Department of Homeland Security
Federal Emergency Management Agency

Modeling and Data Working Group Flood Scenario Analysis

DRAFT

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Contents

Introduction

According to the US Geological Survey (USGS), floods cause $6 billion in property damage and 140 deaths, on average, per year.[1] In recent decades, improved warning systems have decreased fatalities resulting from flood events, but floods have become more costly as populations trend toward increased concentration in urban areas and as development continues in coastal areas.[2] Flood events and their impacts have affected a broad geographic range of the US, though certain regions are particularly prone to flooding. Floods are an ongoing concern for emergency response planning, but the frequency of the event, and therefore the opportunity to collect and analyze data about these events, provide an opportunity for data-driven flood planning, prevention, and mitigation.

Flood modeling and analysis are critical to supporting operational decision making for flood event emergency management. Data analysis and predictive modeling can help address the specific causes of floods at specific locations, and drawing on datasets describing historical events can inform future planning. This report outlines an analysis of models and datasets used across the US federal interagency emergency management community for flood response operations. Through a combination of interviews with subject matter experts, literature research, and analysis, a comprehensive collection of models and datasets used by the federal emergency management community for flood-related emergency operations was recorded and annotated.

This effort was commissioned by the Modeling and Data Working Group (MDWG). The MDWG, chaired by the Director of FEMA's Planning Division, Response Directorate, has broad interagency membership including subject matter experts, program managers, and program directors representing each of the federal Emergency Support Functions and is appointed by the Emergency Support Function Leadership Group (ESFLG). Previous efforts led by the MDWG analyzed models and datasets for response to hurricanes, earthquakes, and in planning for a potential attack by improvised nuclear device (IND). Models and datasets identified for these hazards were incorporated into an interactive, web-based inventory, the ESFLG Model and Data Inventory (MoDI), which has now been expanded to flood hazards.

Report overview

Floods are a diverse and complex hazard. This report outlines key background concepts necessary to understand floods and flood modeling, defines the three flood sub-types most commonly considered in the context of emergency management, and includes a discussion of the type of data and information required to support flood modeling and analysis. The results section outlines the types of models and datasets used by the federal emergency management community for flood events, describes the iterative flow of information through data collection and analysis, and presents the results of a systems-level analysis of the models and datasets available to support flood event response. Finally, these datasets and models are presented along a flood event timeline example to support the application of these tools prior to and during an event. The flood event timeline also details when datasets and models become available and is accompanied by Appendix 3 which describes how each tool supports specific data requirements and highlights key considerations for the most effective use of the specific datasets and models available for flood response operations at the federal level.

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[1] U.S. Department of the Interior, U.S. Geological Survey (January 2006). *Flood Hazards – A National Threat. (Fact Sheet 2006-3026).* Retrieved from http://pubs.usgs.gov/fs/2006/3026/2006-3026.pdf

[2] ibid.

Background: Flooding

To best understand the process of flood modeling, it is important to consider the diversity of flooding and the underlying causes. This section provides an overview of the water cycle and the three major categories of flooding: riverine, coastal, and flash. This background information provides context for the parameters necessary for robust flood modeling for each flood type.

The water cycle

The water cycle is the process by which water is cycled and recycled on Earth (Figure 1). In short, this cycling begins with moisture stored in the air, most notably as clouds. Clouds are moved by wind, allowing the moisture to be transported to new areas. Moisture will remain in cloud form until the temperature or pressure of the surrounding air is no longer sufficient to keep the water suspended. When this threshold is passed, due to a change in the temperature or pressure or the result of the water particles growing too large from collision and coalescence, the water will return to the ground as precipitation (rain, snow, hail, or sleet, depending on climatic conditions). Data regarding the precipitation, such as the rate, amount, and type, can be used to forecast consequent flooding.

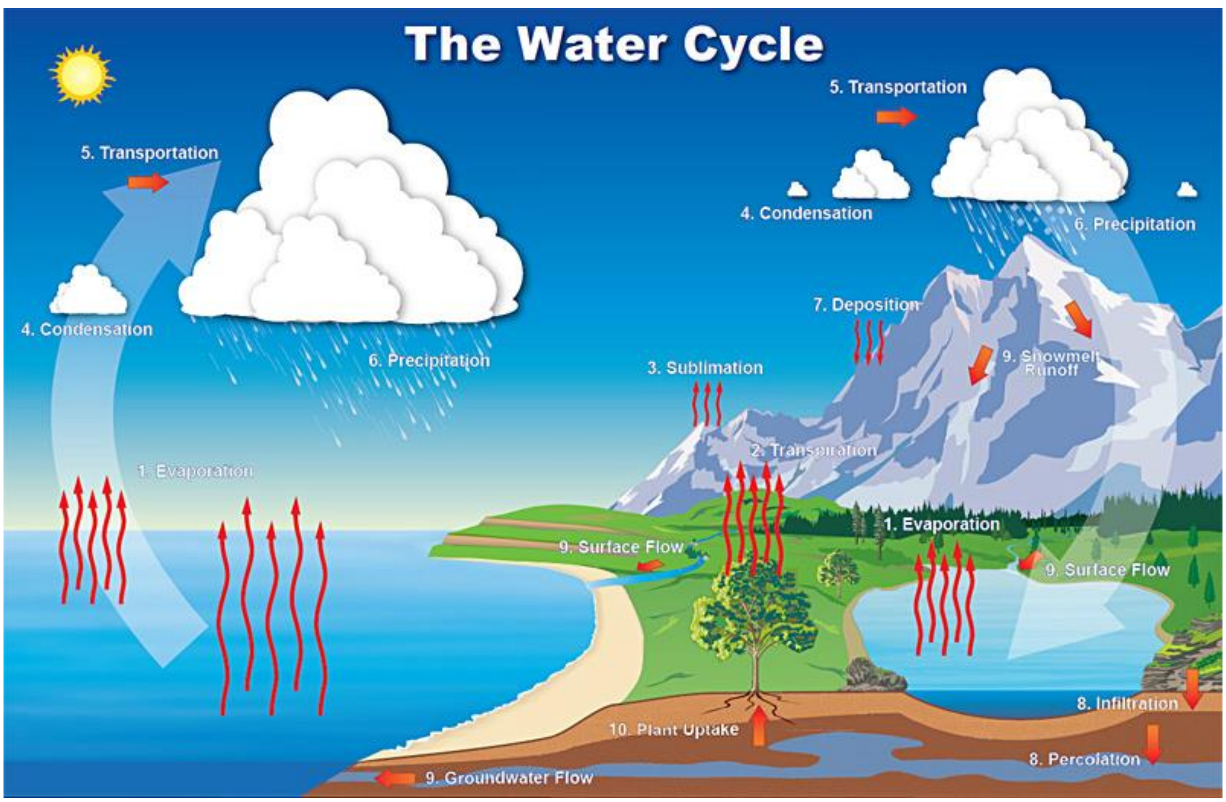

Figure 1. The water cycle.[3] Water moves through Earth's surface, sub-surface, and atmosphere across the water, or hydrologic, cycle.

3 Graphic from the National Weather Service Jetstream Project. *The Water Cycle*. Retrieved from National Oceanic and Atmospheric Administration http://www.education.noaa.gov/Freshwater/Water_Cycle.html

Once on the surface of the earth, precipitation can remain in place, be transported, or soak into the ground where it fell. Lakes, oceans, fallen snow, and glaciers are all the result of precipitation that remains where it falls. Precipitation is transported via moving bodies of water (which in this discussion will be collectively referred to as streams) or as ground runoff. Ground runoff is precipitation that moves along the surface of the ground outside of a stream, such as water running down a hill during a rainstorm. The amount of runoff that occurs during a precipitation event is determined by the precipitation rate, infiltration rate (the rate at which the water is absorbed into the ground), precipitation amount, soil type, and soil moisture level. The precipitation that infiltrates the soil percolates (slowly filters) downward through the subsurface until it reaches an aquifer or some other underground body of water. As depicted in Figure 1, the interdependencies between water and its surrounding environment place the Earth's water in a continual state of flux between the components of the water cycle.

Flood types

A flood occurs when a normally dry area becomes water-covered. Flooding may occur via direct inundation (when there is no protection or barrier), including pooling of precipitation, overtopping a barrier (when the height of the water exceeds the height of the barrier, and thus spills over the top of it), or breaching a barrier. In the context of emergency management, floods are categorized as flash flooding, riverine flooding, and coastal flooding. Flash floods form rapidly and can occur almost anywhere. Riverine floods are restricted to the general area surrounding the riverine system and build more gradually and then fade away. Coastal flooding occurs along the coastline and is usually the result of wind and waves. Each flood type can occur separately, in tandem with one another, or as the result of one another. For example, a storm that has a high volume and rate of precipitation to cause riverine flooding could also cause flash flooding outside the riverine system. Likewise, a flash flood could terminate in an existing stream system that is already swollen from precipitation, causing it to overtop its banks. Flood models quantify the unique factors contributing to flash, riverine, and coastal flooding but the interrelation between flood types can have an important impact on emergency management for floods, particularly when considering cascading effects. Below are detailed descriptions of riverine, coastal, and flash flooding, including a discussion of the differences between several common methods used to describe riverine flood magnitude and a description of the types of data required to model sub-category of floods.

Riverine floods

Riverine flooding occurs when water escapes from the normal confines of the riverine system, such as a stream or lake. A stream is a body of water which flows down a slope along a defined path, or channel. Streams are fed by snowpack and ice melt, ground runoff, and outflows from standing bodies of water. Smaller streams combine and feed together to create larger streams, or tributaries. One stream system can have multiple levels of tributaries, causing all of the precipitation over a large area to feed into a single stream; thus, flooding can occur at significant distance from the source of the precipitation or water influx.

In addition to the structure of the stream system, stream flooding is also affected by the infiltration rates of the soil in and around the stream. If the soil in the area of concern is not able to absorb water quickly, then a large portion of the precipitation will become runoff, which will gather in the stream system and could cause flooding. However, if the soil in the area is capable of rapidly absorbing large quantities of water, then a significantly larger amount of precipitation is required to cause stream flooding.

Stream flooding occurs when the water escapes the channel, either by the stream height reaching the point at which it overtops the banks or by the failure of a levee or dam. To forecast overtopping events, modelers will gather data on measurements such as the stream height, precipitation and infiltration rates (comparing the two can inform modelers regarding what percentage of the precipitation will enter the stream system), and stream state (the overall condition of the stream, e.g. normal, elevated, flooding, etc.). Importantly, overtopping can only occur when enough water enters the stream to cause it to rise above the level of its banks. If sufficient data are available for these parameters, models can forecast overtopping floods, as do the U.S. Army Corps of Engineer's reservoir flood models. These models help account for the increased likelihood of levee or dam failure, as caused by increased stream height.

Failure of a dam or levee can lead to large-scale flooding. A levee is an embankment along a stream, either natural or manmade, which prevents the water from entering the surrounding low-elevation area; dams cross a body of water to restrict its flow. This type of flooding can be particularly damaging as the built environment usually fills areas once prone to flooding but are now dry due to the levee or dam. Therefore, when the barrier fails, the now unprotected area will likely be subjected to severe flooding once again. In this way it is different than basic riverine flooding, as large areas can become flooded at once and there is little warning, rather than the water progressively reaching further and further past the banks of the stream. A well-known example of inundation due to barrier failure is the flooding that occurred in the Lower 9th Ward of New Orleans during Hurricane Katrina.

Lakes and their surrounding regions are likewise susceptible to flooding due to increased precipitation. As most lakes are fed by stream systems, an increase in precipitation anywhere within the system can potentially cause the lake to flood by raising the water level. With the water level raised, land below the new water level will become inundated. Additionally, as with increased stream depth, an increase in the elevation of a lake's surface can result in levee and dam failures due to increased pressure and water reaching portions of levees and dams that are usually not exposed to the effects of the lake.

Terminology

Riverine floods are often described relative to their frequency as 5-year, 50-year, 100-year, or 500-year floods. The longer the time-period, the larger the flood. These terms do not mean that once such a flood has occurred, it will not occur again for another 5, 50, or 100 years. Rather, these are a description of annual exceedance probability. That is, dividing these values by 100 yields the annual exceedance probability for a flood of that size. For example, if a flood is described as a 100-year flood, there is a 1% chance that a flood of that size or larger will occur with a 12 month period. Therefore, a 100-year flood could occur twice within a few years, though it is not statistically likely.

However, frequency is only one way of describing or measuring the size of a riverine flood. Other ways commonly used are flood stage, flood height, or flow rate. A flood stage is a general reference to the level of the water surface of a stream above an established height at a specific location (as measured by gauges). The four commonly used stages are[4]:

- Action Stage –water near or slightly above the elevation of its banks; initiates preparatory activity by the responding organization
- Minor Flooding – minor flooding resulting in minimal or no property damage; minor public threat and Flood Advisory product issued
- Moderate Flooding – some inundation of structures and roads near the stream; evacuations may be initiated due to elevated threat to the public
- Major Flooding – extensive inundation of and damage to structures and roads resulting in significant evacuations and transfer of property to higher elevations; Flood Warning issued if major flooding is expected to occur during an event

Flow rate is also sometimes used to describe the scale of a flood because it describes how much water is entering the area of concern within a given timeframe.

Coastal floods

Coastal flooding, as can be inferred by the title, occurs along coastlines. The basic causes of coastal flooding are storm surge and sea level rise. Coastal or off-shore storms cause coastal flooding by a combination of tide and wind-driven water pushed onto the coast. If the coastline is unprotected (no levees), this influx of water can cause inundation further inland and upland than normal. If the shoreline is protected by levees, the waves generated by the storm surge can generate enough force to break or overtop the barrier. In either case, the surge-driven waves surpass the levees, and flood the protected area.

Sea level rise occurs when global temperatures increase, causing ice and snow to melt, which introduces more water into the active portion of the water cycle. As the water level rises, areas that were only slightly above the water level, and lack further protection, become inundated.

Flash floods

Flash flooding can occur when the rate of precipitation far exceeds the rate of infiltration in an area. Flash flooding can be measured and predicted by precipitation rate, but also factors such as soil type and soil moisture level. Notably, different types of soil have different infiltration rates, and the moisture already stored in the soil will affect how much more it can absorb and can also affect the rate of absorption (e.g., very dry soil can become hydrophobic, decreasing the rate of absorption and increasing the risk of flash flooding). In addition, flash flooding can be the result of the built environment, as infrastructure such as pavement and building foundations affect infiltration rates.

During flash flooding, ground runoff is high enough that it will collect in channels and low-lying areas. This runoff can merge, similar to tributaries feeding into a stream, and form a single, large volume of water that can be powerful and hazardous. Flash floods are especially dangerous due to unpredictability in where and when they will occur. Though some regions or drainages are more likely to be affected by flash floods, unlike coastal and stream flooding, there does not need to be a terrestrial source of water

[4] National Weather Service Alaska-Pacific River Forecast Center. *High Water Level Terminology*. Retrieved from http://aprfc.arh.noaa.gov/resources/docs/floodterms.php

in the area; flash floods can affect regions far from the source of the water or precipitation. Indeed, because flash flooding does not raise the level of an already established body of water, as would occur in riverine flooding, runoff levels can reach flood status very quickly, leaving little time for warnings.

Flash flood waters can retain the bulk of their volume and power over great distances and the front of the flood can become filled with debris that it encounters in its path. This debris can mean that the initial arrival of the flood can be especially hazardous with large debris such as tree branches and rocks all carried and pushed with great force and at a high velocity.

Additional flood types and contributing events

Flooding can also be caused or exacerbated by other corollary events. Two of the most salient include tsunamis and wildfires.

Tsunamis cause extreme coastal inundation in response to large-scale disturbances (i.e., earthquakes) on the ocean flood. The ground displacement causes a rapid, corresponding displacement of the water column; a wave proportional to the displacement moves through the water until it reaches a coastline or otherwise loses force. Predictive modeling and warnings have the potential to significantly reduce the loss of life and are critical for emergency management. However, these events were largely outside the scope of this effort, though the most relevant models and datasets are included in the MoDI.

Wildfires are a significant contributing factor to flooding. Most critically, wildfires affect the infiltration rate of the soil and the stability of the soil, particularly on slopes. A post-fire slope without vegetation is much more susceptible to flooding due to increased runoff rates. The lack of vegetation decreases the physical barriers to runoff that slow flow rate and increase absorption. Post-fire soils can also be more hydrophobic than before the fire, also decreasing absorption rates. Confounding this increase in runoff and flow rate, a lack of ground stability caused by the vegetation loss increases the risk of debris flows, amplifying the risk in post-fire regions. Datasets and models associated with post-fire flood risk are included in the MoDI, though wildfires are not included as an independent hazard.

Flood modeling parameters

Riverine Flooding

The types of data required to model flooding and a general overview of input parameters required for modeling riverine systems are described below, including how these factors relate to prediction of flood severity. Key riverine flood modeling parameters include (Figure 2):

A. Stream height – the depth of the water in the center of the channel
B. Stream flowrate – how quickly the water in the stream is moving; this is measured by stream gauges (permanent or temporary)
C. Stream width – the distance from the center of the stream to the bank
D. Elevation around stream – how much higher or lower the surrounding ground is than the stream

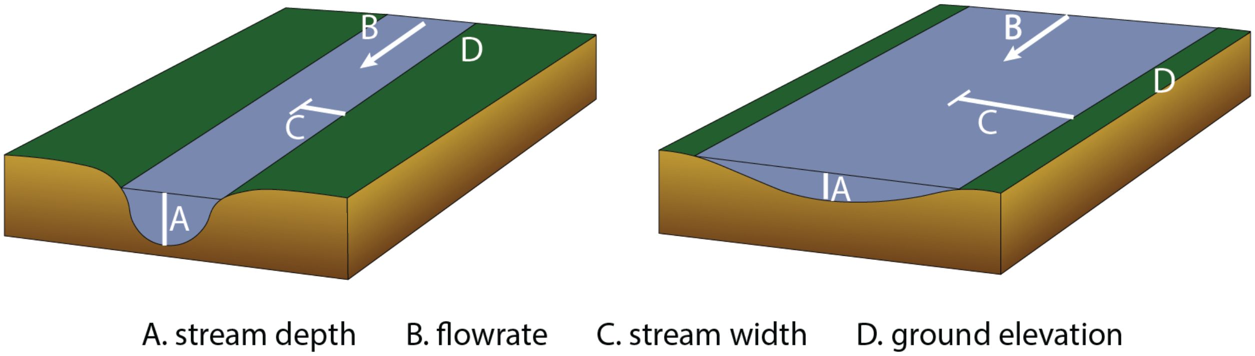

Figure 2. Measures of riverine flooding. Cross-sections of a two streams with approximately the same volume, but of differing width and depth. This figure highlights the importance of complete stream measurements since individual measurements do not accurately describe the true capacity.

Together, these parameters provide the underlying data required for riverine flood models to predict the extent of flooding. Stream depth (Figure 2 – A) corresponds to the total amount of water a channel can hold relative to the ground elevation (Figure 2 – D). This parameter is also affected by the current river stage. For example, at drought stage, there is room in the channel for a significant influx of water without overtopping the banks. Near flood stage, even a small amount of additional precipitation may be sufficient to overtop the banks. The flow rate (Figure B) describes the rate of the water moving through the channel. The stream width (Figure C) describes the width of the channel and horizontal extent of the water. These parameters together can be used to measure and predict water flow and, thus, flooding. For example, if a precipitation event causes more water to enter the system and the flowrate can increase to compensate without causing overtopping, then no flooding will occur. However, if the flowrate is not able to sufficiently increase to accommodate the additional water in the system, the stream height will rise. If the height rises beyond the local ground elevation, the steam width will expand, causing flooding in the surrounding areas. If the elevation around the stream is known, modeling can predict the progression of the flooding for the surrounding area as stream water levels rise to different heights.

The ground elevation around the stream is especially important when modeling streams that are bounded by manmade levees. As was discussed earlier, and depicted in Figure 3, when streams are edged with manmade levees to protect the low lying area around them, those low lying areas are often built upon, which makes flooding more damaging when it occurs. Since the area is lower in elevation than the stream, once the levee has been breached the water will naturally flow into the area, settling in the locations of lowest elevation. A similar scenario would occur with the failure of a large dam. Since the dam restricts the flowrate of the stream, the stream below the dam will be smaller than it originally was. The built environment may encroach on the now reduced stream, putting it directly into the region most susceptible to flooding if the dam fails.

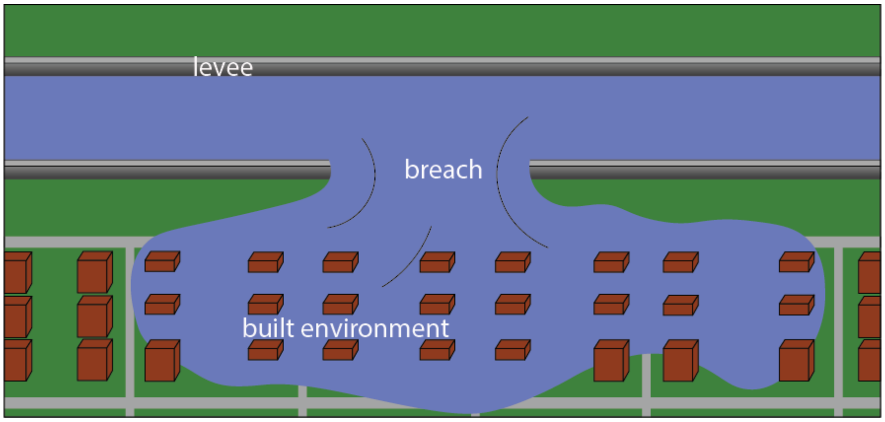

Figure 3. Flood caused by levee breach. Illustration of flooding that has resulted from a breach in a levee impacting the built environment outside the levee.

Other data required for flood event characterization modeling includes precipitation rate, precipitation amount, built environment/level of urbanization, and soil information. Precipitation rate and amount quantifies the water coming to the ground and potentially causing flooding. The built environment and degree of urbanization affect infiltration rate parameters and, sometimes, stream path, as streams are sometimes rerouted to accommodate the built environment. Re-routing can have a particularly significant impact, as the stream no longer follows the path of least natural resistance. Therefore, if a flood were to occur, the water that escapes the manmade channel may flood the built environment where the stream once was. Finally, soil type and soil moisture levels are also important model parameters. Different types of soil have different infiltration rates due to intrinsic soil characteristics and current moisture level; any moisture that can be absorbed into the ground will not contribute to the inundation occurring above ground.

Coastal Flooding

Elevation measurements are also integral to models of coastal flooding. A flat beach immediately adjacent to a neighborhood will provide significantly less protection than a coastline that has sand dunes between the water and the built environment. The coastal bathymetry, or elevation of the ground beneath the water, can also affect the relative risk of coastal flooding. Coastlines for which the ground level beneath the water rises quickly over a short distance will create taller waves, as the water is displaced and forced to rise quickly (as shown in Figure 4). These taller waves can be pushed by the wind further inland. The force of the waves hitting the natural and built environments causes the majority of the damage of the ensuing inundation. Additionally, taller waves create more turbulence in the water when they crash by displacing otherwise secured items and filling the water with dangerous debris.

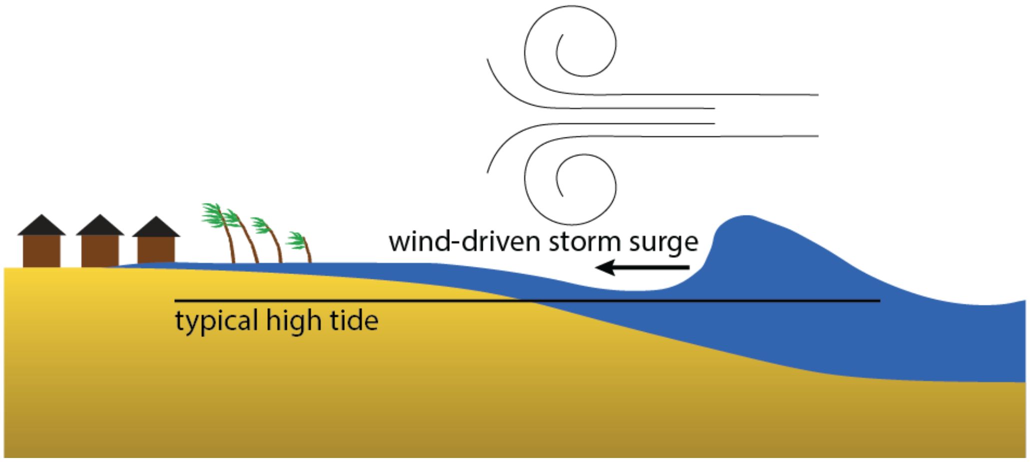

Figure 4. Graphical representation of coastal flooding

Results

Flood Modeling for Emergency Management

Effective emergency management – planning, response, recovery, and mitigation – in response to floods relies on understanding the event, its impacts on population and infrastructure, and the personnel and material requirements needed to support response efforts. Particularly for events as complex, varied, and high-consequence as floods, predictive analysis and modeling can provide advanced warning and inform mitigation efforts that have the potential to significantly reduce the impacts of the event both in financial loss and the loss of life. In the following sections, the data and models actively in use by the federal emergency management community to support operational decision making are described and analyzed to provide context about what information is available and from which sources and to better understand how to effectively leverage that information.

Information flow and network of flood datasets and models

The information needed to support operational decision making is produced by an iterative process of data collection, analysis, and computational modeling (see Figure 5). To understand a flood as it unfolds, raw data are processed by event characterization models to produce situational awareness data describing the event itself. Raw data include elevation datasets, data about soil types and hydrophobicity, the specific location of stream beds, built infrastructure, population, precipitation, and stream flow rates. These data together are processed by event characterization models that interpolate between disparate data collection points in the landscape and calculate the extent of flooding in a specific region in response to a specific event, whether a dam failure, extreme precipitation event, or coastal storm. These modeling outputs – situational awareness data – are most often viewed as layers in geospatial viewers. These data are processed by consequence models and analysis that integrate this event data with raw, locally-relevant infrastructure and population data to produce impact estimate data. In turn, these impact estimate data are processed by decision support tools that calculate the personnel and material required to effectively respond to the event: number of dump trucks required to remove debris, the number of people displaced and seeking shelter, or the amount of drinking water needed in the affected region.

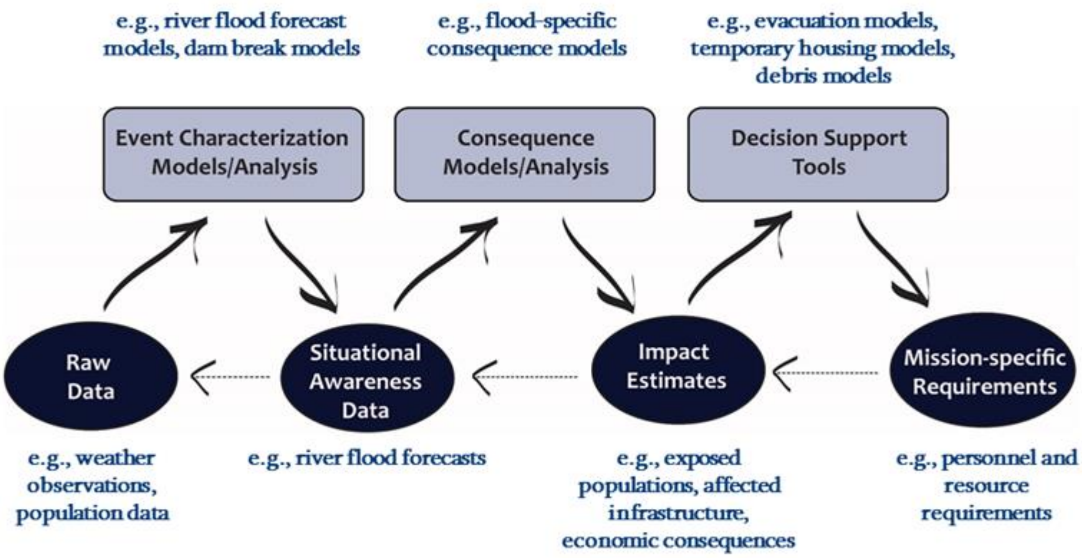

Figure 5. Flow of Information Framework. Iterative process of data collection and analysis through the different types of datasets and models used by the federal emergency management community. Flood-related examples are described above or below each category for the purposes of illustration.

Network of flood datasets and models

Through a series of interviews with federal emergency management stakeholders, 132 models and datasets were identified as actively used in support of operational decision making for flood scenarios. Each of these datasets and models were characterized by their interactions with other tools identified to understand the information linkages between the tools. These linkages indicate that the tools are drawing from the same underlying datasets or are mutually used by downstream tools in the iterative process of data collection and analysis. The network map shown in Figure 6 provides a graphical representation the information sharing between the tools. The datasets and models in the network are colored by where they fall in the flow of information described above and sized by the total number of agency-level users.

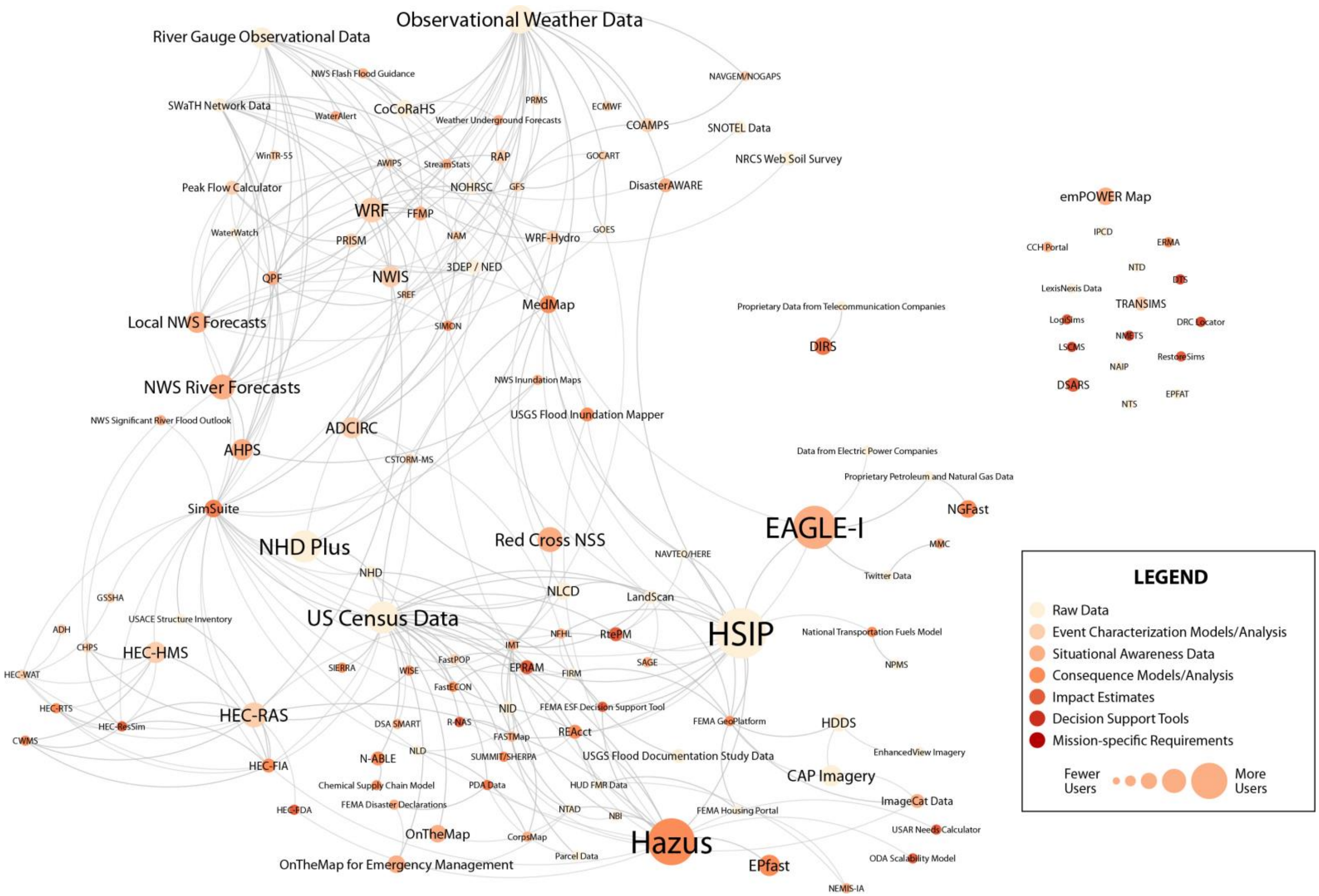

Figure 6. Network map of flood-related datasets and models used by federal emergency management community. Nodes (circles) are sized by the number of federal agencies using the tool. Information flows clockwise along edges (lines) between the datasets and models and indicate data transfer between information resources. Each node is colored by its position in the flow of information framework with raw data and event characterization models colored most lightly and decision support tools and mission specific requirement datasets colored most darkly.

Notably, the results shown in Figure 6 indicate the complexity and degree of connectivity between all the datasets and models in the system, despite a diversity of information owners and users. Moreover, while the total number of datasets and models identified in the inventory is large, relatively few are widely used. The most frequently used models and datasets are listed in Table 1 (below). Notably, of these models and datasets, all but one is used for event characterization (i.e., have a resource type of raw data, event characterization models/analysis, or situational awareness data). As will be discussed in more depth below, this overrepresentation suggests an imbalance in types of information that are widely used or available with only a limited number of resources associated with consequence or impact analysis. As a result, operationally-relevant translation of those impact estimates into decision support or mission-specific requirements is not readily available.

Table 1. Flood models/datasets in the full flood inventory with the most federal agency users. Models/datasets with at least 5 federal agency users are listed in decreasing order of number of users. Models/datasets with the same number of users are listed by their position in the flow of information. Asterisks next to model/dataset names indicate that the model/dataset is not response ready.

Models/Datasets	Users	Hazards	Resource Types
HSIP	12	All-Hazards	raw data
Hazus*	11	Flood	consequence model
EAGLE-I	10	All-Hazards	situational awareness data
NHD Plus	7	Flood	raw data
US Census Data	7	All-Hazards	raw data
Observational Weather Data	6	All-Hazards	raw data
HEC-RAS	5	Flood	event characterization models/analysis
WRF	5	All-Hazards	event characterization models/analysis
NWS River Forecasts	5	Flood	situational awareness data
Red Cross NSS	5	All-Hazards	situational awareness data

Centrality in the network

Figure 7 shows the same network of 132 models and datasets, but colored by their relative centrality. Centrality is an important network measure that describes the relative number of connections between dataset and models within the network. Based on an algorithmic analysis that calculates the number and weight of both upstream and downstream connections within the network, centrality can be used as a measure of relative weight of specific tools (see Appendix B for a more detailed discussion of centrality).

As shown in Figure 7, the most central models and datasets in the flood network are also used for event characterization. This highlights the importance of event characterization tools as information bridges that connect models and datasets to each other. The most central models and datasets in the flood network include flood forecast and warning products, such as the National Weather Service (NWS) River Forecasts; flood event characterization models, such as the Hydrologic Engineering Center River Analysis System (HEC-RAS) model; precipitation forecasts; and key underlying datasets used as inputs to models, such as Homeland Security Infrastructure Program (HSIP) data.

Notably, Hazus, a widely-used consequence model owned and managed by FEMA, is the most central information resource in the network. As a consequence model, the tool integrates a large amount of raw and situational awareness data, and its results are widely used by downstream decision support tools that rely on its impact estimates to establish personnel and material mission-specific requirements.

HAZUS has been in use since the mid-1990’s. Although it was originally designed to support mitigation activities, it has been used for preparedness (e.g. exercise planning), response, and recovery operations in the absence of tool more suited for these activities. Hazus is, therefore, a critical tool for federal interagency flood mitigation and planning for and mitigating against the impacts of floods. When the event characterization can be quickly generated externally (e.g. earthquake ShakeMap, Hurricane SLOSH) HAZUS can function reasonably well as a response tool. Because there is no near-real time event characterization for riverine flood (flood boundaries, depth grids), these must be generated by HAZUS or other means, which can take days.

Because of this, HAZUS is ill-suited as a flood response tool. This can be viewed as a limitation of HAZUS, but it can also be viewed as a gap in the ability of the federal interagency community to have a national solution for characterizing riverine flood event specifics. Put another way, HAZUS is a poor tool to model the riverine flood hazard in the response environment, but when provided flood extents and depths, it would be an adequate impact and consequences estimation tool in the response environment.

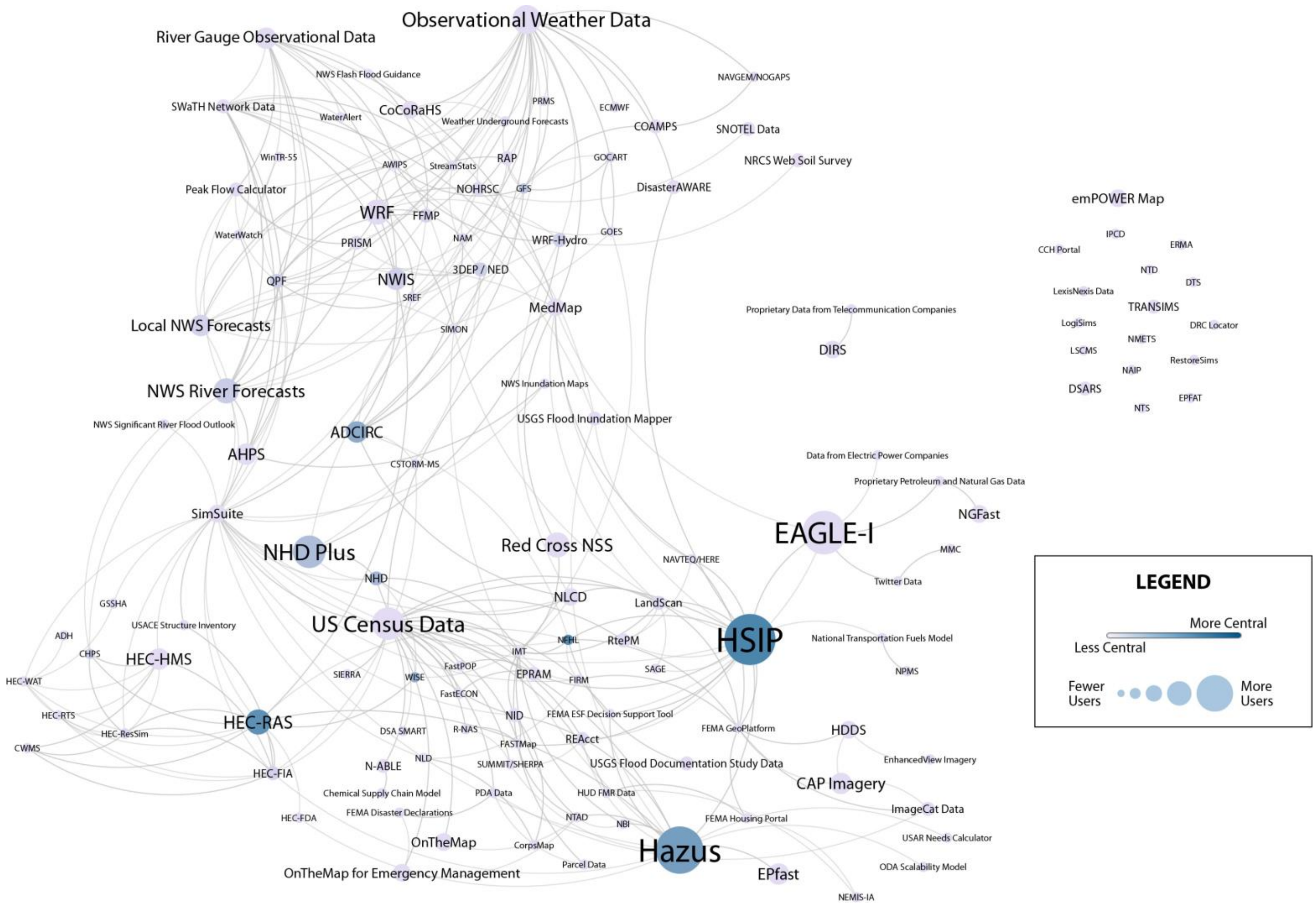

Figure 7. Centrality map of flood-related datasets and models used by federal emergency management community. Nodes (circles) are sized by the number of federal agencies using the tool. Information flows clockwise along edges (lines) between the datasets and models and indicate data transfer between information resources. Each node is colored by its relative centrality with the most central tools most darkly colored.

Event characterization modeling for floods

Of the event characterization models in the flood information resource network (Figures 6 and 7), some are specific to a single type of flooding as coastal, riverine, and flash flooding, with each requiring distinctly different models. The most widely used event characterization models associated with each type of flooding are discussed below. The relevant access and real-time utility of each is discussed in the section Flood modeling on and event timeline.

Coastal floods

The most robust and widely used coastal flooding model is the ADvanced CIRCulation (ADCIRC) model. ADCIRC is the USACE and University of North Carolina at Chapel Hill coastal surge model that predicts water height over time, inundation depth above ground, significant wave heights, and related outputs both during storm events and during normal operations for the Gulf Coast and the East Coast. In the context of coastal flooding that is not caused by storms, the ADCIRC model also provides these coastal surge outputs during normal operations when no storm event is being reported, but at less frequent time intervals. It is important to note that for hurricane scenarios, the National Hurricane Center uses the Sea Lake and Overland Surge from Hurricanes (SLOSH) model to predict coastal storm surge. The coastal surge predictions provided by SLOSH are widely used. However, as the SLOSH model is only run in the context of specific storms and is not available for on-going analysis of flood-specific events, it is not included in the flood inventory.

Riverine floods

NOAA, USGS, and USACE work together to model riverine flooding. The Advanced Hydrological Prediction Service (AHPS) website, hosted and managed by NOAA, serves as the access point for river flood forecasts and current river conditions, supported by robust, local modeling performed both at the national level and at local and regional National Weather Service (NWS) River Forecast Offices (RFOs). The NWS River Forecasts are a widely used and authoritative source of river flood forecasts. These forecasts incorporate data from the USGS real-time river gauge network, which provide data about real-time stage and flow rates at approximately 7,500 gauged locations in US rivers. A set of short-term gauges are also available from USGS to collect data during an event. However, these gauges (also used for coastal and flash floods) must be deployed before the event to be effective, requiring interagency coordination and tasking.

The USGS river gauge data also feed models owned by the Hydrologic Engineering Center (HEC) at USACE, including the widely used HEC River Analysis System (HEC-RAS) model and others, such as the HEC Hydrologic Modeling System (HEC-HMS) and the HEC Reservoir System Simulation (HEC-ResSim) models. These USACE models are, arguably, the most widely used authoritative source for flood event characterization modeling. These models are used with forecast and real-time meteorological data as input to generate riverine inundation maps that show the predicted extent and height of flooding. HEC-HMS, a watershed runoff model, accepts forecast and real-time precipitation, temperature, snowpack, and other data as input, and it produces runoff flow predictions. These flows are fed into the HEC-ResSim model, which determines their effect on reservoirs and linking channels. HEC-ResSim outputs the final flows, which are fed into HEC-RAS, the model which determines the extent and depth of flooding in the area.

Flash floods

The primary tool for flash flood event characterization is the NWS Flash Flood Monitoring and Prediction (FFMP) service. This service publishes flash flood advisories created using NWS Flash Flood Guidance and precipitation estimates from Quantitative Precipitation Forecasts (QPF) to highlight which counties are most at risk for flash flooding.

Consequence modeling for floods

Hazus is the single widely-used consequence model for floods. As shown in Table 1, Hazus is highly used in the network of floods models and datasets. However, while it is a powerful damage, impact, and economic loss model used broadly and heavily across the interagency for consequence analysis, the Hazus model for developing the flood hazard is not sufficiently robust to produce results for large-scale flooding events, and it can take a matter of days to produce a single set of results for a single flood scenario. It is therefore not considered response ready for flood scenarios. The US Geological Survey (USGS) Flood Inundation Mapper (FIM) offers preliminary, high-level Hazus flood impact estimates for various flood stage heights at a limited number of stream reaches, but the locations where these impact estimates are available are so limited that it is unlikely to be available for a given flood event.

While significantly less known, HEC Flood Impact Analysis (HEC-FIA) model is a consequence model now available from the HEC at USACE. HEC-FIA allows users to analyze the consequences from a riverine flood event by calculating damages to structures, losses to agriculture, and estimated potential for loss of life. The outputs of HEC-RAS, discussed in the previous section, are fed into the HEC-FIA to produce these impact estimates for the study area. HEC-FIA is currently operationally used by USACE for flood control projects and studies that are focused on USACE-managed water control structures. Additionally, the US Department of Agriculture (USDA) has used HEC-FIA to predict agricultural losses from flood scenarios. However, no steady-state modeling center currently exists to provide authoritative runs of HEC-FIA for large-scale riverine flood events for emergency management. HEC-FIA is applicable to riverine and flash floods, but it has not been used for coastal floods.

Lack of response ready consequence models and connections to operational tools

To analyze the relative strength of the information network available for flood emergency management in the context of planning and response, the bulk flow analysis shown in Figure 8 combines all the information resources in each flow of information category and illustrates the total number of resources and connections between each resource type. To better understand the information resources necessary to support emergency response, the bulk flow of information is compared between all flood-related inventory tools and those that are response-ready. Response-ready tools are those that are immediately available and useful in the context of emergency response. These tools may be open source and user-friendly for emergency managers or the results from the tools (e.g., modeling results) may be readily and publically available or from an analysis group or expert during a real-time event.

Despite the importance of consequence modeling to link and translate event characterization data into actionable information for operations there is a significant lack of response-ready consequence models available to support emergency management operations for flooding. This gap is particularly obvious when visualized as part of the bulk flow of information. Indeed, only a single consequence model in the flood inventory, USACE's HEC-FIA, is response-ready, and even the utility of and access to HEC-FIA outputs is limited by the lack of analysts tasked to run the model as a part of response activities.

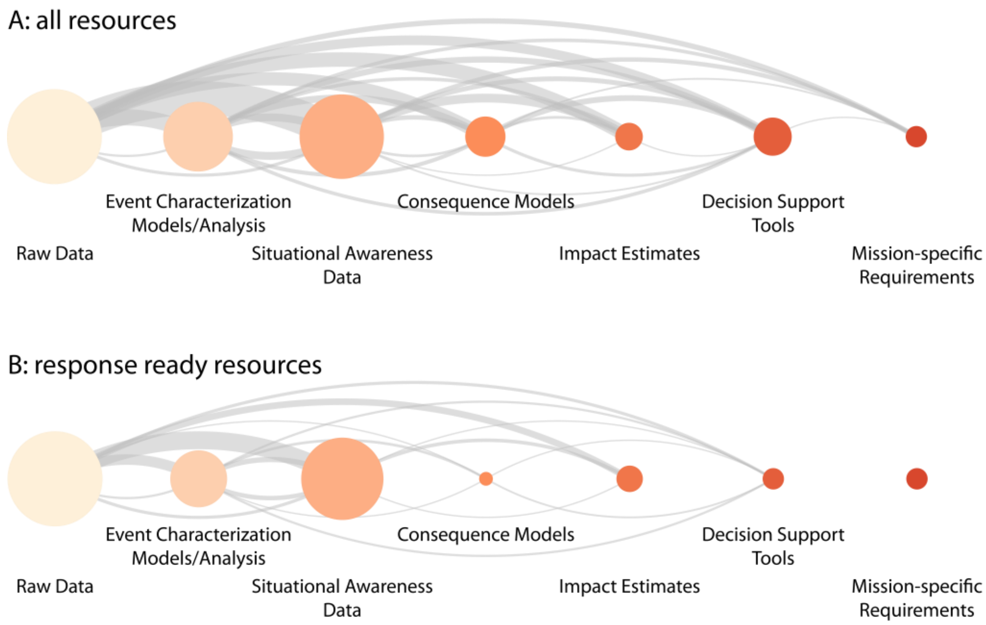

Figure 8. Bulk flow of information for all inventory resources (A) and response ready inventory resources (B). Nodes represent each Flow of Information category and edges represent the flow of information from a model/dataset in one category to a model/dataset in another. Node size is proportional to number of models/datasets in each category. Edge width is proportional to the number of connections between the two resource types. Information flows clockwise. Model/dataset connections between two resources of a single type not included.

Decision support for floods

Lack of integrated decision support tools and mission specific requirement datasets

Decision support tools and mission specific requirements are critical information sources for emergency managers, especially during crisis action planning and response when assets are being requested and deployed and the response tempo is most rapid. However, as shown in Figure 8 (above), there is a paucity of decision support tools and mission specific requirements actively in use. Beyond a lack of tools themselves, the available decision support tools and mission-specific requirement datasets that are available are not well integrated into the network. This is particularly true for the response ready network, shown in Figure 8B, in which connections between mission-specific requirements and other resource types are totally absent. Termed "orphan tools," (and shown in the region of all orphan tools in the upper right corner of Figure 5), these datasets and models do not exchange data with any other tools in the network. This lack of integration is particularly concerning for decision support tools, as these tools are intended to define event-specific requirements and rely heavily on accurate situational awareness data and impact estimates. Without linkages to the widely used sources of these data available from interagency partners, these tools can return outputs that diverge widely between agencies and even within an agency.

Flood modeling on an event timeline

Ultimately flood models and datasets are only useful during actual flood emergencies if users know where to access information and if data are in a usable format, with sufficient geographic coverage and resolution, and in time to inform event-specific data requirements. To this end, a detailed flood event timeline was developed to define the models and datasets currently used and useful for flood response operations (Figure 9, next page).

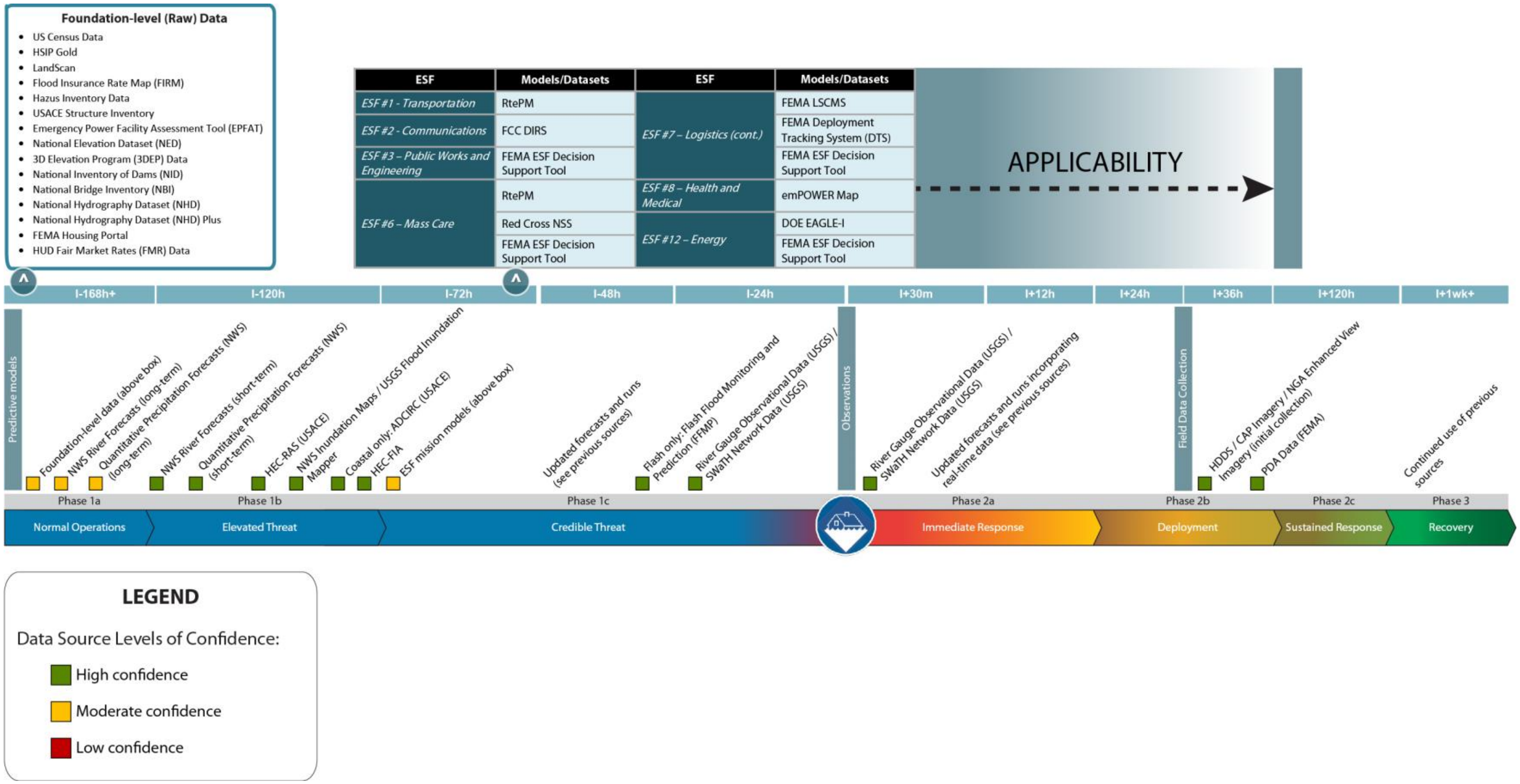

Figure 9. Overview of models and datasets used for flood event response operations. Timing (in hours) listed across the top, phase listed across the bottom, and data confidence noted in between, as defined in the legend. Upper left box lists foundation-level (raw) data relevant to informing response to a flood by informing planning during normal operations and serves as inputs to flood models. The table toward the top right lists the ESF-specific tools that support response operations as soon as sufficient event-specific inputs are available to utilize them. As depicted, ESF-specific tools continue to supply ESF-specific information through the response and deployment phases.

The timeline lists the most widely used and relevant datasets and models needed to support operational decision making for each phase of a specific notional flood event. The datasets and models listed early in the event should each be re-run and the data refreshed later in the event as needed to ensure the data remain up-to-date.

Expressing confidence in data sources

Each model or dataset is marked with a confidence level specific to flood response activities: high (green), moderate (yellow), or low (red). These confidence levels are based on three factors: number of key assumptions required, the credibility and diversity of sourcing in the knowledge base, and the strength of argumentation (Figure 10). Each factor was assessed independently and then in concert with the other factors to determine the confidence level for each model or dataset. High confidence models and datasets feature well-corroborated information from proven sources, minimal assumptions, and strong logical inferences and methods. Moderate confidence models and datasets are weaker in some of these characteristics, and low confidence models and datasets are weakest. No low confidence data sources are included in the timeline as they are not currently available for flood emergency management.

Models or datasets that appear on the timeline more than once may have different levels of confidence at different time points. For example, long-term NWS River Forecasts at I-168h+ are assigned a moderate confidence level because long-term river forecasting is technically challenging and expectations are that only moderate confidence will be placed in these results. In contrast, short-term NWS River Forecasts are assigned high confidence because they are well established and are expected to produce robust, high-confidence information during the elevated threat stage.

Additionally, supporting assessments derived from these models and datasets may feature likelihood terms or expressions to distinguish them from assumptions or reporting. Specific sets of likeliness terms generally correspond to the three confidence levels (Figure 10). Confidence levels help present analysis and conclusions to decision makers in a uniform, consistent manner.

LOW	MODERATE	HIGH
▪ Uncorroborated information from good or marginal sources	▪ Partially corroborated information from good sources	▪ Well-corroborated information from proven sources
▪ Many assumptions	▪ Several assumptions	▪ Minimal assumptions
▪ Mostly weak logical inferences, minimal methods application	▪ Mix of strong and weak inferences and methods	▪ Strong logical inferences and methods
▪ Glaring information gaps exist	▪ Minimum information gaps exist	▪ No/minor information gaps exist
Terms/Expressions:	Terms/Expressions:	Terms/Expressions:
▪ Possible	▪ Likely, unlikely	▪ Will, will not
▪ Could, may, might	▪ Probable, improbable	▪ Almost certainly, remote
▪ Cannot judge, unclear	▪ Anticipate, appear	▪ Highly likely, highly unlikely
		▪ Expect, assert, affirm

Figure 10. Levels of confidence in data sources. Models and datasets are assigned high, moderate, or low confidence depending on how the information they provide meets or does not meet the criteria above. Additionally, specific sets of terms and expressions can be used to express confidence in analytical judgments derived from those models and datasets. These levels of confidence are used in the timeline depicted in Figure 9.

An alternative presentation of the event timeline is presented in Appendix C with a more detailed description of each dataset and model, including a correlation between each tool and the specific data requirements it supports. Descriptions of the key considerations related to interpretation of the data confidence rating are also included.

The remainder of this section describes the application of the datasets and models identified in the MoDI to a flood event with specific consideration of the application of models and datasets at each phase.

Phase 1a. Normal Operations

Many floods can be predicted well in advance because precipitation, snow melt, or a recent fire can suggest that flood-prone regions in certain areas are at increased risk. In addition, areas within floodplains, coastal areas, and areas protected by water control structures or downstream of dams have a known, on-going flood risk. With this extended advance notice, flood response planning and emergency management efforts can begin well before the event.

Key questions can be addressed during advance planning include:

- What is the risk (i.e., how big will the flood be and what will flood)?
- What can be done to save life and property (i.e., who needs to be evacuated and when)?
- What preparations can be made now to support likely mission-specific needs?

Addressing these questions requires an understanding of the characteristics of the region threatened by flooding. As for any hazard, flood models depend on a range of raw data inputs about the population and infrastructure in the affected area, termed foundation-level data.

Foundation-level data

Foundation-level data, such LandScan population data, Homeland Infrastructure Security Program (HSIP) infrastructure data, and the National Hydrography Dataset (NHD), describe conditions in the incident area during steady-state. These datasets are critical inputs to and provide context for predictive and real-time flood modeling, and include information about the natural land characteristics (e.g., elevation data) and who and what may be affected by flooding (e.g., population and infrastructure data). While these datasets should be updated as often as possible to ensure up-to-date data, the update frequency depends on the dataset itself. For example, LandScan population data are updated annually, while Flood Insurance Rate Maps (FIRMs) may be updated several times per year as floodplains are altered by the construction of levees and changing river channel morphologies.

To move from foundation-level data to the event-specific information required for an actual event, it is important to consider the differences between the individual flood sub-types. For example, different inundation models apply only to riverine flooding and not coastal or flash flooding. In the following sections, where operations for riverine, coastal, and flash floods are informed by different datasets and models, those information sources are introduced in sections specific to the flood type.

Identify long-term flood risks (riverine floods)

Identifying areas at risk for floods weeks or months into the future is technically challenging. The most widely used, authoritative sources for characterizing long-term riverine flood risk are the NWS River Forecasts and Quantitative Precipitation Forecasts. Both are described as moderate confidence sources because of the limited fidelity of long-term flood forecasting. No long-term predictions are available for flash flooding. For coastal flooding, long-term climate models can help inform the overall picture of coastal flooding risk, but are not currently used for long-term flood risk analysis.

NWS River Forecasts (long-term)

The NWS has developed experimental, long-term river flood risk forecasts that predict the likelihood that a specific river gauge will exceed flood levels over a three-month period. Geospatial maps show whether each gauge is predicted to experience minor, moderate, or major flooding so that geographic areas most at risk can be quickly identified. These forecasts are not precise predictors of eventual floods, but can be used to prioritize seasonal flood monitoring. Of the approximately 7,500 operational USGS stream gauges, long-term river flood risk forecasts are available for approximately 2,500. Coverage is provided for CONUS and Alaska, but is most dense in the Eastern US. These river forecasts are open access and available online through the NWS Advanced Hydrological Prediction Service (AHPS) website. Short-range NWS river forecasts should be used to predict more imminent flood threats and are discussed later.

Quantitative Precipitation Forecasts (long-term)

The NWS Quantitative Precipitation Forecasts (QPF) provide the estimated amount of liquid precipitation expected to fall in a 6-hour period. The forecasts are available out to 7 days from the present with the shorter-term forecasts offering higher fidelity. The longer-range precipitation estimates from QPF can be used to predict flooding before short-term NWS River Forecasts are available and when the NWS River Forecasts are not available for the region of interest. QPF products are open access and available online for CONUS through the NWS Weather Prediction Center (WPC) website.

Phase 1b. Elevated Threat

As an elevated flood risk emerges, precipitation forecasts, inland and coastal inundation models, and flood-specific consequence modeling are used to update the event characterization and predict impacts to populations and infrastructure that may be affected. Specifically, emergency responders and the public need to know what areas are likely to flood, when, and to what extent. As in the credible threat phase, different models apply to riverine and coastal flooding. No models or datasets are available to predict flash floods at this early stage.

Riverine floods

NWS River Forecasts (short-term)

The short-term NWS River Forecasts predict river flood stage height and flow rate and can be used to determine which gauged rivers are at risk for imminent flooding. The forecasts incorporate real-time stage heights and flow rates recorded by USGS stream gauges. The short-term NWS River Forecasts are made approximately hourly. The forecast provides flood stage predictions for each 6-hour time point out to 5 days. Users can also view the maximum predicted flood category for each stream gauge over a multi-day period up to 5 days out (Figure 11). Of the approximately 7,500 operational USGS stream gauges, short-term river forecasts are available for approximately 3,500. Coverage is provided for CONUS and Alaska, but is most dense in the Eastern US. These river forecasts are open access and available online through the NWS Advanced Hydrological Prediction Service (AHPS) website.

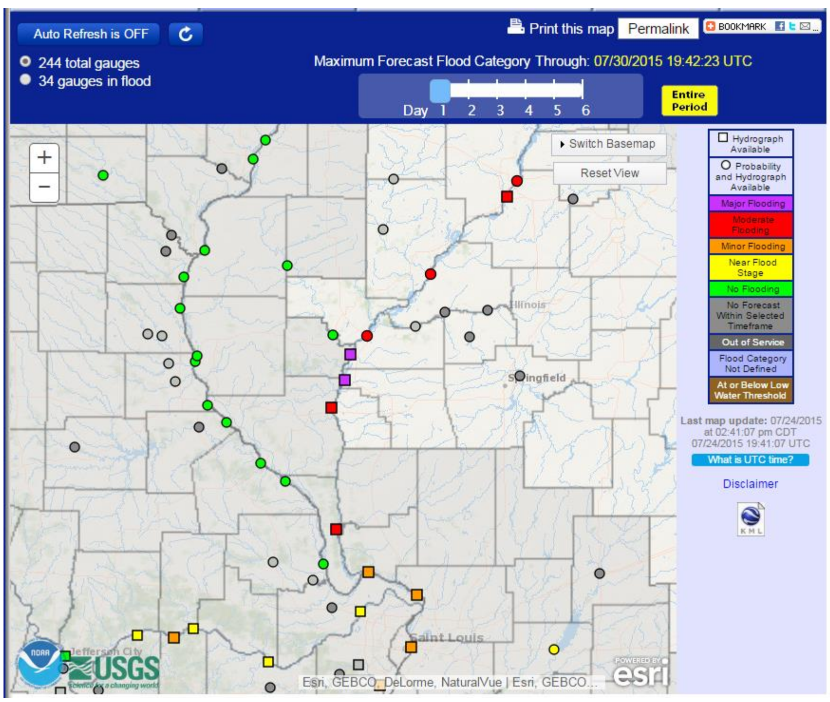

Figure 11. NWS River Forecasts map. NWS River Forecasts map depicting stream gauge maximum flood categories over a one-day forecast period. The NWS reports real-time and forecast streamflow conditions at many USGS stream gauges. Stream gauges are colored by their current flood category. Clicking on a stream gauge will display a hydrograph with predicted flood stage height and flow rate for future times.

Quantitative Precipitation Forecasts (short-term)

Short-term QPF products can be used to determine the estimated amount of liquid precipitation expected to fall in a 6-hour period in the incident area. As with the long-term QPF products, the short-term QPF products can be used as a proxy for flood risk if no NWS River Forecasts are available and are useful for assessing how rainfall could affect response operations during a flood event. QPF products are open access and available online for CONUS through the NWS WPC website.

HEC-RAS

The Hydrologic Engineering Centers River Analysis System (HEC-RAS) model analyzes river flows in the context of riverine flooding, dam breaks, levee ruptures, and ice blockages (Figure 12). It is the most widely-used source of riverine flood event characterization. This system is used by FEMA to support the NFIP and by NOAA and USGS to generate pre-run inundation map libraries accessible through NWS Inundation Maps and the USGS Flood Inundation Mapper (FIM), respectively.

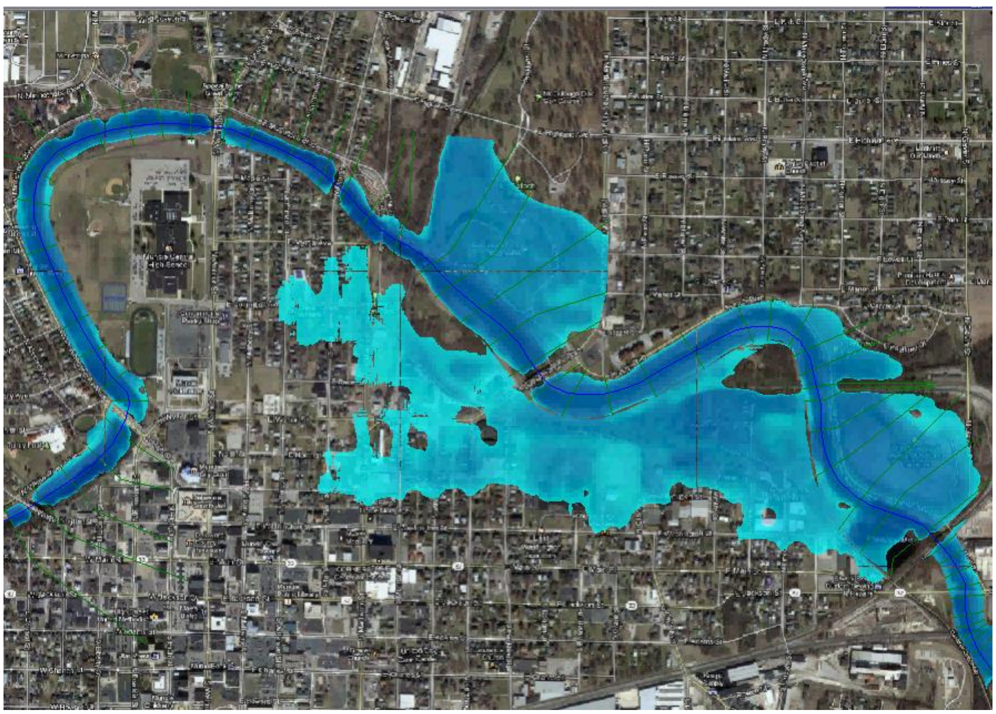

Figure 12. Levee break animation created by the HEC-RAS inundation mapping model. The HEC-RAS model can be used to evaluate flood risk posed by water infrastructure in advance of an event. It provides event-specific inundation maps that show the predicted extent and depth of flooding, here for a levee breach.

The HEC-RAS model provides a geospatial map of the extent and depth of flooding for a specific flood event. This information can be used pre-event to predict which areas will be inundated and how severely. It is usually used together with the HEC-HMS and HEC-ResSim models, which provide the stream flow inputs required by HEC-RAS to predict inundation extent and depth.

The HEC-RAS model itself and all models the HEC model suite are open access and can be downloaded online, but there is no real-time source of authoritative runs of HEC models during events. Using HEC models, therefore, requires investment during Normal Operations in trained staff that can run the model and interpret the results during a flood event. HEC can provide a list of software vendors that provide HEC model support services for a fee, but is not available to provide technical support for non-Corps users.

NWS Inundation Maps / USGS FIM

The publicly available NWS Inundation Maps and the USGS Flood Inundation Mapper are sister data-mapping capabilities for flood event characterization that currently cover a limited portion of CONUS. Both tools are open access and available online through the AHPS website and the USGS Flood Inundation Mapping Science website. The two tools have different, sometimes overlapping coverage areas that focus on the Eastern US. For supported locations, both tools provide libraries of inundation maps centered near USGS stream gauges that show the predicted extent and depth of flooding for a series of flood stage heights at the gauge. These inundation map libraries are often created from pre-runs of HEC-RAS (described previously) and resemble the output shown above in Figure 12. Where available, NWS River Forecast predictions of flood stage height can be ingested by the application to view inundation maps corresponding to the current river forecast. Due to limited geographic coverage, neither the NWS Inundation Maps nor the USGS Flood Inundation Mapper provide data relevant to the majority of flood events; expanded geographic range would significantly improve the utility of both tools.

HEC-FIA

The HEC-FIA consequence model is now available from USACE as a component of the HEC model suite and is applicable to any geographic region. HEC-FIA performs consequence simulations using input from the HEC-RAS model to define the extent and depth of inundation in the incident area. Outputs include detailed damage reports for each structure in the structure inventory, which can be a combination of data from the USACE Structure Inventory, Hazus building data, and user-entered, local data. Users can also view agriculture flood area and loss estimates. Finally, HEC-FIA calculates the population at risk in the flood area and estimates potential loss of life using comprehensive analysis of total inundation area, building type, and dangers of evacuation itself.

HEC-FIA is not as widely used as HEC-RAS, and there is no source of authoritative runs of HEC-FIA during an event. Subject matter expertise is required to run the HEC-FIA thought the model itself is open access and can be downloaded online. HEC-FIA impact estimates for floods based on HEC-RAS outputs could be used to guide response and recovery efforts, but only if expertise necessary to operate these systems is established in advance.

Coastal floods

ADCIRC

ADCIRC is the USACE and University of North Carolina at Chapel Hill model for coastal surge event characterization that can be used to predict wave heights and inland flooding heights during both storm and non-storm coastal flooding. ADCIRC covers both the Gulf Coast and the entire East Coast. ADCIRC outputs include significant wave heights, a measure of average weight height; inundation depth above ground (when over land) and sea level (when over water); and peak wave periods, or how often wave will impact the coast. During normal operations (i.e., non-storm conditions), the model outputs are published twice daily and predict current conditions and future conditions for every 3 hours out to 3 days. Results are published more frequently during storms and may be viewed by storm name or by forecast date. ADCIRC and its outputs are freely accessible online at the Coastal Emergency Risks Assessment (CERA) website with no advance registration required.

Phase 1c. Credible Threat

As an elevated threat begins to transition to a credible threat about three days before forecast flooding, updated forecasts are available and all of the previously described predictive flood modeling should be re-run with these data. The specific datasets and models newly relevant to this phase are described below.

Evacuation modeling and ESF-specific planning

As the forecasts and predictive impact analysis refine the regions and population most likely to be affected by an event, evacuations can be modeled to select among potential evacuation scenarios. In addition, the event-specific impact estimates are now available can be used to set parameters for ESF-specific mission models to help predict personnel and material needs to support the response effort. While the credible threat phase is typically the first phase where sufficient data are available to operate most decision support tools, these tools continue to be useful throughout the event and should be updated as new predictive analysis and real-time impact data become available. A few of the decision support tools relevant during this phase are described below; a more complete list can be found in Table 2 under “Initial Response.”

RtePM

RtePM is an evacuation model developed by Old Dominion University (ODU) based on transportation routes and traffic patterns. Up to 1,500 Census blocks in CONUS may be selected per simulation to calculate the time required to evacuate that population. While the model is open source and can be freely used online, it requires expertise to operate and should be run by a trained user. Notably, the scale of individual runs is limited and runs that include an entire large metropolitan area are likely to exceed the model’s computational limits. However, this evacuation tool is currently the only such model available for flood scenarios.

FEMA ESF Decision Support Tool (ESFs 6 and 7)

The FEMA ESF Decision Support Tool contains modules specific to ESF 6 – Mass Care and ESF 7 – Logistics. Together, these modules are used by FEMA to determine the amount of logistical support required for at-risk populations, estimate emergency meal and water requirements (72-hour needs projections), shortfalls and costs, and estimate the logistical resources required to transport commodities to the incident location. Data are available at the county level for the US and territories. It is FEMA-owned and operated, and it must be requested in advance of an event from the FEMA technical contact.

emPOWER Map

The Department of Health and Human Services (HHS) emPOWER Map provides the location and number of people who rely on electricity-dependent medical equipment in a given area. This information allows emergency managers to consider the medical needs of special populations in the flood incident area. emPOWER Map data are updated approximately monthly, and the data are available at the state, county, and ZIP code level. emPOWER Map covers the US and territories and is freely available for viewing online at the HHS emPOWER Map website.

Updated forecasts

In addition to evacuation and ESF-specific mission planning, within the last 24 hours prior to flooding, two additional assets become useful. The first is USGS river gauge observation data that can indicate that flooding is about to occur. The second are flash flood forecasts produced by NWS.

River Gauge Observational Data / SWaTH Network Data

Near-real-time water level observations at approximately 7,500 river gauged instrument locations are provided by the USGS, updated hourly. Coverage is provided for the entire US, Puerto Rico, and the Virgin Islands, but is densest in the Eastern US. River gauge observational data can be rapidly accessed online in several ways. The USGS National Water Information Center (NWIS) website shows maps of stream gauges colored by their current stage relative to average historical conditions, and the NWS AHPS portal shows maps of stream gauges colored by their current flood category. These real-time data indicate when current streamflow conditions are approaching flood stage in the incident area. To facilitate rapid access to these data during flood conditions, users can register online with the USGS WaterAlert notification system, which sends a text/email when a river gauge exceeds the gauge height or discharge threshold set by the user.

Additionally, prior to storm and coastal surge events, the USGS can deploy temporary instrument networks to record and report water elevation, wave height and frequency, and selected meteorological data for the event to response agencies. This sensor network, called the Surge, Wave, and Tide Hydrodynamics (SWaTH) Network, covers the Northeastern Atlantic Coast from North Carolina to Maine. SWaTH instruments must be requested and pre-deployed in the days preceding an event. The network includes rapid deployment stream gauges (RDGs), which transmit water levels in real-time, and storm-tide sensors (STS) which collect similar data and must recovered and downloaded post-event. Data reported include high water marks (HWM), which mark the highest elevation (peak) of the water surface. The SWaTH network is integrated with existing permanent tide gauges that provide real-time water level and discharge data and is intended to complement these data in areas where permanent gauge coverage is incomplete for a given event. Deployment of SWaTH instruments and access to SWaTH network data must be coordinated with the USGS in advance of an event.

Flash Flood Monitoring and Prediction (FFMP)

Beginning about 24 hours before an event, the NWS can forecast areas at high risk for flash flooding and issue watches or warnings. Flash Flood Monitoring and Prediction (FFMP) is a NWS tool that analyzes current Flash Flood Guidance (FFG) and QPF products to determine which counties should be issued flash flood advisories. The FFG for a given county may be viewed directly, or the NWS flash flood warnings and watches created using the FFG may be viewed to see which counties are currently at a high flash flood risk. These county-level flash flood advisories are freely available online for the US and territories and provide the best guidance on flash floods currently available.

Phase 2a. Initial Response

Updated forecasts and runs

When the response phase begins, the predictive models and ESF mission tools mentioned previously are re-run as post-event real-time data describing the flood extent and impacts are collected. Post-event observations, field data collection, and aerial imaging provide the best available information to characterize the extent of damage. This information is used to plan for the response and deployment phases along with the continued use of ESF-specific mission models. In addition, different mission-specific tools are also newly relevant during the initial response phase.

During a flood response, the key questions to inform lifesaving and life sustaining activities are:

- What is happening, where, and at what scale?
- What are the likely consequences?
- What needs to be done? (i.e., what is the status of emergency services and what support will they need?)

River Gauge Observational Data / SWaTH Network Data

The real-time USGS river gauge data provide data about current streamflow conditions as flooding occurs. These data are useful to help assess which areas are currently inundated and may be most severely impacted in the early hours of the event before aerial imagery is collected. These data can also be used to inform event characterization modeling based on updated parameters to develop inundation maps for the impacted areas that more accurately reflect the known extent and depth of flooding.

SWaTH network data from the USGS may be used for similar applications during coastal flooding events, provided that the SWaTH instruments have been requested and pre-deployed in advance of the event.

ESF mission models

Red Cross National Shelter System (NSS)

The Red Cross National Shelter System (NSS) provides information about the amenities and locations of shelters in the impacted area. It provides location information for general population shelters, medical shelters, and Points of Distribution. In addition, the NSS is used to track and report information on open shelters, managing agencies, capacities, and current occupant counts during an event. This information is updated approximately twice daily, and can be used to direct the population seeking shelter to open shelters with vacancies. The Red Cross also operates a website for the general public to find open shelters in their area. The NSS covers the entire US, but it is only accessible to emergency management personnel who have requested and been approved for accounts at the NSS website.

EAGLE-I

The Department of Energy EAGLE-I system is a situational awareness viewer, providing a web-based, near real-time energy sector monitoring capability. The tool contains information about current power outages and damage to energy infrastructure that can be used to inform response operations and anticipate the needs of the population in the incident area. EAGLE-I provides customer outage totals, transmission line status, natural gas pipeline anomalies, and locations of energy-sector infrastructure. EAGLE-I provides coverage for approximately 75% of CONUS. EAGLE-I is only accessible to emergency management personnel who have requested and been approved for accounts at the EAGLE-I website.

FEMA ESF Decision Support Tool (ESFs 3 and 12)

The ESF 12 module can be used to view limited real-time EAGLE-I data describing the potential population and infrastructure in the region affected by the outage. Outputs include maps of time without power and percent population without power by county; plots of outages and time without power over time; and maps of infrastructure in located in the incident area.

The ESF 3 module can be used to estimate the potential number of generators needed to provide backup power to damaged infrastructure for an incident; damaged infrastructure are a user input. Outputs include the numbers and types of generators needed, the time needed to deliver generators, and the cost of generator fuel and transportation. This tool can be used to assess generator requirements based on known infrastructure damage for a specific event.

The FEMA ESF Decision Support Tool is FEMA-owned and operated, and it must be requested in advance of an event from the FEMA technical contact. Additionally, access to EAGLE-I (described previously) is required to use the ESF 12 module.

FEMA LSCMS and FEMA DTS

FEMA uses the Logistics Supply Chain Management System (LSCMS) and Deployment Tracking System (DTS) to support response logistics internally. LSCMS tracks meals, blankets, and water in near-real-time from warehouse to consumption, and it can be used to project when more supplies will be needed. DTS supports personnel logistics by tracking all FEMA deployable employees. Both tools provide visibility on FEMA resources and personnel for all geographic locations and can be used to monitor resource movements in relation to resource needs predicted by the FEMA ESF Decision Support Tool. The LSCMS and DTS tools are accessible only to FEMA personnel.

Additional operational tools by ESF mission

In addition to those tools described in detail above, tools available to support each ESF are described in the table below (Table 2). Notably, a number of decision support tools that are widely used for other hazards are markedly absent for floods. USACE has robust calculators for debris removal requirements, temporary housing needs, and ice/water commodities requirements widely used for hurricanes, but none are optimized or available for flooding. An additional set of tools, primarily developed by FEMA, rely on the outputs of Hazus for estimates, including a USAR needs calculator, a JFO staffing model, and others. Hazus is not an operational or response ready tool for flood events, and the outputs needed to support the downstream decision support tools are not available.

Table 2. Mission-specific models/datasets by relevant Emergency Support Function (ESF). “None” is written where no flood-applicable mission models are available for a given ESF.

ESFs	Models/Datasets	Descriptions
ESF #1 - Transportation	RtePM	Calculates evacuation times (user-run)
ESF #2 - Communications	FCC DIRS	Reports communications infrastructure status
ESF #3 – Public Works and Engineering	FEMA ESF Decision Support Tool	Estimates generator requirements for back-up power
ESF #4 - Firefighting	None	n/a
ESF #5 – Information and Planning	None	n/a
ESF #6 – Mass Care	Red Cross NSS	Shelter amenity and capacity data
	FEMA ESF Decision Support Tool	Estimates emergency meal/water requirements, shortfalls, and costs
ESF #7 - Logistics	FEMA LSCMS	Tracks meals, blankets, and water supplies in near real-time
	FEMA Deployment Tracking System (DTS)	Tracks locations/availability of disaster assistance employees in near real-time

	FEMA ESF Decision Support Tool	Calculates resources needed to transport water/meals from distribution centers to incident location
ESF #8 – Health and Medical	emPOWER Map	Gives population relying on electricity-dependent medical equipment by county/ZIP
	HHS MedMap/GeoHEALTH	Situational awareness viewer for health-specific incident and facility data during an event
ESF #9 – Search and Rescue	None	n/a
ESF #10 – Oil and Hazardous Materials	None	n/a
ESF #11 – Agriculture and Natural Resources	None	n/a
ESF #12 – Energy	DOE EAGLE-I	DOE situational awareness viewer for energy system infrastructure and status
	FEMA ESF Decision Support Tool	Uses EAGLE-I real-time outage data to map outage durations, customers without power, and more by county
ESF #13 – Public Safety and Security	None	n/a

Phase 2b. Deployment

As the event response transitions into the Deployment phase, the response to a flood will primarily focus on deploying resources and personnel to support the affected population and facilitate transition to recovery efforts. Post-event aerial imagery used to determine the extent of the flooding and perform damage assessments will be collected and used to inform these operations.

The key questions that arise during the deployment phase are:

- What supplies are needed to care for evacuees?
- What secondary impacts or cascading consequences can be avoided?
- What resources are needed for recovery?

HDDS / CAP Imagery / EnhancedView Imagery

The main portal providing general access to post-event aerial imagery is the USGS Hazards Data Distribution System (HDDS). Users can search for imagery in HDDS by event name or by geographic location. The imagery hosted on HDDS usually includes crowd-sourced imagery and imagery from the Civil Air Patrol (CAP) and the National Geospatial-Intelligence Agency (NGA), who often provide imagery for large-scale events. While HDDS is the most common portal through which to access this imagery, others exist, and the specific portal(s) that should be used to access imagery are usually specified when imagery is pushed to the emergency management community. Event-specific pages on FEMA GeoPlatform may be used to host publically available CAP imagery. NGA imagery is often provided through the limited access EnhancedView web hosting service. Additionally, some imagery hosted on HDDS may be restricted to certain user groups. During an event, access to imagery may be limited and require authorization, or it may be made publically available, depending on licensing restrictions. Importantly, collection of imagery may be delayed by cloud cover or other severe weather.

Preliminary Damage Assessment (PDA) Data

Preliminary Damage Assessment (PDA) data collected by FEMA post-event describe the number of residences damaged and to what degree, and the estimated funding needed for FEMA programs to provide assistance to the affected population, including Individual Assistance (IA), Public Assistance (PA), and the Hazard Mitigation Grant Program (HMGP). The program funding estimates in PDA data can provide a measure of the economic burden caused by a flood event. This information is also used by the State as a basis for the Governor's request for a major disaster or emergency declaration and by the President in determining a response to the Governor's request. These data are FEMA-internal and shared selectively until they are released in post-event reports on the FEMA website.

Phase 2c. Sustained Response

The sustained response and recovery phases activities require much of the same information as previous phases and many of the same datasets and models will be useful. In the sustained response phase, mission models (Table 2) will continue to support the efforts of individual ESFs until they are no longer needed. Likely areas of emphasis include energy as efforts are made to restore power and ensure fuel supplies for response and recovery operations, and mass care and logistics to support those needing shelter. Both real-time situational awareness viewers and operationally-focused decision support tools will continue to inform decision making during this phase.

Phase 3. Recovery

Inundation, damage to homes, and the cascading consequences of a flood may extend the full recovery long beyond the initial event. Recovery will require much of the same information as sustained response; many of the same models and datasets will be useful.

Conclusions

As one of the most frequent and costly natural hazards, effective emergency management for flooding is critical. Accurate and operationally-relevant datasets and models are a key component for ensuring flood emergency management is data-driven and founded on shared assumptions that accurately reflect the most up-to-date information available.

In the course of this effort, 128 datasets and models used to inform federal emergency management for flood scenarios were identified and characterized. The conclusions from a systems-level analysis of the datasets and models identified and the findings derived from analyzing those datasets and models most relevant to emergency response are described below.

Effective event characterization

The majority of the flood-related datasets and models identified through this effort are targeted toward characterizing the event. Whether raw data, event characterization models, or situational awareness data, a wide range of robust, authoritative, and scientifically-founded datasets and models are available from NOAA, USGS, USACE, and others. These tools are broadly available and the data typically publically accessible. Predictive models are available for all three major types of floods addressed in this report (riverine, coastal, and flash flooding), and the results are made available in viewers designed for immediate use by decision makers.

Solution needed to enable consistent real-time data collection

Real-time data are a critical source of information both to capture the on-going status of a flood, but, even more importantly, to support the updating and validation of existing event characterization modeling and analysis. These data, typically collected by rapidly-deployed water gauges on either riverine or coastal systems, are only available if the equipment is deployed ahead of the event. Currently, this deployment relies on a federal mission assignment that is vulnerable to changes in response authority during an event. A robust solution is needed to ensure that real-time data are collected and analyzed to support event characterization for floods.

Lack of real-time consequence analysis

There are two major consequence models available and used by the federal interagency to support consequence modeling for floods. Hazus, the FEMA economic consequence model, is used to support the flood insurance mission at FEMA and more broadly to support detailed consequence analysis by a wide range of federal users. However, Hazus is not response-ready and would require significant investment in software upgrades to be useful for short-turnaround analyses. This lack of real-time utility is amplified by a lack of an authoritative, expert source to run the model in the context of crisis action planning and emergency response. HEC-FIA, the USACE consequence model, is, like Hazus, publically available and could be an important addition to the federal tool kit for emergency response, though it has not yet been sufficiently tested for the emergency management mission. Indeed, the USACE does not currently provide modeling support for emergencies without prior activation, and HEC-FIA is not currently used within any known emergency response centers during an event.

Steady-state support for long term forecasting and pre-event planning

Most major hazards that require federal response are no-notice or limited-notice events. Predictive analysis for flooding can begin months in advance with the assessment of snowpack, the effect of drought on soils, wildfire mapping, and long range climate forecasting. However, with the current event-focused funding mechanisms for federal emergency response, the emergency management community has only a very limited ability to plan for flood events with the necessary time horizon. This lack of programmatic support for complete, advance planning is amplified by the lack of an emergency response-focused team to perform the analysis. While the scientific agencies tasked with event characterization perform analysis in an on-going manner, the extrapolation of their findings to the emergency management mission would significantly augment Federal flood response capabilities.

Data-driven decision support for response

Robust decision support relies on solid consequence modeling. However, decision support for emergency management is inherently response-focused, and there are very limited sources of real-time consequence modeling for floods. Moreover, those decision support tools and mission specific datasets available (of which there are not many) are largely unconnected to the upstream consequence modeling that is available; indeed, these decision support tools and sources of mission-specific requirement data are largely unlinked to any other data sources and rely almost solely on subject matter expertise and operational knowledge for parameters. This lack of data integration risks a divergence of assumptions about the underlying event and undermines the validity of the tools.

Appendix A: Interviewees

Table A1: List of interviews conducted

Name	Agency
Bolinski, Brandon	FEMA (Federal Emergency Management Agency)
Farmer, Bob	FEMA
Juskie, John	FEMA
Longenecker, Gene	FEMA
Matthews, Mike	FEMA
McAfee, Scott	FEMA
Penney, Christopher	FEMA
Rozelle, Jesse	FEMA
Ruiz, Benigno	FEMA
Bronowicz, Kelly	FEMA FIMA (Federal Emergency Management Agency Federal Insurance and Mitigation Administration)
Callister, Kathy	FEMA FIMA
Finch, Christina	FEMA FIMA
Huang, Paul	FEMA FIMA
Sacbibit, Rick	FEMA FIMA
Clark, Ed	NOAA NWS (National Oceanic and Atmospheric Administration National Weather Service)
Glaudermans, Mark	NOAA NWS
Guerrero, Hector	NOAA NWS
Mullusky, Mary	NOAA NWS
Gochis, David	UCAR (University Corporation for Atmospheric Research)
Maidment, David	University of Texas
Dunn, Chris	USACE (United States Army Corps of Engineers)

Markin, Chad	USACE
Shadie, Chuck	USACE
Talbot, Cary	USACE
Webb, Jerry	USACE
Hoeft, Claudia	USDA NRCS (United States Department of Agriculture Natural Resources Conservation Service)
Leuhring, Penny	USFS (United States Forest Service)
Aichele, Steve	USGS (United States Geological Survey)
Mason, Robert	USGS
McCallum, Brian	USGS
Peppler, Marie	USGS
Rea, Alan	USGS
Wood, Nathan	USGS
Crumpler, Brian	Virginia Information Technologies Agency

Appendix B: Methods

The workflow of used to understand the use of models and datasets for response to floods involved three parts: data collection, data processing, and analysis, as depicted in Figure B1. This process led to the identification of models and datasets in use by the interagency for floods and yielded metadata describing each of these models and datasets. Using the framework outlined below, each model and dataset was categorized based on its attributes and how it is used for emergency management. Metadata describing each model and dataset were cataloged in a series of metadata categories and entered into the Emergency Support Function Leadership Group (ESFLG) Model and Data Inventory (MoDI). Finally, the metadata were analyzed using custom web applications to quantify information about the models and datasets currently available for floods, and network analysis techniques were used to analyze the relationships between these models and datasets.

Data Collection

Data collection was performed through interviews flood emergency management stakeholders, emergency managers, and subject matter experts who work with and develop flood models and datasets. In brief, the interviewees were asked how they use models and datasets in general to answer questions relevant to their emergency management missions, and what specific models and datasets they use to meet their information needs. Based on the data collected during interviews, a systems-level analysis of the information requirements specific to flood emergency management was performed. This analysis used an information ontology, or categorization system, developed in prior iterations of the project to capture the flow of information between resource types. This information ontology is described in detail in subsequent sections. Metadata about the specific models and datasets identified during interviews were compiled in an inventory; only models and datasets that were both operational and used by the federal emergency management community were included. Metadata characteristics about each model and dataset were determined both through interviews and through additional background research.

Each model and dataset in the MoDI is characterized by over thirty metadata categories, including information about the owners and federal users of the model/dataset and its connections to other models and datasets. These metadata characteristics provided the basis for two types of analyses: a network analysis based on the upstream and downstream connections of each model and dataset, and a statistical analysis of the types of models and datasets in the MoDI. The network analysis is based on network maps, visualizations of the models and datasets and the flow of information between them. Analysis of the metadata characteristics of the models and datasets was used to calculate the types and number of models and datasets in the MoDI.

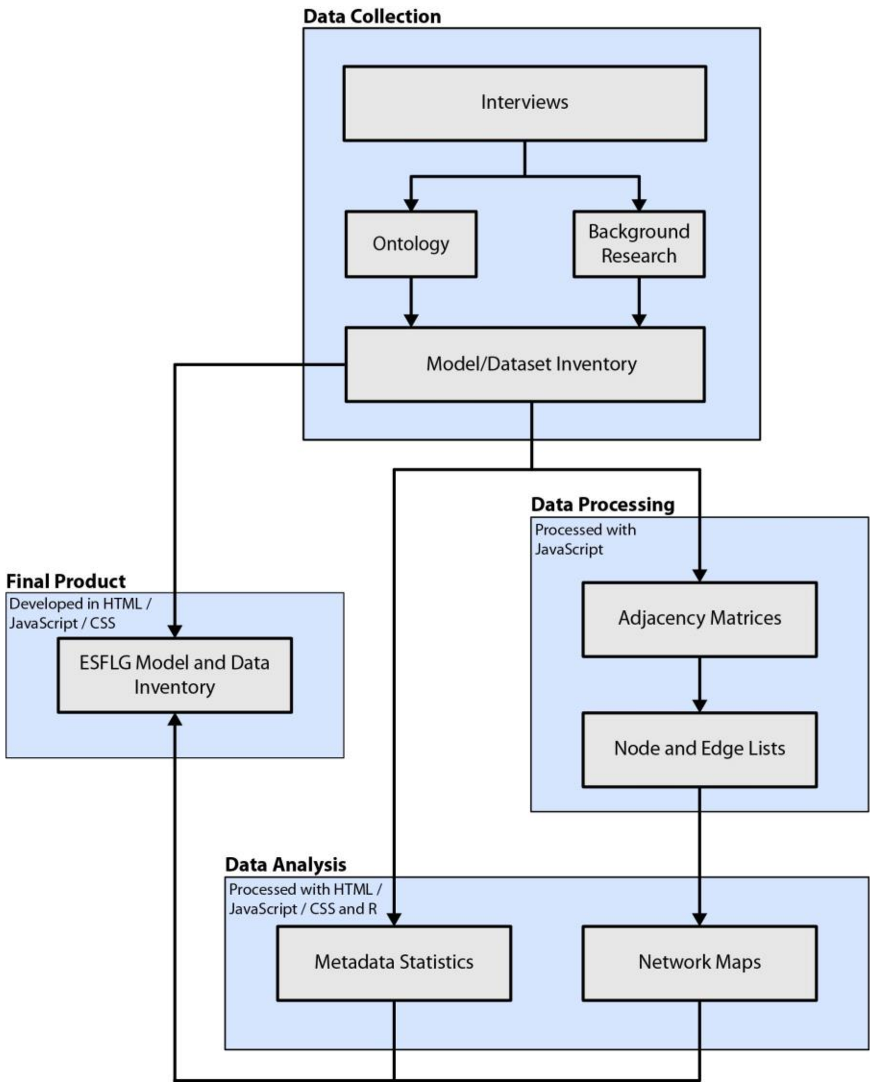

Figure B1. Analysis workflow. A depiction of the sequence of work involved in producing quantitative analysis of the inventory.

Interviews

The information required to analyze the available models and datasets was collected through a series of in-person and phone interviews with floods emergency management stakeholders, including emergency management personnel and subject matter experts, and further interviewees they recommended. A comprehensive list of the interviews completed can be found in Appendix A. During these interviews, the users and producers of each model and dataset identified and characterized the ways in which each model and dataset is used to support planning and operational decision making for flood scenarios. Initial interviews were based on a list of recommended interviewees developed by MDWG members. These interviews focused on members of the scientific and operations-focused agencies with missions particularly relevant to floods, including the National Oceanic and Atmospheric Administration (NOAA) National Weather Service (NWS), the US Geological Survey (USGS), the US Army Corps of Engineers (USACE), the Federal Emergency Management Agency (FEMA), and others. Interviews with additional emergency management personnel, subject matter experts, and senior leadership were scheduled upon recommendation to provide further breadth or depth of information depending on the size of the agency or division represented and the expertise of each interviewee. In addition to federal officials, some regional and state emergency managers were interviewed to assess their use of models and datasets in their respective agencies and roles.

Interviews were opened with an introduction to the project. A questionnaire (see Appendix 2) was developed to outline the topics to be addressed during the interviews. The questionnaire was used as a general guide for the discussions. Throughout the project, interviewees have included those who are providers of data or are tool developers; those who are analysts and users of those data and tools; those who make operational decisions informed by data and modeling resources; and those who have roles that include a combination of tool development, analysis, and decision making. Interviews are designed to capture an overview of the roles and responsibilities of each group and the ways in which data and data processing tools, including modeling, support those roles. The flow of the conversation varied widely based on the expertise of the interviewee and attempted to capture both the general and specific information requirements from each interviewee across the spectrum of emergency management missions and the phases of an emergency.

Model and Data Inventory (MoDI)

A comprehensive inventory (the MoDI) of models and datasets used across the federal interagency and the linkages between them was initial generated in prior iterations of this project, focusing on models and datasets used for emergency management during hurricane, earthquake, and improvised nuclear device (IND) detonation scenarios. The MoDI was expanded to include flood-relevant models and datasets on the basis of the models and datasets discussed during interviews, followed by background research to identify inputs and outputs of each model and dataset. Only models and datasets with federal users were included in the MoDI. Models and datasets under development or not currently used to support emergency management activities were identified, but not included in the MoDI. Information about these models and datasets and how they function within the flow of information has been retained in an archive. This information allows for more a more detailed analysis and verification of the analyses. Additionally, these models and datasets can be used in future iterations of the project to suggest mechanisms to fill gaps identified in the current inventory. The inclusion of only used and operational models and datasets in the MoDI enables an analysis of how information currently travels within the interagency and results in a streamlined inventory containing the information immediately useful for emergency managers.

Metadata

The flow of information framework captures the functional, time-dependent, and mission-specific variation between resources used across the federal interagency. However, it does not describe other essential characteristics such as how those resources are accessed, used, and updated. These additional characteristics, or metadata, must also be collected to properly organize and analyze the resources to maximize effective usage during all phases of emergency management. These metadata are available in the MoDI, the interactive inventory of models and datasets.

Metadata categories include: the model/dataset’s full name, abbreviation, model/data, owner, users, upstream models/datasets, downstream models/datasets, relevant hazards, Core Capabilities supported, Emergency Support Functions (ESFs) supported, Recovery Support Functions (RSFs) supported, keywords, resource types, data collection methods, phase-specific utility, access information, access type, processing requirements, geographic coverage, refresh rate, last known version, programming langauge, output file type, technical contact information, real-time contact information, website, and a brief summary of the model/dataset's function and use. Complete descriptions of each metadata categories and their respective tags are available on the Background page of the MoDI.

Data processing

A network is defined as a system consisting of interconnected components; network analysis is the process of understanding the connections between those components. The individual components of the network are called nodes and the connections between them are called edges, with information moving through the network by a defined, or directed, flow. To build network maps describing the linkages between models and datasets in the MoDI, the metadata defining the upstream and downstream linkages for each model and dataset were quantified in an adjacency matrix. An adjacency matrix is a mathematical method of representing a network that provides a simple way to calculate many network measures and statistics.[5] The adjacency matrix was then converted into separate node and edge lists. A node is a point on a network, and in this case, each node represents a single model or dataset in the MoDI. The nodes list contains the metadata of each node in the network, allowing that information to be visualized on the network map and analyzed in the context of the network. An edge is a line in the network that connects two nodes, and in this case, represents the transfer of information from one model or dataset to another. The edge list contains a list of connections between nodes in the network. These node and edge lists were derived from the MoDI metadata using JavaScript code and standard libraries, and the network maps and analyses were performed using the web standards model (HTML, JavaScript, and CSS) relying heavily on the D3.js data visualization JavaScript library.[6]

Additional data processing was performed using R, an open source, statistics-based programming langauge.[7] R was chosen because of its ease and flexibility in manipulating data.

Data analysis

Network analysis

The analysis presented in this report describes the connections between the data and models used by the federal interagency in the context of emergency management. Two metadata categories (upstream and downstream inventory resources) describe linkages between the models and datasets based on the flow of information between them. These linkages were used to build a flow-based network of the datasets and models collated in the MoDI. This inventory, including the models and datasets and their associated metadata, and the network based on this inventory, were used to perform an analysis of the flood inventory, as described in the results section.

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5 A short, rigorous definition of an adjacency matrix: For a network of n nodes, the adjacency matrix A is an *n* x *n* matrix where the i,j^{th} entry in the matrix represents the number of connections from the i^{th} node in the network, to the j^{th} node in the network.

6 Bostock *et al* (2011). *D3: Data-Driven Documents*. IEEE Trans. Visualization & Comp. Graphics (Proc. InfoVis). http://vis.stanford.edu/papers/d3

7 R Core Team (2013). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing, Vienna, Austria. URL http://www.R-project.org/

To visualize the metadata contained in the MoDI, network maps were generated of the models and datasets based on their upstream and downstream connections. In these networks, each dataset or model is a node in the network with each edge representing the flow of information and processing of data as it passes between those nodes. The size of a node and its label is directly proportional to the number of users of that model or dataset, an indicator of the relative utility of each model and dataset, which is defined by the number of federal agencies that directly use it in the context of their work. The edges curve in a clockwise fashion, distinguishing which model or dataset is the source and which is the target of the information. In this case, the source node is the upstream model or dataset. A downstream model or dataset is defined as the one that the source node feeds. Figure A2 illustrates an example of a simple network map. Both the inputs (upstream models and datasets) and outputs (downstream models and datasets) of each model and dataset in the network were identified based on in-depth analysis of interview data and a review of the technical documentation of the model or dataset, when available.

Unless explicitly stated otherwise, the nodes in each network are arranged by a Force-Direction algorithm that groups closely linked nodes. This algorithm treats each node as a charged particle that repels all other nodes, and each edge as a spring, pulling the nodes back together.

Several network maps were generated to visualize the general flow of information between different models and datasets. These network maps also explored two attributes of the network: betweenness centrality and model/dataset connectivity.

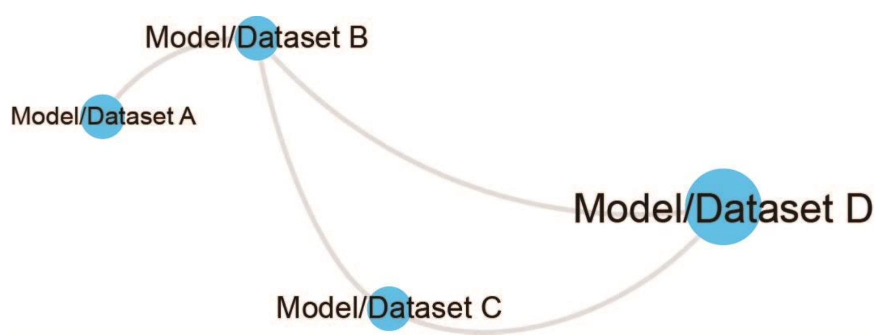

Figure A5.2. Example of a simple network map. Individual models and datasets are represented by blue discs (nodes). Direct connections between models and datasets are represented by gray curved lines (edges). The flow of information travels clockwise. In this example, information flows into Model/Dataset B from Model/Dataset C and D. Information from Model/Dataset A flows into Model/Dataset B. The size of each node can convey additional information; for the network maps presented in this report, nodes are sized relative to the number of users of that model or dataset.

Resource type

Each network map (see Figure A5.2 for example) depicts the flow of information. In resource type network maps, each node is colored according to its category in the flow of information so that trends in information flow between resource types can be seen. The size of each node in these maps is proportional to the number of federal users identified for that model or dataset.

Additionally, resource type maps were created showing the bulk flow of information between resource types. In these bulk flow maps, seven nodes are displayed, each representing one of the seven resource types. Each node is sized based on how many models and datasets in the MoDI are of that resource type. Edges represent a connection between models and datasets of different types and are their widths are proportional to the number of those connections. These network maps show the bulk flow of information between resource types in the MoDI.

Betweenness centrality

The importance of specific nodes was also investigated using the betweenness centrality measure, which is a common centrality measure that characterizes how often a node is between other nodes in the network.[8,9] Specifically, the betweenness centrality of a specific node is calculated as the number of times that node appears on the shortest path between any other two nodes in the network, measuring the degree to which a node acts as an intermediary between other nodes. With betweenness centrality, the most important nodes are those that act as “shortcuts” or “bridges” between different parts of the network. However, betweenness centrality only considers the shortest paths between nodes and therefore gives no weight to alternative paths over which information could be passed within a network. In the network diagrams, nodes were colored on a gradient such that more central nodes were darker and less central nodes were lighter.

Data source confidence

An event timeline for flood response mapping sources to data to specific time points was created based on the FEMA Flood Decision Support Architecture (or, “Whiteboard”). These data sources represented models and datasets collated in the MoDI that were considered particularly useful during specific phases of the flood response.

Each model or dataset was assigned a level of confidence based on three factors: number of key assumptions required, the credibility and diversity of sourcing in the knowledge base, and the strength of argumentation. Each factor was assessed independently and then in concert with the other factors to determine the confidence level for each model or dataset. High confidence models and datasets featured well-corroborated information from proven sources, minimal assumptions, and strong logical inferences and methods. Moderate confidence models and datasets were weaker in some of these characteristics, and low confidence models and datasets were weakest.

8 Freeman LC (1977) A set of measures of centrality based on betweenness. *Sociometry*: 35-41
9 Freeman LC (1979) Centrality in Social Networks Conceptual Clarification. *Social Networks* 1: 215-239

Appendix C: Flood data requirements and supporting datasets/models

Table C1: Flood response data requirements with corresponding available datasets/models. Flood-related data requirements for each time point are matched with models/datasets that are available to fill these information needs. Data confidence is listed for each model, including explanations. If no model/dataset exists for a data requirement, these gaps are noted and data confidence is low (red).

Time	Data requirement	Model/dataset	Data provided	Data confidence
Pre-event planning (I+168h+)	Identify long-term flood risk	NWS River Forecasts (long-term)	Predicted chance of river flooding at the forecast point over a 3-months	[yellow] Limited fidelity for long-term forecasts
		NWS QPF (long-term)	Predicted total precipitation over 6-hour periods up to 7 days out	[yellow] Limited fidelity for long-term forecasts
I-120h	Identify and characterize potential threat	Continue use of above models/datasets	See above; use short-term forecasts	[green]
		HEC-RAS (USACE)	Comprehensive model suite for floodplain mapping and inundation modeling	[green]
		NWS Inundation Maps; USGS Flood Inundation Mapper	Predicted flood extent/depth for select locations using gauge height forecasts	[green]
		ADCIRC (USACE)	Coastal floods only: predicted coastal surge and wave heights	[green]
	Predict potential impacts to population and infrastructure	HEC-FIA (USACE)	Predicted loss of life, population at risk, structural damage, and agricultural damage	[green]

I-72h	Evaluate evacuation timing	RtePM (ODU)	User-run evacuation model to select routes and determine clearance times by region	(yellow) Several assumptions made; study area size limited
I-48h	Calculate food/water requirements; logistics for pre-positioning	FEMA ESF Decision Support Tool (ESFs 6 and 7)	Food and water assets and transportation logistics for pre-staging and delivery	(green)
	Determine population medically-dependent on electricity	emPOWER Map	Provides number of people in a given county/zip code who rely on electricity-dependent medical and assistive equipment	(green)
I-24h	Determine areas at risk for flash flooding	NWS Flash Flood Monitoring and Prediction (FFMP)	Flash floods only: Current flash flood warnings by county, precipitation threshold to cause flash flooding	(green)
	Characterize event using real-time data	River Gauge Observational Data (USGS) / SWaTH Network Data (USGS)	Provides measures of streamflow relative to normal; indicates high water areas, wave heights, and wave frequencies	(green)
Flooding begins				
I+30m	Characterize event using real-time data	River Gauge Observational Data (USGS) / SWaTH Network Data (USGS)	See above (post-event measurements)	(green)
I+12h	Estimated impacts to population and infrastructure	None	N/A	(red)
	Search and rescue team deployments	None	N/A	(red)

	Debris removal estimates	None	N/A	
	Shelter locations and amenities	Red Cross National Shelter System	Shelter locations, capacities, and remaining space for affected region	
	Electrical outages and infrastructure impacts	EAGLE-I (DOE)	Current status of electricity and energy infrastructure damage	
		FEMA ESF Decision Support Tool (ESF 12)	EAGLE-I outages mapped with infrastructure in incident area	
	Estimate generator requirements	FEMA ESF Decision Support Tool (ESF 3)	Generator requirements and fuel/transport costs given confirmed infrastructure damage	
	Logistics for FEMA Response/ Recovery personnel and resources	FEMA LSCMS	Amount of supplies ready and available for deployment	
		FEMA Deployment Tracking System	Number of personnel deployed in each category, where, and for how long	
I+36h	Characterize event using post-event imagery	HDDS (USGS) / CAP Imagery (DoD) / EnhancedView Imagery (NGA)	Shows extent of flooding; NGA post-event imagery with damage assessment tagging	
	Determine potential size of FEMA Recovery programs	Preliminary Damage Assessment (PDA) Data	Number of residences damaged and to what degree; estimated funding needed for FEMA Recovery programs	
>I+120h	On-going response and recovery needs and activities	Continue use of above models/datasets	See above	See above
	Continue recovery	Continue use of above models/datasets	See above	See above

	efforts			