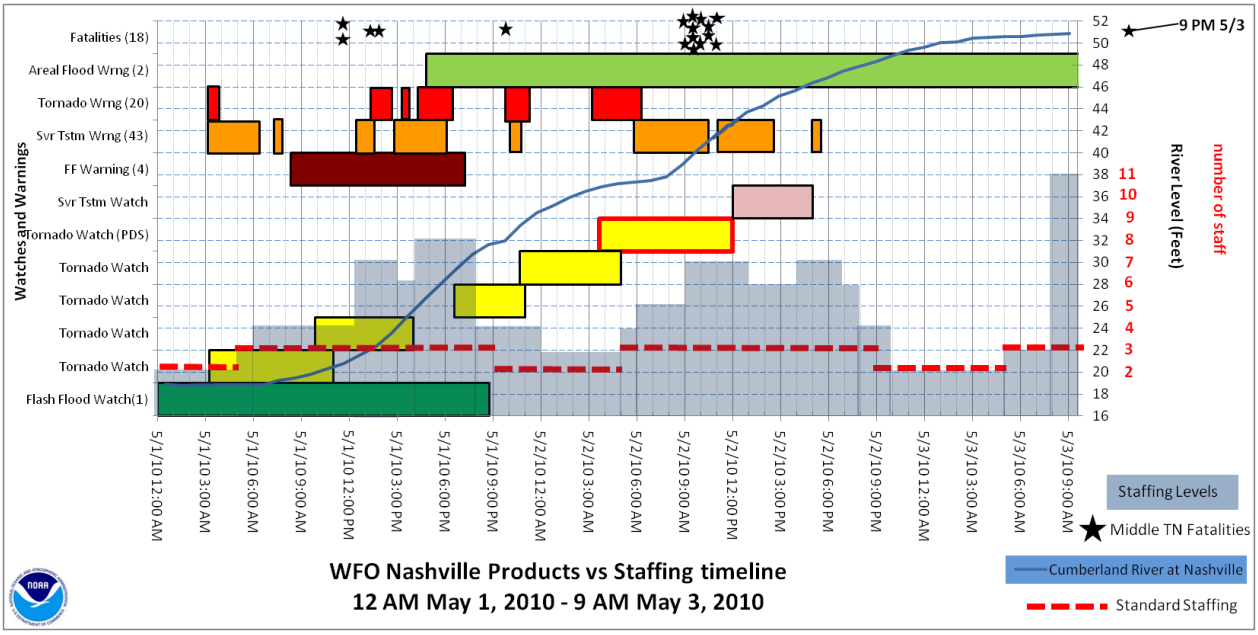

Figure 34: The graph depicts the numerous products issued by WFO Nashville, Middle Tennessee fatalities, the rise of the Cumberland River at Nashville, and WFO Nashville staffing from Midnight Saturday, May 1 to 9:00 a.m., Monday, May 3.

Finding 14: Not all WFOs staff and prioritize adequately for high-impact hydrologic events.

Recommendation 14: WFOs should employ a team approach to working hydrologic events

similar to how significant severe weather events are handled. This approach should include appropriate prioritization of staffing resources and hydrologic related duties.

Finding 15: There were several instances in which OHX and OHRFC should have communicated more effectively with respect to forecasts for the Cumberland River at Nashville. On Sunday the initial Flood Warning for Nashville was exceeded within an hour and a half, but no official forecast update was issued for another 6 hours. WFOs and RFCs should ensure that they understand each other's data needs, forecast processes and product suites and that they communicate effectively with each other when updates are necessary.

Recommendation 15: Operational staff at WFOs and RFCs should routinely participate in forecaster exchange and familiarization visits to better facilitate communication and understanding of each other's operational processes.

Finding 16: As a result of an inadequate training tool to efficiently drill on hydrological events, not all NWS forecasters are confident in their abilities to handle difficult, rare flooding episodes. One forecaster stated, "We do not use river programs much. They are difficult for meteorologists to integrate into operations." This relates to an agency-wide emphasis on severe weather, difficulty in using several different pieces of software for river flood monitoring and product issuance, and lack of routine exposure to and training for non-routine hydrologic events. Currently, there is no end-to-end simulator mode for hydrologic services in WFOs.

Recommendation 16: NWS should develop the capability for WFO forecasters to conduct training sessions using archived operational data from historic flood events. Such training should use operational hydrologic tools to provide a simulation capability analogous to the functionality provided by the WES used in WFOs.

Fact: TEMA stated that it would have been beneficial to have had an OHX staff member onsite at the Emergency Operations Center (EOC) during the critical flooding periods. During an August 2010 meeting, an agreement was reached for OHX to staff the TEMA EOC during high-impact weather events.

Fact: An updated NWS Directive 10-405 went into effect on July 22, 2010. This directive requires all NWS staff who provide phone briefings or issue "spot" forecasts to first responders to take certain FEMA Incident Command courses. Following Southern Region Headquarters guidance, all WFO OHX meteorologists had completed at least two of these courses prior to this event.

Finding 17: Most local, state, and federal agencies that deal with incidents, including weather-related disasters, do so under the National Incident Management System (NIMS). They follow an Incident Command System (ICS) model for staffing and resource management to further enhance communication and collaboration between agencies. Many field offices staff EOCs that are managed by partner agencies during high-impact events.

Recommendation 17: WFOs should incorporate proven WFO staffing models that have been successfully employed prior to and during high impact events. These models should include adopting relevant ICS staffing principles during non-routine, high-impact events. Relevant ICS staffing practices should be considered for daily operational use as well.

3.4.3. Event Products and Services (OHX)

In general, there was very positive feedback from Nashville media, EMs, Nashville OEM and TEMA concerning relationships with WFO OHX and its performance during this unprecedented event.

During the event, OHX staff issued hundreds of products. Several river flood warnings were not issued properly however, as the magnitude of flooding increased and forecast crests changed categories, i.e., from moderate to major flooding.

On Saturday morning, three flash flood warnings were issued, none of which included Greater Nashville. At 9:50 a.m., Saturday, an Areal Flood *Advisory* was issued that covered Greater Nashville. That afternoon, an Areal Flood *Warning* was issued to cover 22 counties in Middle Tennessee, including Greater Nashville. Per NWS Directive 10-922, areal flood warnings, as well as flash flood warnings, are appropriate for situations involving threats to life and property. However, areal flood warnings were not EAS-activated or tone-alerted on NWR, but an option to do so is detailed in NWS Directive 10-922. Although Nashville suffered catastrophic flash flooding and record river flooding, Davidson County, in which Nashville is located, was never under a flash flood warning or, for that matter, an EAS-activated flood warning.

From late Saturday through Monday, seven Civil Emergency Messages (CEMs) were issued at the request of the Nashville Metro Office of Emergency Management (OEM) in coordination with TEMA and at the request of Hickman County. Several of these advised of major flooding in the Nashville area and urged residents to stay off roads. These CEMs stated "This is an extremely dangerous situation." The messages were EAS-activated and tone-alerted on NWR. CEMs were a positive and well-received Decision Support Service (DSS) provided by OHX.

NWSChat was used extensively during this event to communicate directly with EMAs and the media (**Appendix D**). These partners were positive about this interaction. A review of NWSChat logs showed that on Saturday, over 30 NWSChat messages were sent to the attention of OHX concerning significant, extreme, and widespread flooding across Middle Tennessee, with reports of water rescues, vehicles under water, homes flooded and evacuated, and boat rescues on I-40. *[Example: NWSChat 5:20 pm May 1: …Watertown completely under water, houses under water, Still reports of vehicles under water, numerous water rescues still being made to stranded motorists. Numerous homes flooded and being evacuated…]*. However, flood products were not updated to indicate the increasing urgency of the event.

Sunday afternoon, Wilson County EM stated on NWSChat: *"Lebanon's town square could be flooding within the hour.*" That evening the Wayne County EM stated: "*Ham radio reports Buffalo River out of banks and highest seen in 20 years. Water still rising*," and another EM stated, "*I've seen a lot of flooding in the industrial areas around downtown [Nashville]. Water has risen quite fast. Downtown areas flooded very quickly. Several streets now impassable down in those areas on the low side of the river; Waterford Subdivision [Nashville] being evacuated in Old Hickory from rising Cumberland River*." Again, flood products were not updated as a result of this additional information.

Upon a review of OHX products and services, a particular theme emerged. When it became clear that a primary and immediate threat to life and property was due to catastrophic flooding, OHX did not shift to using elevated "emergency" type products and very strongly worded flood

warning products to convey that threat. The many reports of catastrophic flooding, water rescues, and even fatalities via NWSChat, never prompted an escalation of the level of warning or heightened wording in products, such as the use of "Flood Emergency" terminology. A Nashville TV meteorologist stated, "*[OHX] could have used Flash Flood Emergency to communicate seriousness of situation.*" Nashville OEM stated, "*We needed a higher level of warning.*"

Local TV meteorologists and Nashville OEM stated that the numerous flood warnings and products were confusing and made people "numb" to warnings. *This fact further validates Recommendation 5 from the Southeast United States Floods, September 18-23, 2009, Service Assessment* **(C13, Appendix C)**, *as well as a similar Recommendation from the Big Thompson Canyon Flash flood July 31-August 1, 1976* **(C1, Appendix C).**

Saturday through Monday, OHX issued a total of 34 River Flood Warnings (FLW) and 220 River Flood Statements (FLS) for 25 locations. At 18 of the 25 locations, an initial FLW was issued; however, follow-up products were all in the form of FLSs, even though many projected levels crossed categories, i.e., from moderate to major flooding. When a river flood forecast changes category, for example, from moderate to major flooding, pursuant to Directive 10-922, a new FLW should be issued. For example, OHX should have issued an FLW for the Cumberland River at Nashville, instead of an FLS, at 4:19 p.m., Sunday, when the forecast went from minor to major flood.

Sunday morning, OHX issued a Flood Advisory for the Cumberland River at Nashville. The product stated that the "*current stage is 35.4 feet…rising to 27.3 feet by this morning….*" The product, which indicated a fall in the river through the morning, was not checked by OHX staff, nor was the content discussed with the OHRFC. The Flood Advisory was upgraded to a Flood Warning about 3 hours later. The Flood Warning stated that "*minor flooding is forecast*." Within 6 hours, by 4:00 p.m., the floodwaters at Nashville had exceeded major flood stage. OHX issued seven subsequent FLS products to increase the forecasted crest between noon Sunday and Monday afternoon **(Figure 36, Table 6).**

Nashville OEM stated that they needed more accurate and timely river forecasts. They had to go into reactive mode and all partners, federal agencies, and first responders were in "*the flood fight*" starting Saturday and continuing into Monday.

Gaylord Entertainment, the owners of Opryland Hotel and the Grand Ole Opry, rapidly lost confidence in Cumberland River forecasts on Sunday because the forecasts were changing frequently and dramatically. Gaylord Entertainment officials said that they were told by the Nashville Mayor's office that the NWS was confident in a 48-foot crest for the Cumberland River. The 48-foot level was a critical threshold for the Opryland Hotel area as above that point they begin to flood. Gaylord officials noted the river continuing to rise on Sunday evening, at which time they took the initiative to evacuate around 1700 people from their hotel before flooding occurred. They repeatedly said that NWS forecasts for the Cumberland River at Nashville were not timely or accurate.

Fact: Nashville TV meteorologists, TEMA, and EMs that were interviewed had high praise for WFO OHX and their work during this extreme event. TEMA officials in particular said that "*the relationship we have with the Weather Service is outstanding*."

Best Practice 2: OHX had built strong relationships with media and partners, helping them communicate effectively before, during, and after the event. One EM stated, "*Every agency was*

taxed during this event. Overall, one of the best interactions we have is with WFO Nashville; a good relationship." TEMA stated, "We have a fantastic relationship with the NWS Nashville WFO."

Fact: Numerous tornado watches and a flash flood watch were in effect over the May 1-2 weekend for Middle Tennessee (**Figure 34**). Tornado Watches were continuously in effect from early Saturday through noon Sunday, including a "PDS" Tornado Watch **(Figure 35).**

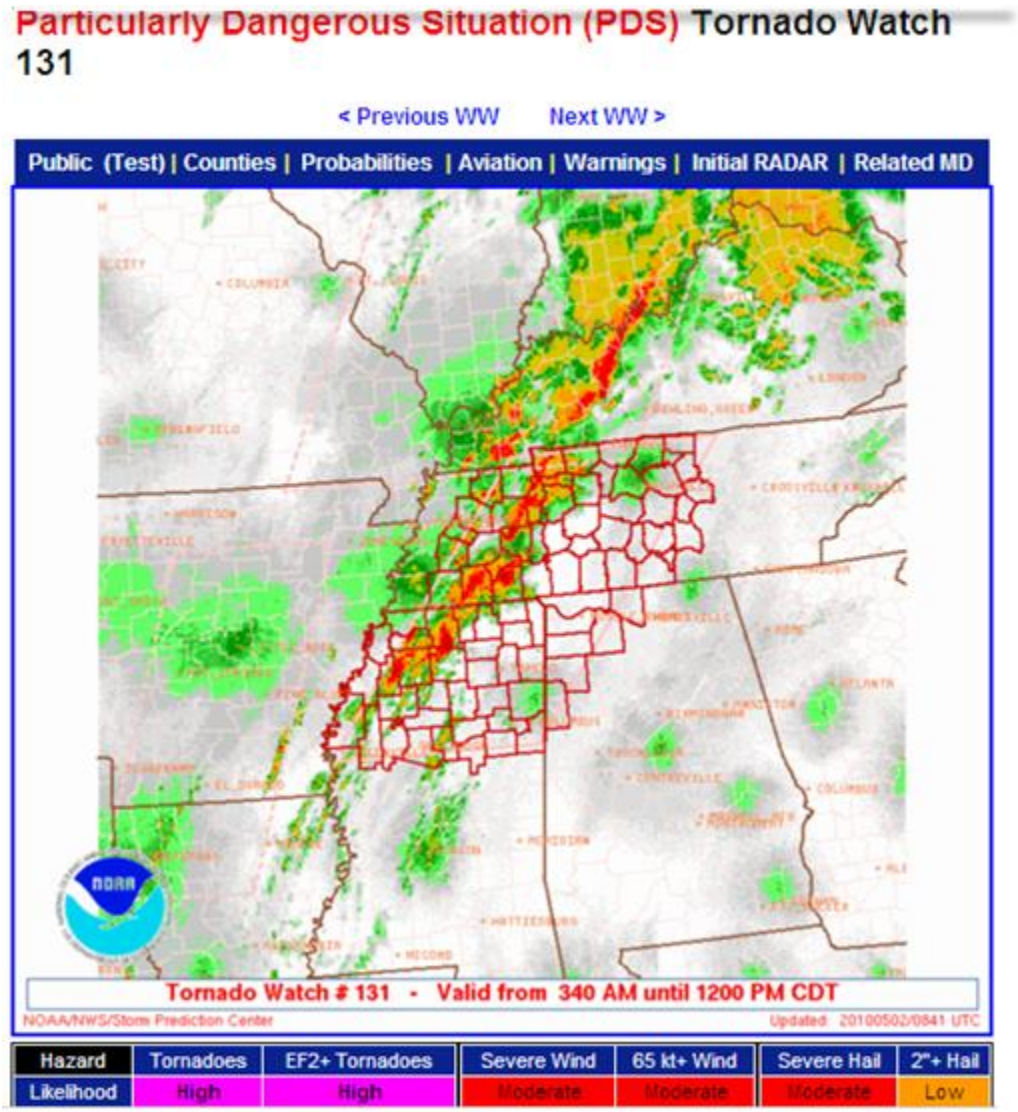

Figure 35: PDS Tornado Watch valid 3:40 a.m. to noon, Sunday, May 2.

Over the weekend, the following warnings were issued (**Table 5**):

Table 5: Products issued by WFO Nashville (OHX) from midnight, May 1 to midnight, May 3. Grey highlighted tabs indicate the products that activate EAS.
* indicates the PDS tornado watch

Products	SVR	TOR	FFW	Areal Flood Advy	River Flood Warning	Areal Flood Warning	Flood Watch	TOR Watch	SVR Watch	CEM	LSR	Graphicasts
12AM Sat - 12AM Sun	23	15	4	1	15	2	1	4	0	4	27	22
12AM Sun – 12AM Mon	19	5	0	0	7	1	0	1*	1	3	24	40

Fact: Saturday afternoon, an EM requested via NWSChat, "*any way to get a flash flood warning out on All-Hazards [for Wilson County; bordering Davidson County on the east] – we have numerous water rescues occurring across the county–in process of putting out public notifications.*" OHX decided not to put out a flash flood warning since Wilson County "was covered" under the Areal Flood Warning. *This fact further validates Recommendation 5 from the Southeast United States Floods, September 18-23, 2009 Service Assessment* **(C13, Appendix C)**.

Fact: Saturday evening, reports of three fatalities from flooding were communicated to WFO OHX via NWSChat. One fatality was in Greater Nashville. On Sunday, nine fatalities occurred in the Nashville area between 9:00 a.m. and 11:00 a.m., and there were many NWSChat reports Sunday evening of severe flooding and water rescues across Middle Tennessee and for Nashville.

Best Practice 3: At 10:15 a.m., Friday, April 30, Southern Region Headquarters sent an email reminding Southern Region WFOs of the option to use "Flash Flood Emergency" in headlines to convey extreme flooding and threat to life and property. This email went to all MICs, WCMs, and Hydrology Program Managers at each WFO.

Fact: The terminology "*flood emergency*" did not appear in any OHX flood products. NWS Directive 10-922, Section 6.3.4 adds the following language to guide use of the flash flood emergency headline in flash flood statements: *"In exceedingly rare situations, when a severe threat to human life and catastrophic damage from a flash flood is imminent or ongoing, the forecaster may insert the headline '... FLASH FLOOD EMERGENCY FOR [GEOGRAPHIC AREA]…' Such headlines should only be used when reliable sources provide clear evidence that people have been placed in life-threatening situations by rapidly rising floodwaters."* This directive does not allow for initial issuance of a flash flood warning using the "Flash Flood Emergency" headline, just the follow-up statements. *This fact further validates Recommendation 4 from the Southeast United States Floods, September 18-23, 2009, Service Assessment* **(C12, Appendix C)**.

Fact: At 6:36 a.m., Sunday, a Flood Advisory was issued for the Cumberland River at Nashville. This was upgraded to a Flood Warning at 9:50 a.m., which stated that "minor flooding is forecast." Within 6 hours, by 4:00 p.m., the floodwaters at Nashville had exceeded major flood

stage. Seven subsequent FLS products were issued to increase the forecasted crest between Sunday morning and Monday afternoon **(Figure 36; Table 6)**.

Fact: The official flood warnings for the Cumberland River at Nashville had negative lead times in initial forecasts for Flood Stage, Moderate Flood Stage, and Major Flood Stage.

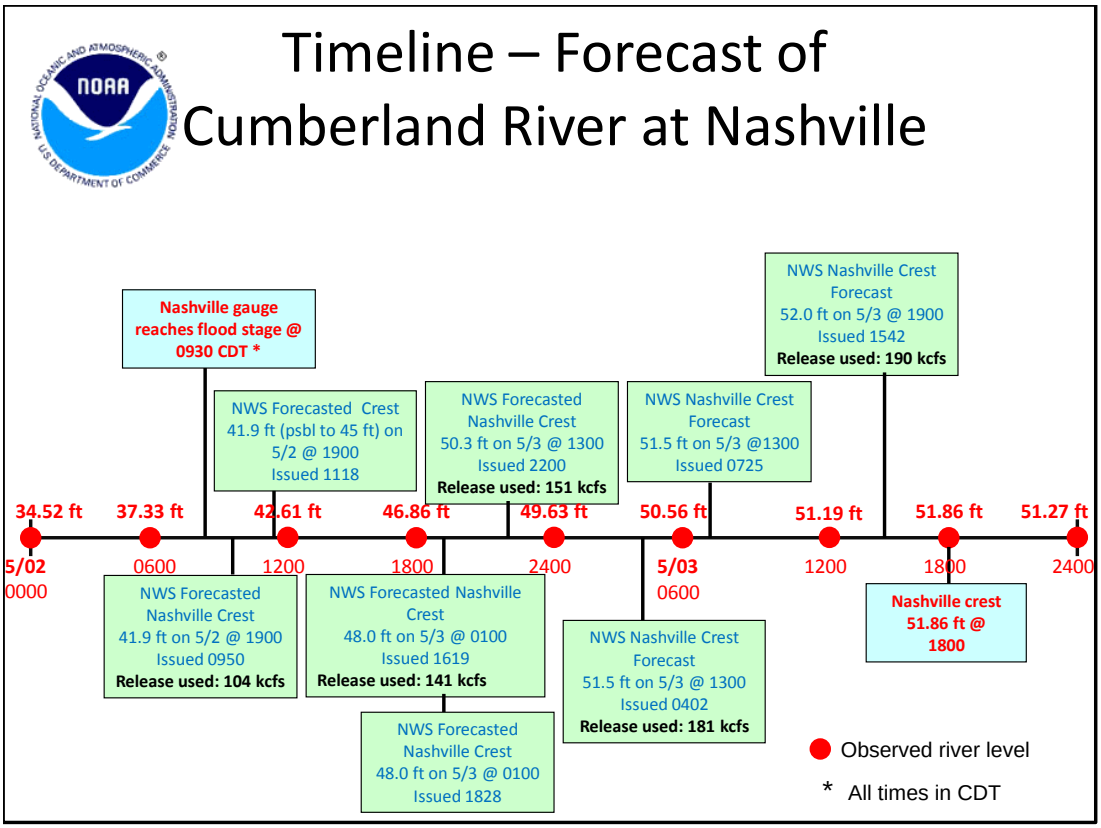

Figure 36: Timeline of NWS River Forecasts for the Cumberland River at Nashville, TN, showing Old Hickory Project peak release data that were used in forecast process as depicted in **Figure 21**.

Table 6: An overview of critical data related to NWS forecast products issued by WFO OHX for the Cumberland River at Nashville from Sunday, May 2, until the river crested on Monday evening. Included are river levels, Old Hickory releases, lead times until the forecasts were exceeded and relevant communications.

Product Issued By WFO OHX	Issue Date/ Time CDT	Forecast Crest & (Time of crest)	Latest Observed Stage at Product Issuance	Lead Time[3] & Time of Exceedence	Peak Old Hickory Release Used by OHRFC (cfs)	Old Hickory Release (cfs) & Gate levels[2] at Product Issuance	Relevant Communication between OHRFC, OHX, USACE & OH release info
FLS	**5/02 0216**	27.3 ft (5/3 a.m.)	35.4 ft	None 5/1 1530	**Est 20,000**	**Est 74,000** 7.6' – 8.4'	Based on 5/1 a.m. USACE forecast releases
FLS	**5/02 0636**	39.8 ft (5/3@ 0100)	37.3 ft	~3 hr 5/2 0950	**110,000**	**Est 78,000** 8.4'	--
FLW	**5/02 0950**	41.9 ft (5/02@1900)	39.7 ft	1hr 30 min 5/2 1120	**104,000**	**Est 80,300** 0930: 9.2' 1000: 10'	5/02 0830 Conf. Call: 100 kcfs
FLS	**5/02 1118**	41.9 ft (5/02@1900) to 45 ft possible tonight	41.0 ft	0hr 2 min Est 5/2 1120	**104,000**	**Est 94,900** 1100: 11.6' 1130: 12.4'	No updated RVF from OHRFC
FLS	**5/02 1619**	48.0 ft (5/3@0100)	45.4 ft	~4 hr Est 5/2 2015	**141,000**	**Est 176,000** 1615 32' 1700 34'	5/02 1330 Conf. Call: 124, 130-140 kcfs
FLS	**5/02 1828**	48.0 ft (5/3@0100)	46.6 ft	1hr 45 min Est 5/2 2015	**141,000**	**Est 212,000** 1700 34' 2100 33'	5/02 1643 – LRN can hold 150 kcfs
FLS	**5/02 2200**	50.3 ft (5/3@1300)	48.6 ft	4hr 45 min Est 5/03 0240	**151,000**	**204,960** 2200 32'	5/02 1950; OHRFC used 150 kcfs
FLS	**5/03 0402**	51.5 ft (5/3@1300)	**50.5 ft**	9hr 28 min Est 5/03 1330	**181,000**	**Est 183,500** 5/03 0400 31'	5/02 2300 LRN to OHRFC "use estimated 220[1] kcfs"
FLS	**5/03 0725**	51.5 ft (5/3@1300)	50.7	6hr 5 min Est 5/03 1330	**181,000**	**Est 197,400** 0615 32' 1300 31'	--
FLS	**5/03 1542**	52.0 ft (5/3@1900)	51.6	*Crest 51.86 5/03 1800*	**190,000**	**Est 168,600** 1530 27' 1545 25'	--
Final Crest	**5/03 1800**	--	51.86	Crest 51.86 5/03 1800	--	**150,183** 1730 22.8 ft	--

[1]Release of 220 kcfs release imposed in one forecast run following conference call, but that run was not used to produce a forecast; 222 kcfs setting was superseded by Nashville flow settings.
[2] Maximum Gate Opening (full release) at Old Hickory is 34 feet. This resulted in a release of about 212,000 cfs (this magnitude of release had never been seen at Old Hickory)
[3]Time elapsed from product issuance to reaching Forecast Crest Stage
Note: In Table 5, river stages are taken from the 15-minute time series published on the USGS website http://waterdata.usgs.gov/tn/nwis/uv/?site_no=034315005 at the time of this report and are considered provisional. For times not on the hour, stages are interpolated. Old Hickory project releases include the total of the hourly turbine and gate flow records provided by USACE LRN, and are interpolated to the nearest 100 cfs increment for times not on the hour. "Peak Old Hickory releases used by OHRFC" describe the approximate maximum Old Hickory release during the forecast period in the NWSRFS model runs.

3.5. WFO Louisville (LMK)/WFO Paducah (PAH)

3.5.1. Pre-Event (LMK/PAH)

WFO LMK was preparing for the May 1 Kentucky Derby the weekend before the flood event and had issued their first Hazardous Weather Outlook (HWO) on April 25. The nationally televised Derby was expected to attract more than 150,000 people, elevating the importance of the weather forecast and potential for severe weather or heavy rain for the weekend. The HWO indicated the potential for thunderstorms and heavy rain Friday, April 30, through Saturday, May 1. Increased specificity with respect to the heavy rain was added to AFDs early in the week.

WFO PAH communicated a consistent message concerning the potential for severe flooding as early as Thursday, April 29, when it issued a flash flood watch. PAH never wavered from that message up to and through the event. This instilled a sense of confidence and credibility in NWS forecasts with EM and other users.

WFO LMK began to discuss staffing on Wednesday, April 28, and had a firm plan in place by Thursday. On Friday, staff members were assigned shifts that included coverage for river flooding. Two staff members were onsite at the Kentucky Derby on May 1. The Kentucky Regional Response Manager for Jefferson and nearby counties stated, "*We got the most extreme top-notch service from the NWS during the Kentucky Derby*." WFO PAH also had schedules for additional staffing fixed as early as Thursday, April 29, for the upcoming weekend event.

On Wednesday, April 28, WFO LMK DSSs began with a briefing to the Kentucky State EMA during a weekly conference call. On Thursday and Friday, Media/EMA Hazardous Weather Conference Calls were held with 83 and 139 people, respectively. The SH made numerous one-on-one calls to EMAs, observers, the USACE, and dam operators on Friday.

Fact: WFOs LMK and PAH pre-planned staffing for the weekend as early as Wednesday, April 28, and Thursday, April 29, respectively.

Best Practice 4: Proactive and explicitly defined pre-event staff planning served WFOs PAH and LMK well and enabled them to stay largely proactive throughout the weekend.

3.5.2. Event Operations, Products, and Services (LMK/PAH)

WFOs PAH and LMK issued numerous products. There were many positive comments about the accuracy and timeliness of products issued and the responsiveness of WFO staff. The Assistant Director of Operations for the Kentucky EMA said, "*There were sufficient warnings, timely, good heads up, and dead on target.*" The LMK WCM also received many positive comments about his work with EMAs and development of positive working relationships, including his onsite assistance during a potential dam break in Metcalf, KY.

Kentucky EMAs made comments concerning the number and urgency level of flood warnings and statements. Several EMAs and media interests mentioned that there were too many warnings and extensions, causing confusion and overloading systems. The urgency of warnings was also noted, and one media person stated, *"[We] felt like there was not a sense of urgency… maybe can use Flash Flood Emergency… no clue it was a major, big deal until it was too late."* An EM said, *"products need to convey urgency…use phrases like, 'this has the potential to be on the scale of*

flooding in 1969, 1975, etc.;' the public expected typical flooding." Even in AFDs, there was no sense of urgency or comments like *"could rival 1969 (Camille) flooding, and comparisons would have been useful."* Another EM stated that *"[the NWS] needs a DSS position at the WFOs, focusing on local communications needs and one-on-one communication*."

USACE LRD hosted conference calls on Sunday at 8:30 a.m. and 1:30 p.m., which included the OHRFC. The OHRFC did not extend an invitation for affected WFOs to participate in these calls, which may have been beneficial with respect to communications. On Sunday afternoon, USACE LRD called PAH to inform them of high releases, in terms of flow, from Barkley Dam. USACE LRD did not relay the information in a manner that would have prompted a more urgent response from the WFO, such as providing impact information that high releases would flood communities downstream. Likewise, WFO PAH did not ask clarifying questions to determine expected downstream river levels or impacts.

PAH issued a Special Weather Statement Sunday afternoon to address the high releases from Barkley Dam, which was not EAS-activated, while the USACE had anticipated an EAS-activated flash flood warning. WFO PAH issued a Flash Flood Warning at 8:17 p.m., Monday, which was EAS-activated. As a result of uncertainty with respect to impacts of high flows out of Barkley Dam, there were differing expectations in terms of WFO products issued. Technical communication and lack of understanding of each agency's operations played a large role in this misunderstanding.

3.6. Verification

River flood warning lead times ranged from 4-6 hours **(Table 7 and 8)** but varied considerably based on river basin topography and response to extreme rainfall intensity.

The official flood warnings for the Cumberland River at Nashville had negative lead times in initial forecasts for Flood Stage, Moderate Flood Stage, and Major Flood Stage. The performance of forecasts at *regulated* locations (at which USACE release data were incorporated) was notably less accurate than that of forecasts at *unregulated* locations (at which USACE release data were *not* used).

Flash flood warnings for the event had generally 1-2 hours of lead time, with OHX averaging nearly 2 hours of lead time **(Table 7)**.

Table 7: Summary of individual WFO statistics for river and stream locations that either flooded or were forecast to flood. Discrepancies exist between WFOs in how flooding is reported. WFOs can report an incident as either a Flood, which does not count in Flash Flood Verification, or as a Flash Flood.

River Flood Verification Summary								
NWS Office	**River Flood Warnings Verified**	**River Flood Warnings Missed**	**False Alarms**	**Total Warnings**	**Average Lead time**	**POD**	**FAR**	**CSI**
Nashville (OHX)	9	7	5	21	4 hours 41 min	0.56	0.36	0.43
Louisville (LMK)	6	1	0	7	9 hours 48 min	0.86	0	0.86

Flash Flood Verification Summary							
NWS Office	**Flash Flood Warnings Verified**	**Flash Flood Warnings Missed**	**Unwarned Events**	**Total Warnings***	**Average Lead Time**	**POD**	**FAR**
Nashville (OHX)	7	0	1	7**	110 Min	0.86	0
Louisville (LMK)	15	10	20	25	65 Min	0.46	0.40
Paducah (PAH)	10	2	2	12	62 Min	0.80	0.167

* Total flash flood warning numbers includes extensions to initial warnings.
**OHX discontinued the issuance of flash flood warnings on May 1 in lieu of areal flood warnings.

Table 8: Significant river and stream location verification statistics.

Location (WFO)	First Flood Warning Issuance (CDT)	Time Above Flood Stage (CDT)	Lead Time
Green River at Woodbury **(LMK)**	5/1/2010 9:45 PM	5/2/2010 4:55 AM	7 hours 10 min
Kentucky River at Frankfurt **(LMK)**	5/2/2010 9:31 AM	5/3/2010 3:48 AM	18 hours 17 min
Mill Creek at Antioch **(OHX)***	5/1/2010 12:39 PM	5/1/2010 1:20 PM	41 min
Harpeth River at Kingston **(OHX)**	5/1/2010 3:10 PM	5/1/2010 3:08 PM	0
Harpeth River at Bellevue **(OHX)**	5/1/2010 3:10 PM	5/1/2010 6:20 PM	3 hours10 min
Harpeth River at Franklin **(OHX)**	5/1/2010 3:10 PM	5/1/2010 5:48 PM	2 hours 38 min
Cumberland River at Nashville (**OHX)**	5/2/2010 9:50 AM	5/2/2010 9:44 AM	0
Cumberland River at Clarksville **(OHX)**	5/1/2010 9:31 PM	5/2/2010 1:04 AM	3 hours 33 min
Duck River at Columbia **(OHX**)	5/1/2010 8:47 PM	5/2/2010 2:14 PM	17 hours 27 min

***** Mill Creek is a Site Specific Forecast Point

4. Summary of Findings, Recommendations, and Best Practices

4.1. Findings and Recommendations

Finding 1: Limited interactions among OHRFC, USACE LRN, and TN USGS prior to this historic flood contributed to a lack of understanding of each agency's operational procedures, forecast processes, and critical data needs. This led to a breakdown in effective interagency communication, especially on Sunday, May 2.

Recommendation 1: OHRFC management and operational staff should increase regular interactions and table-top exercises with USACE LRN and the TN USGS. These management and operational staff interactions should include defining interagency procedures and mutual data needs to optimize collaboration and effective operations/forecasting services during routine and extreme events.

Finding 2: Real-time exchange of critical data among agencies during this event was insufficient and limited. In the short term, additional automation of this critical data exchange would have enhanced the forecast process at OHRFC.

Recommendation 2: OHRFC should develop a list of data exchange processes that can be automated. The list should be provided to USACE and USGS. Candidates for automation should include updated headwater/tailwater conditions and real-time water release data for USACE projects.

Finding 3: There is no framework for the Federal agencies involved with water forecasting to seamlessly exchange data, leverage each agency's models/systems, and work from a common operating picture.

Recommendation 3: Federal water agencies should accelerate efforts to develop and implement technological advances and a framework that enables seamless data exchange and a common operating picture. The interagency Integrated Water Resources Science and Services (IWRSS) initiative is an appropriate framework to promote such enhanced collaboration.

Finding 4: There is an urgent need for dynamic GIS-based flood inundation mapping that can be integrated into NWS watch and warning operations and be made available to the public, partners, and emergency management entities.

Recommendation 4: Tri-agency collaboration on development and implementation of dynamic GIS-based flood inundation mapping should be expedited as part of the interagency IWRSS initiative.

Finding 5: USACE district offices in Huntington, WV and Pittsburgh, PA and LRD had taken the necessary training to allow them access to the MMEFS results. USACE district offices in Louisville (LRL) and LRN and TEMA, had not taken the training and therefore, had no access to the MMEFS forecasts during this flood event.

Recommendation 5: The OHRFC should provide onsite MMEFS training to relevant partners including the USACE, USGS, and other appropriate state and local agencies.

Finding 6: Several OHRFC staff did not understand that river model updates could be made with 6 UTC and 18 UTC QPF data.

Recommendation 6: RFCs should update QPF input during 06 and 18 UTC model runs when river forecasts need to be updated to ensure the latest QPF is used in NWS hydrologic river modeling.

Finding 7: OHRFC consistently reduced the HPC QPF used in river forecast operations before the event on Friday and during this event on Saturday. Reducing QPF beyond 24 hours is a common practice at RFCs, due to uncertainty in extended periods. However, there was no coordination with HPC on these changes.

Recommendation 7: To increase communication between field offices and HPC before and during significant hydrological events, field offices should request, or HPC should initiate, HPC hosted conference calls with affected WFOs and RFCs. These calls should be modeled after those successfully used by NWS's Storm Prediction Center.

Finding 8: Not all RFCs communicate how they are using QPF and observed rainfall, or Quantitative Precipitation Estimation (QPE), in their river forecast models with critical external partners, such as the USACE and USGS.

Recommendation 8: RFCs should communicate in detail their use of QPF and QPE in generating river forecasts to the USACE and USGS, and other critical partners. One possibility would be to provide this information on the Advanced Hydrological Prediction Service (AHPS) webpage.

Finding 9: Leadership on operational shifts is critical for an office to function effectively and efficiently during a rapidly changing, non-routine, extreme event. Additional staff on Sunday would have allowed for in-depth review of data and critical forecast processes and procedures by

senior operational forecasters, enhanced communication with WFOs and partners, including obtaining real-time rainfall observations, and more frequent updates of river crest forecasts that had been exceeded.

Recommendation 9: RFCs should implement proven staffing models that other RFCs have employed prior to and during high impact events.

Finding 10: OHRFC staff members did not deviate from the established Cumberland River forecast process of incorporating USACE projections, even when faced with a rapidly deteriorating meteorological/hydrological situation and a lack of real-time information and projections from USACE LRN. OHRFC did not use the RES-J model for Old Hickory appropriately, negatively affecting the forecast for the Cumberland River at Nashville. A staff member at OHRFC stated, "we would never overwrite information from the USACE." Another said, "…felt that was a lot of water at Nashville, but felt the USACE would hold it as they always had."

Recommendation 10: RFCs should evaluate their forecast processes for "standard" dependencies on forecast data from partners (e.g., release data from USACE projects), and develop procedures to recognize and address situations in which such standard forecast processes are no longer valid.

Finding 11: There is no comprehensive training tool available to RFC forecasters to build confidence in working extreme hydrologic events and to assess the reliability of alternative forecast processes and methodologies if standard operating procedures become invalid as an event unfolds.

Recommendation 11: NWS should develop the ability for RFC forecasters to conduct training sessions using archived operational data from historic flood events, allowing forecasters to experiment with alternatives to standard forecasting procedures. This 'simulator program' should use operational hydrologic tools, providing a capability analogous to that of the Weather Event Simulator (WES), which WFO forecasters use to train on meteorological events.

Finding 12: Many forecasters do not have the tools or experience to routinely incorporate pattern recognition, and use of anomalies and short range ensemble data, into the forecast process.

Recommendation 12: The NWS should enhance training for operational forecasters on pattern recognition for extreme events and use of anomaly data in the forecast process in an effort to better predict rare or record events.

Finding 13: AFDs are widely used by media and EMs to assess severity of events. Despite mention of possible flooding in AFDs, there was no discussion of potential severe impacts and consequences from the heavy rain or flooding. In this case, "up to 8 inches" of rain and the potential for record rainfall amounts implied serious hydrologic consequences.

Recommendation 13: Include a hydrology section in AFDs, including possible impacts, when there is a potential for significant rainfall and flooding.

Finding 14: Not all WFOs staff and prioritize adequately for high impact hydrologic events.

Recommendation 14: WFOs should employ a team approach to working hydrologic events

similar to how significant severe weather events are handled. This approach should include appropriate prioritization of staffing resources and hydrologic related duties.

Finding 15: There were several instances in which OHX and OHRFC should have communicated more effectively with respect to forecasts for the Cumberland River at Nashville. On Sunday the initial Flood Warning for Nashville was exceeded within an hour and a half, but no official forecast update was issued for another 6 hours. WFOs and RFCs should ensure that they understand each other's data needs, forecast processes and product suites and that they communicate effectively with each other when updates are necessary.

Recommendation 15: Operational staff at WFOs and RFCs should routinely participate in forecaster exchange and familiarization visits to better facilitate communication and understanding of each other's operational processes.

Finding 16: As a result of an inadequate training tool to efficiently drill on hydrological events, not all NWS forecasters are confident in their abilities to handle difficult, rare flooding episodes. One forecaster stated, "We do not use river programs much. They are difficult for meteorologists to integrate into operations." This relates to an agency wide emphasis on severe weather, difficulty in using several different pieces of software for river flood monitoring and product issuance, and lack of routine exposure to and training for non-routine hydrologic events. Currently, there is no end-to-end simulator mode for hydrologic services in WFOs.

Recommendation 16: NWS should develop the capability for WFO forecasters to conduct training sessions using archived operational data from historic flood events. Such training should use operational hydrologic tools to provide a simulation capability analogous to the functionality provided by the WES used in WFOs.

Finding 17: Most local, state, and federal agencies that deal with incidents, including weather-related disasters, do so under the National Incident Management System (NIMS). They follow an Incident Command System (ICS) model for staffing and resource management to further enhance communication and collaboration between agencies. Many field offices staff EOCs that are managed by partner agencies during high impact events.

Recommendation 17: WFOs should incorporate proven WFO staffing models that have been successfully employed prior to and during high impact events. These models should include adopting relevant ICS staffing principles during non-routine, high impact events. Relevant ICS staffing practices should be considered for daily operational use, as well.

4.2. Best Practices

Best Practice 1: The MMEFS results, HAMs and the Significant River Flood Outlook products were used by OHRFC as a way to alert to partners such as USACE, USGS and FEMA that significant flooding was possible.

Best Practice 2: OHX had built strong relationships with media and partners, helping them communicate effectively before, during, and after the event. One EM stated, "Every agency was taxed during this event. Overall, one of the best interactions we have is with WFO Nashville, a good relationship." TEMA stated, "We have a fantastic relationship with the NWS Nashville WFO."

Best Practice 3: At 10:15 a.m., Friday, April 30, Southern Region Headquarters sent an email reminding Southern Region WFOs of the option to use "Flash Flood Emergency" in headlines to convey extreme flooding and threat to life and property. This email went to all MICs, WCMs, and Hydrology Program Managers at each WFO.

Best Practice 4: Proactive and explicitly defined pre-event staff planning served WFOs Paducah and Louisville well and enabled them to stay largely proactive throughout the weekend.

Appendix A: Acronyms

12Planet	Internal NWS Chat Software
AFD	Area Forecast Discussion
AGL	Above Ground Level
AHPS	Advanced Hydrologic Prediction Service
AWIPS	Advanced Weather Interactive Processing System
cfs	Cubic Feet per Second
CEMs	Civil Emergency Messages
CHPS	Community Hydrologic Prediction System
CDT	Central Daylight Time
CWA	County Warning Area
D2D	Display Two Dimensions
DSS	Decision Support Service(s)
EAS	Emergency Alert System
EM	Emergency Management/Manager
EMA	Emergency Management Agency
EOC	Emergency Operation Center
ER	Eastern Region
FEMA	Federal Emergency Management Agency
FFG	Flash Flood Guidance
FFMP	Flash Flood Monitoring and Prediction
FFS	Flash Flood Statement
FFW	Flash Flood Warning
FLS	River Flood Statement
FLW	Flood Warning
GEFS	Global Ensemble Forecast System
GIS	Geographic Information System
GPRA	Government Performance and Results Act
HAM	Hydrologic Alert Message
HAS	Hydrometeorological Analysis and Support
HMD	Hydrometeorological Discussion
HPC	Hydrometeorological Prediction Center
Hz	hertz
ICS	Incident Command System
iNWS	Interactive NWS, mobile weather service delivery
ITO	Information Technology Officer (at an NWS Weather Forecast Office)
IWRSS	Integrated Water Resources Science and Services
LF	Lead Forecaster
LMK	Identifier for Weather Forecast Office Louisville
LMRFC	Lower Mississippi River Forecast Center
LRL	USACE District Offices in Louisville
LRD	USACE Great Lakes and Ohio River Division
LRN	USACE Nashville District
LSR	Local Storm Report
mb	Millibar
MIC	Meteorologist-in-Charge at an NWS Weather Forecast Office

MMEFS	Meteorological Model-Based Ensemble Forecast System
MPE	Multisensor Precipitation Estimator
MSL	Mean Sea Level
NCDC	National Climatic Data Center
NIMS	National Incident Management System
NOAA	National Oceanic and Atmospheric Administration
NWR	NOAA Weather Radio All Hazards
NWS	National Weather Service
NWSRFS	NWS River Forecast System
NWSChat	Internet-based chat software
NWSI	National Weather Service Instruction
OCWWS	Office of Climate, Water and Weather Services
OEM	Office of Emergency Management
OHRFC	Ohio River Forecast Center
OHX	Identifier for Weather Forecast Office Nashville
PAH	Identifier for Weather Forecast Office Paducah
PDS	Particularly Dangerous Situation (Tornado Watch)
POD	Percentage of Detection
PW	Precipitable water
QPE	Quantitative Precipitation Estimation
QPF	Quantitative Precipitation Forecast
RES-J	Joint Reservoir Operation
RFC	River Forecast Center
RR1/RR2	Hydrologic Data Products
RVF	Deterministic Hydrologic Forecast
SAME	Specific Area Message Encoding
SCEP	Student Career Employment Program
SDM	Station Duty Manual
SDH	Senior Duty Hydrologist
SHEF	Standard Hydrologic Exchange Format
SOO	Science Operations Officer
SPC	Storm Prediction Center
SRH	Southern Region Headquarters
SSHPS	Site Specific Hydrologic Prediction System
TADD	Turn Around, Don't Drown™
TEMA	Tennessee Emergency Management Agency
USACE	United States Army Corps of Engineers
USGS	United States Geological Survey
UTC	Coordinated Universal Time
WCM	Warning Coordination Meteorologist
WES	Weather Event Simulator
WFO	Weather Forecast Office
XEFS	eXperimental Ensemble Forecast System

Appendix B: Definitions

Partners: Refers to organizations acting in an official capacity such as federal agencies (e.g., USACE, USGS), media, local Nashville officials, and local and state EM agencies.

Customers: General public and private entities such as businesses.

Fusion Team: A tri-agency (NWS, USACE, USGS) consortium formed in response to the 2008 upper Mississippi River flood. The team's mission is "to improve accuracy and utility of river/rainfall observations and river forecasts with an emphasis on collaboration, interoperability, and a common operating picture." The Fusion Team's mission was extended to address collaboration issues uncovered during the Kentucky and Tennessee floods of May 1-2, 2010, the subject of this Service Assessment.

National Weather Service offices are responsible for forecasts and warnings with respect to hydrological events as outlined below.

HPC provides forecasts, guidance, and analysis products and services to support the 24x7 public forecasting activities of the NWS and other HPC customers. HPC develops and distributes daily QPFs to all CONUS NWS offices and posts them online for public use. QPFs are evaluated and used by the RFCs to prepare river stage forecasts.

RFC: There are 13 NWS RFCs across the United States, which provide hydrologic forecasting. RFCs also provide a range of hydrometeorological data, including river stage forecasts for over 4,400 locations. Each RFC provides these river forecasts to local WFOs within the RFC's service area. The OHRFC, located in Wilmington, Ohio, is responsible for forecasts along the Ohio River and its tributaries, including the lower Cumberland River Basin. Cumberland River forecasts from the OHRFC are provided to the Nashville Weather Forecast Office for evaluation and public dissemination.

WFOs receive river forecasts and guidance from RFCs. After reviewing the river forecasts for accuracy, WFO forecasters use this guidance to compose river flood watches, warnings, and advisories for public dissemination.

Appendix C: Findings and Recommendations from Previous NWS Service Assessments

Note: *The following Findings and Recommendations from previous Service Assessments/Natural Disaster Surveys, were found to be relevant to "*Record Floods of Greater Nashville: Including Flooding in Middle Tennessee and Western Kentucky, May 1-4, 2010." *These are summarized below; wording may not be exact.*

C1 Finding: Warnings and statements did not convey to users the needed sense of urgency.

C1 Recommendation: NWS should review its directives in regard to the wording of severe thunderstorm and flash flood watches and warnings. The degree of seriousness and urgency of the situation should be conveyed by the warnings. – ***Big Thompson Canyon Flash Flood July 31-August 1, 1976***

C2 Finding: …many demonstrated an inability to accept fully the reality of the situation and to take rational actions under the extremely danger conditions with which there were faced…

C2 Recommendation: NWS should provide community self-help, education, etc… – ***Big Thompson Canyon Flash Flood July 31-August 1, 1976***

C3 Finding: …Improved QPF for mesoscale heavy precipitation events is needed..

C3 Recommendation: …highest priority a coordinated R&D program to develop an improved capability for forecasting rainfall amounts associated with convective activity…- ***Johnstown, Pennsylvania Flash Flood of July 19-20, 1977; Southeast United States Floods, September 18-23, 2009***

C4 Finding: …most field forecasters have difficulty with forecasting rare events…

C4 Recommendation: NWS should model the Flash Flood Warning program more closely after the hurricane and tornado warning programs. - ***Johnstown, Pennsylvania Flash Flood of July 19-20, 1977***

C5 Finding: …Forecast uncertainty information, such as ensemble forecasts of river stage prepared by NCRFC, was very useful to the USACE and others in their contingency planning…

C5 Recommendation: The NWS should expand its provision of forecast uncertainty information to the USACE and other local and state agencies involved in flood contingency planning – ***Central United States Flooding of June 2008***

C6 Finding: A number of users of NWS products would benefit from an expanded suite of probabilistic QPFs, river stages, and river flows.

C6 Recommendation: The NWS should make available as expeditiously as possible HPC's experimental probabilistic QPF capability and the XEFS for river forecasting – ***Central United States Flooding of June 2008***

C7 Finding: The NWS did not sue chat/instant messaging to collaborate with its Federal partners, such as USGS and USACE during this event.

C7 Recommendation: The NWS should investigate using current technologies such as chat/instant messaging to facilitate communication and collaboration with Federal partners, such as the USGA and the USACE, and with partners during flood events – ***Central United States Flooding of June 2008***

C8 Finding: There were occasions when not aware… of USGS activities… and USGS/USACE were not acquainted with details of the NWS flood forecast process…

C8 Recommendation: Periodic meetings should be scheduled at least annually between collaborating offices of the NWS, USGS, and USACE to discuss their common data and forecast needs and ensure all points of contact are current. – ***Central United States Flooding of June 2008***

C9 Finding: The NWS, USGS, USACE should initiate a scientist/engineer exchange program so staff better understands the operations, requirements, and constraints of each organization.

C9 Recommendation: The NWS should pursue the proposed creation of an Interagency Fusion Cell… - ***Central United States Flooding of June 2008***

C10 Finding: Flood inundation mapping will help the public, media, emergency managers, and others visualize the spatial extent and depth of flood waters in the vicinity of NWS river forecast locations.

C10 Recommendation: The NWS should expand efforts with state and Federal agencies and other groups to accelerate the implementation of flood inundation mapping across the United States. Such information should use standardized geospational reference systems and should include indications of its accuracy and derivations. - ***Central United States Flooding of June 2008***

C11 Finding: …forecasters did not initially recognize the extreme magnitude of flash flooding…

C11 Recommendation: The NWS should develop enhanced situational awareness tools to help forecasters recognize extreme nature of unusual events by comparing against critical values, historical events, and climatology… - ***Southeast United States Floods, September 18-23, 2009***

C12 Finding: …few WFOs were aware of the NWS instruction 10-922 authorizing use of a Flash Flood Emergency…

C12 Recommendation: Warnings should be as specific as possible regarding area and severity of impact…Statements should include severity wording, i.e., flash flood emergency, life threatening, etc... - ***Southeast United States Floods, September 18-23, 2009***

C13 Finding: …WFO allowed flash flood warnings to expire and issued areal flood warnings because flooding was persisting more than 6 hours beyond the causative event…

C13 Recommendation: A review of the current suite of NWS flash flood and flood products should be conducted…including how best to handle flash flooding that is expected to last more than 6 hrs beyond the causative effect… taking into account public perceptions of the severity of flash flooding vs. areal flooding, use of Flash Flood Emergency, etc…- ***Southeast United States Floods, September 18-23, 2009***

C14 Finding: WFO concerning color coding on WFO AHPS web pages and the national Web site (water.weather.gov) consistency in time scales…s because flooding was persisting more than 6 hours beyond the causative event…

C14 Recommendation: NWS should review AHPS web displays of river forecast information to ensure forecasts are consistently depicted in terms of length of forecasts and color coding of categories and stages…- ***Southeast United States Floods, September 18-23, 2009***

C15 Finding: WFO staffing during the night and weekend was insufficient for aggressively soliciting feedback reports and providing a full level of decision-support services…

C15 Recommendation: WFO staffing levels for significant flash flood events should be similar to those for severe weather events, including use of a Warning Coordinator position. - ***Southeast United States Floods, September 18-23, 2009***

C16 Finding: The loss of river gage data played a significant role in underestimating the river crest forecast…

C16 Recommendation: The RFC and WFO should use alternate methods to assess river stage when automated gages fail…including on-site readings from the USGS…- ***Southeast United States Floods, September 18-23, 2009***

Appendix D: WFO Nashville NWSChat Log

May 1 – May 2, 2010 (CDT)

Date	Time	Description of Event
5/1/2010	0747	Flooding on I-24
5/1/2010	1131	US-70 flood
5/1/2010	1152	10.76" rain Humphreys
5/1/2010	1159	Flood Mill Creek
5/1/2010	1243	Flash Flood Nashville
5/1/2010	1244	I-40 boat rescues
5/1/2010	1253	13.34" rain—Humphreys Co
5/1/2010	1301	I-40 water rescues
5/1/2010	1342	Road flood—Nashville
5/1/2010	1359	I-65 water 2 ft. deep/car stranded
5/1/2010	1409	I-40 @ MM148 closed/flooded
5/1/2010	1422	Road flood Wilson Co
5/1/2010	1423	Massive flood: homes/cars; Stewarts Ferry, Nashville
5/1/2010	1434	Water across road Nashville
5/1/2010	1439	1-2 ft water, Nashville
5/1/2010	1441	Downtown Lebanon-home flooded; roads impassable
5/1/2010	1443	Nashville: 3"-6"on roads
5/1/2010	1452	Water up to headlights—Nashville
5/1/2010	1454	People trapped - Maury Co
5/1/2010	1455	Water rescues/persons trapped in car on I840 @ MM66 SE Nashville
5/1/2010	1456	Water 4-5 ft deep Ashland-NW Nashville
5/1/2010	1459	Lebanon road Flood
5/1/2010	1504	Cars lifted in yard from road flood: Wilson Co
5/1/2010	1519	Person trapped car @ Lebanon Arpt
5/1/2010	1524	All roads LaVerge City closed: Rutherford Co
5/1/2010	1551	Road washing into creek: Williamson
5/1/2010	1605	Flash flood Hwy 96 Williamson
5/1/2010	1625	Lawrenceburg flood: Lawrence
5/1/2010	1638	Harpeth over road—Nashville
5/1/2010	1647	Request for FFW on NWR: water rescues Wilson Co
5/1/2010	1654	Severe flooding: Lawrence
5/1/2010	1709	Hill slide road flood: Smith
5/1/2010	1720	Many homes flood under water; evacuations: Watertown
5/1/2010	1724	Flood Yellow Ck Clarksville
5/1/2010	1739	Lebanon Town Sq closed flood
5/1/2010	1741	Many roads under water: Lawrence

5/1/2010	1745	Bridge under water: Rutherford
5/1/2010	1802	Hwy 296 closed flood: Fentress
5/1/2010	1851	Roads impassable: Coffee
5/1/2010	1948	1 fatal: flood I-24: Nashville
5/1/2010	1959	2 fatal: SUV crossing creek: Stewart
5/1/2010	2238	Hwy 20 flash flood: Lawrenceburg
5/2/2010	0719	Torrential rain in downtown Nashville
5/2/2010	0731	Flooded highways 49&52
5/2/2010	0735	1 ft. of water on roads in Nashville
5/2/2010	0752	Flooded roads: Wayne
5/2/2010	0807	4 ft. of water at Central SportPlex downtown Nashville
5/2/2010	0845	Creek flood: Sumner
5/2/2010	0921	Road flooded—Nashville
5/2/2010	1042	Swift water rescues-hwy 20: Lewis
5/2/2010	1121	OHX: req damage reports other than flooding
5/2/2010	1211	Req when will Cumberland River crest Nashville: Davidson EC
5/2/2010	1228	OHX: 11.03" rainfall Sat-noon Sun
5/2/2010	1241	OHX: expect Cumberland River rises thru evng—crest later tonight
5/2/2010	1249	Home & farm under water/fast water: Davidson
5/2/2010	1252	10 homes flooded; nursing home evacuated: Wayne
5/2/2010	1253	Cumberland River cresting: numerous homes threatened: Wilson
5/2/2010	1310	Cars abandoned—S Nashville: Williamson
5/2/2010	1322	Severe flooding Lawrenceburg
5/2/2010	1325	Numerous streets flooded: Columbia
5/2/2010	1546	Lebanon's town square could be flooded within the hour: Wilson
5/2/2010	1559	OHX: "Roger that, Wilson Co"
5/2/2010	1614	OHX: officially rainiest day Nashville history: 13.06/2 days
5/2/2010	1720	Fielding many calls re: flood levels: Wilson
5/2/2010	1725	OHX: Cumberland River @ Hunters pt 57ft; rising sharply; info not online
5/2/2010	1735	Buffalo River out of banks/highest in 20 yrs: Wayne
5/2/2010	1953	Media—Cumberland River Nashville still crest @ 48ft?
5/2/2010	2002	OHX: keeping our fingers crossed…hoping for 48 ft could go to 49 ft
5/2/2010	2005	Media: lot of flooding downtown Nashville. Water has risen quite fast.
5/2/2010	2007	OHX: from EOC LT hr. ago: 2-ft surge; Stones Rvr into Cumberland Rvr
5/2/2010	2009	Media: Downtown flooded fast. Several streets impassable low side river
5/2/2010	2031	Houses evacuated Bigby Creek: sure of 40ft crest?
5/2/2010	2037	OHX: could rise 2 more ft. Update forecast in hr
5/2/2010	2038	OHX: confirm 42 ft Columbia
5/2/2010	2138	Media: Waterford Subdivision evacuated in O.H. from rising C.R.

Appendix E: NWS-USGS-USACE Correspondence

April 28 – May 3, 2010 (CDT)

Date	Time (CDT)	Description
4/29/2010	NA	(OHRFC) Conference call with USACE-LRD to expect widespread 3-5 inches, 9-10 inches in some places
4/29/2010	1430	(OHRFC) Sent email to Customer Advisory Committee with latest MMEFS Summary Map
4/29/2010	1449	(OHRFC) Sent email to Customer Advisory Committee with correction to MMEFS
4/30/2010	1230	(NWS Nashville) Sent email briefing EMAs and TEMA
4/30/2010	1239	(OHRFC) Coordinated with FEMA IV, TEMA, USGS, USACE and 167 other partners via Hydrologic Alert Message
5/1/2010	0235	(OHRFC) Sent email to Customer Advisory Committee with updated MMEFS
5/1/2010	0700	(USACE-LRD) Initiated coordination with TVA and NWS LMRFC in anticipation of initiating flood operations according to protocol.
5/1/2010	0700	(USACE-LRD) Requested LMRFC delay of lower Ohio/Mississippi River forecast until TVA provided afternoon release schedule
5/1/2010	0715	(USACE-LRD) Provided preliminary Kentucky and Barkley reservoir release schedules to LMRFC
5/1/2010	0730	(USACE-LRD) Conducted coordination call with USACE-Nashville to discuss conditions and provide reservoir release schedule
5/1/2010	0756	(OHRFC) Urgent email from Tom Adams to WFOs and USACE Great Lakes & Ohio Division (LRD)
5/1/2010	0830	(USACE) Conference call with OHRFC led by USACE-LRD
5/1/2010	0845	(USACE-LRD) Complete Ohio River model update and forecast; coordinate with LMRFC
5/1/2010	0900	(USACE-LRD) Issued forecasts, internal flood messages and Water Management Update to LMRFC
5/1/2010	1146	(OHRFC) Sent email to Partners List with Hydrologic Alert Message
5/1/2010	1330	(NWS Nashville) Conducted webinar for EMAs and TEMA
5/1/2010	1430	(OHRFC) Sent email to Customer Advisory Committee with MMEFS
5/1/2010	1432	(OHRFC) Sent email to Customer Advisory Committee with latest contingency forecast for Bluestone
5/1/2010	1730	(NWS Nashville) Briefed Nashville OEM & Mayor on potential for much more rain on Sunday

5/1/2010	1845	(NWS Nashville) Briefed Nashville OEM regarding a break in the rain overnight
5/1/2010	1900	(USACE) Nashville sent email to USACE-LRD stating 40-42 feet on Cumberland River at Nashville and 45 feet possible if QPF verified
5/1/2010	2114	(OHRFC) Sent email to Partners List with Hydrologic Alert Message specifically for Major to Record Flooding possible
5/1/2010	2200	(OHRFC) attempted to contact USACE-Nashville about updated flow forecast. No answer and no message was left.
5/2/2010	0000	(OHRFC) Called NWS Nashville and told them Cumberland River at Nashville will probably make flood stage
5/2/2010	0235	(OHRFC) Sent email to Customer Advisory Committee with MMEFS
5/2/2010	0416	(USACE-LRD) forwarded email from USACE Nashville to OHRFC saying they would try to hold Nashville at 40-42ft based on the USACE model runs, speculated flood may exceed 1984 if QPF realized.
5/2/2010	0500	(OHRFC) Midnight shift told day shift it was imperative to talk to USACE Nashville. Model showed 54 feet at Nashville with full QPF
5/2/2010	0515	(USGS) Received call from NWS Nashville concerning gage status, measurement priorities of Harpeth River at Bellevue and Kingston Springs, and that NWS Chat was not being used. Report also relayed to OHRFC.
5/2/2010	0538	(OHRFC) Tried to call USACE-Nashville to coordinate. No answer.
5/2/2010	0638	(OHRFC) Called USACE-LRD to find way to contact USACE-Nashville. Was told they should be there at 0715. Also indicated to USACE-LRD that using OHRFC simulations, Nashville stage would exceed 54ft.
5/2/2010	0715	(USACE-LRD) called LMRFC to provide latest reservoir and release information, but stressed it would probably change
5/2/2010	0730	(NWS Nashville) Sent email briefing EMAs and TEMA
5/2/2010	0803	(USACE-LRD) Arranged conference call between OHRFC, USACE-Nashville, and USACE-LRD for 0830.
5/2/2010	0830	(USACE LRD) facilitated conference call with OHRFC, scheduled next call for 1330.
5/2/2010	0830	(NWS Nashville) Briefed Nashville OEM and Mayor's Office
5/2/2010	0852	(USACE-LRD) Sent email to set up conference call with OHRFC for afternoon
5/2/2010	0900	(OHRFC) called OHX to coordinate Nashville forecast of 42 feet, but local rainfall could push it higher.
5/2/2010	0908	(NWS Nashville) Coordinated with USGS about gage outages
5/2/2010	0930	(OHRFC) called USACE Nashville and USACE-LRD to coordinate further.
5/2/2010	1001	(OHRFC) Sent email to Partners List with Hydrologic Alert Message

5/2/2010	1046	(NWS Nashville) Relayed message from TN USGS to OHRFC with flow measurement for Kingston Springs. Indicated that Bellevue and Kingston Springs gages inundated... out of service indefinitely
5/2/2010	1100	(USGS) Called NWS Nashville back to confirm gages inundated at Bellevue and Kingston Springs
5/2/2010	1300	(USACE-LRD) Conducts a teleconference call with USACE-Nashville and TVA to discuss and approve proposed releases
5/2/2010	1330	(USACE-LRD) Conference call with OHRFC, Old Hickory flows 124000cfs, pool 1 ft surcharge. Increasing to 130,000cfs, maybe 135,000-140,000cfs. Cordell Hull will hold 60,000cfs until 1800 CDT tomorrow. Cheatham dam under water, unregulated
5/2/2010	1505	(USACE-LRD) Received call from LMRFC with final public forecast for the lower Ohio River
5/2/2010	1430	(USACE-LRD) called OHRFC and requests they coordinate with NWS-Paducah about Kentucky and Barkley increased releases. OHRFC requests USACE-LRD call NWS Paducah directly to ensure information relayed correctly.
5/2/2010	1430	(USACE-LRD) called NWS-Paducah to communicate release schedule and requested that appropriate public advisories and warnings are issued
5/2/2010	1440	(USACE-LRD) notified USACE-Nashville and OHRFC of planned teleconference call for 0830 CDT next day
5/2/2010	1515	(OHRFC) DOH called in Dunham Lake KY dam potential failure as seen on Weather Channel
5/2/2010	1536	(NWS Nashville) Communicated new Nashville forecast to Nashville OEM
5/2/2010	1610	(NWS Nashville) Coordinated with Nashville OEM
5/2/2010	1643	(NWS Nashville) Relayed new Nashville forecast to USACE. USACE now fairly confident they can hold at 150,000 cfs
5/2/2010	1700	(NWS Nashville) called OHRFC with TN USGS observation at BELT1 33.23 feet and steady
5/2/2010	1824	(NWS Louisville) called OHRFC with information on Harrington Lake.
5/2/2010	1834	(NWS Louisville) called OHRFC with updated information on Dunham Lake Dam.
5/2/2010	1839	(NWS Nashville) OEM calls WFO Nashville asking about the 2-3 foot rise in Cumberland River
5/2/2010	1943	(NWS Nashville) Called USACE-Nashville to coordinate
5/2/2010	1950	(USACE) Called NWS Nashville about releases, Percy Priest increased from 5,000 to 10,000 cfs; Old Hickory at 150,000 cfs
5/2/2010	1900	(NWS Nashville) Called USACE Nashville about the latest dam releases
5/2/2010	1900	(NWS Nashville) Passed USACE info onto Nashville OEM
5/2/2010	2004	(NWS Nashville) relays Percy Priest and Old Hickory information to OHRFC based on information received from USACE.

5/2/2010	2126	(OHRFC) Issued 50.3 feet for Cumberland River at Nashville based on info from NWS Nashville
5/2/2010	2247	(OHRFC) coordinates with NWS Nashville, updated Clarksville to 57 ft and Kingston Springs to 44.5 ft.
5/2/2010	2259	(OHRFC) Calls NWS Nashville to talk with Service Hydrologist--no updates from USACE Nashville. Sandbagging not working.
5/2/2010	2300	(OHRFC) called USACE Nashville for Cumberland project flows. Old Hickory 222,000 @8 PM ballpark number because they were above gate ratings. Situation going from bad to serious
5/2/2010	2310	(USACE Nashville) called OHRFC to discuss how they were going to estimate the flow at Cheatham Dam.
5/2/2010	2315	(USACE Nashville) called OHRFC with estimated Cheatham dam flows of 220000cfs
5/2/2010	2320	(OHRFC) called NWS Nashville to coordinate update of Carthage forecast.
5/2/2010	0830-0940	(OHRFC) Coordination calls to USACE-LRD, USACE Nashville, and WFOs based on 41.9 ft forecast for Nashville.
5/3/2010	0000	(NWS Nashville) Time between 2300 and 0245 CDT. Called OHRFC stating sandbagging in Nashville ongoing but ineffective.
5/3/2010	0020	(USACE Nashville) called OHRFC with releases at Cordell Hull of 90k cfs. Old Hickory ~ 220000 cfs going down to no lower than 175,000 cfs and being lowered by 5,000 cfs per hour.
5/3/2010	0100	(OHRFC) Updated Cumberland at Carthage forecast to 43.0 feet from 39.0 feet
5/3/2010	0235	(OHRFC) Sent email to Customer Advisory Committee with MMEFS
5/3/2010	0245	(OHRFC) Coordinated with NWS Nashville on 51.5 feet at Cumberland River at Nashville
5/3/2010	0700	(USACE-LRD) Received latest reservoir and release schedule from TVA and provided LMRFC with preliminary release schedule
5/3/2010	0830	(OHRFC) Conference call with USACE-LRD and NWS Nashville. Kept Nashville forecast at 51.5 feet
5/3/2010	0852	(NWS Louisville) Called OHRFC to update them on situation on Green River at BWG.
5/3/2010	0900	(OHRFC) Sent major to record alert to partners via Hydrologic Alert Message
5/3/2010	1001	(NWS Nashville) Briefs TEMA regional director about Cheatham Dam levels
5/3/2010	1030	(NWS Nashville) Conducts webinar with EMAs and TEMA
5/3/2010	1054	(NWS Nashville) Requests flood assessment support from OHRFC through email.

5/3/2010	1120	(USACE) Nashville calls OHRFC with Cordell Hall gate openings and Old Hickory gates were being lowered
5/3/2010	1140	(NWS Nashville) Briefs TEMA regional director about Cheatham Dam levels
5/3/2010	1157	(USACE - LRD) Sent email to OHRFC and NWS Nashville to set up conference call for 1330 CDT
5/3/2010	1230	(OHRFC) Conference call with USACE Nashville
5/3/2010	1243	(NWS Nashville) Emailed middle TN EMAs and TEMA about webinar to be held Monday 5/4 at 1030 AM CDT
5/3/2010	1330	(OHRFC) Conference call with USACE-LRD and Nashville, and NWS Nashville w/ Nashville forecast at 52.0 feet. On same call, forecast for 61.5 feet was stated for Cumberland River at Clarksville
5/3/2010	1345	(OHRFC) Hosted conference call with City of Nashville, TEMA, NWS Nashville, and USACE-LRD. Forecast was 52.0 feet
5/3/2010	1347	(NWS Nashville) Provides update to OHRFC on Opry Land evacuations.
5/3/2010	1430	(OHRFC) Sent email to Customer Advisory Committee with MMEFS
5/3/2010	1430	(OHRFC) Conference call with USACE Nashville to see if Percy Priest could be used to hold 52.0 feet at Nashville
5/3/2010	1432	(OHRFC) Sent email to Customer Advisory Committee with latest contingency forecast for Bluestone
5/3/2010	1700	(USACE-LRD) received a call from EOC stating they were getting calls about flooding below Barkley Dam in town of Luka
5/3/2010	1730	(USACE-LRD) held conference call with TVA and USACE-Nashville to discuss flow reduction scenarios
5/3/2010	1730	(USACE-LRD) On this same call, the decision was made to reduce flows, possibly resulting in record pool levels and dam safety implications
5/3/2010	1919	(NWS Nashville) Coordinates with OHRFC
5/3/2010	1930	(OHRFC) Conference call with USACE Nashville
5/3/2010	1930	(NWS Nashville) Coordinates with USACE
5/3/2010	1955	(NWS Nashville) Sent email for conference call with OHRFC, USACE/LRD/Nashville for 10 am Tuesday