NCHRP 20-59(53): FLOODCAST

A Framework for Enhanced Flood Event Decision-Making for Transportation Resilience

TECHNICAL MEMORANDUM #1

Prepared for

The National Highway Cooperative Research Program

Transportation Research Board

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Dewberry
Venner Consulting

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TECHNICAL MEMORANDUM 1

1 FLOOD FORECASTING TO SUPPORT SAFE OPERATION DURING FLOOD CONDITIONS

In 2012, the California Department of Transportation (Caltrans) identified the need for a flood alert system that would allow Caltrans to "proactively monitor, assess, and respond to flood-related disasters and associated hazards in real time. This system would focus on providing bridge and infrastructure management during destructive flood conditions in order to predict infrastructure failure." Caltrans called the system they desired "Floodcast," similar to Caltrans's current ShakeCast system for early situational awareness of earthquake impacts. This concept was presented at the Transportation Research Board (TRB) in workshop form in January 2015. The proposed system would integrate multiple sources of data and provide automated notifications to various audiences. In response to this idea, a floodcast project was initiated by the National Cooperative Highway Research Program (NCHRP), with support from multiple American Association of State Highway and Transportation Officials and TRB committees. The focus of this memorandum, which was developed as part of the floodcast project, is therefore twofold: First, to identify tools, methods, and models to support forecasting, operations, and response activities, and second, to support pre- and post-event mitigation planning and risk reduction.

Resources in the first category will be identified to support the immediate concerns of reducing fatalities and infrastructure damage in the face of impending flooding. This is a nontrivial task, as the roads and bridges state Departments of Transportation (DOTs) are responsible for carry an enormous amount of freight and people each day, even during extreme weather events. Despite road closures, weather, and traffic warnings from multiple sources, attempted road crossings during flood events account for more than half of all flood fatalities (NOAA, 2013) and significant traffic disruptions (Berz et al., 2001; Browering et al., 2003; Drobot et al., 2007). We take the transportation systems we rely on for granted, and as Newman et al. (2005) observes, "[W]e are typically shocked when one of these systems fails." Still, flood-related deaths due to attempted crossings of flooded roadways are preventable. With advanced warning, DOTs can prioritize limited resources to close roads, plan detours, and communicate to the public before motorists are exposed to flood hazards, and travelers can avoid delays and the demands they are placing on roadway capacity at the worst times. Further, with the right analytical tools, high-vulnerability locations can be identified, and, where feasible, flooding can be prevented through mitigation.

Resources in the second category focus on longer-term concerns, such as mitigation planning, that benefit from good record-keeping technologies and database development, which can support queries to identify risks and priorities. Increasing knowledge of risk areas where more extreme weather events may compromise mobility and safety is a first step in cost-effective adaptation investment, maintenance, and management decisions. Technology currently exists to accurately pinpoint areas along a transportation corridor that are susceptible to flooding. Many state DOTs have a bridge flood monitoring program for structures that are susceptible to bridge scour. Some states, such as Iowa, have expanded these systems to predict flood hazard areas. Geographic information systems (GISs) are an important tool for some states where DOT asset databases are used to support flood planning, risk management, mitigation, operations, and emergency response activities.

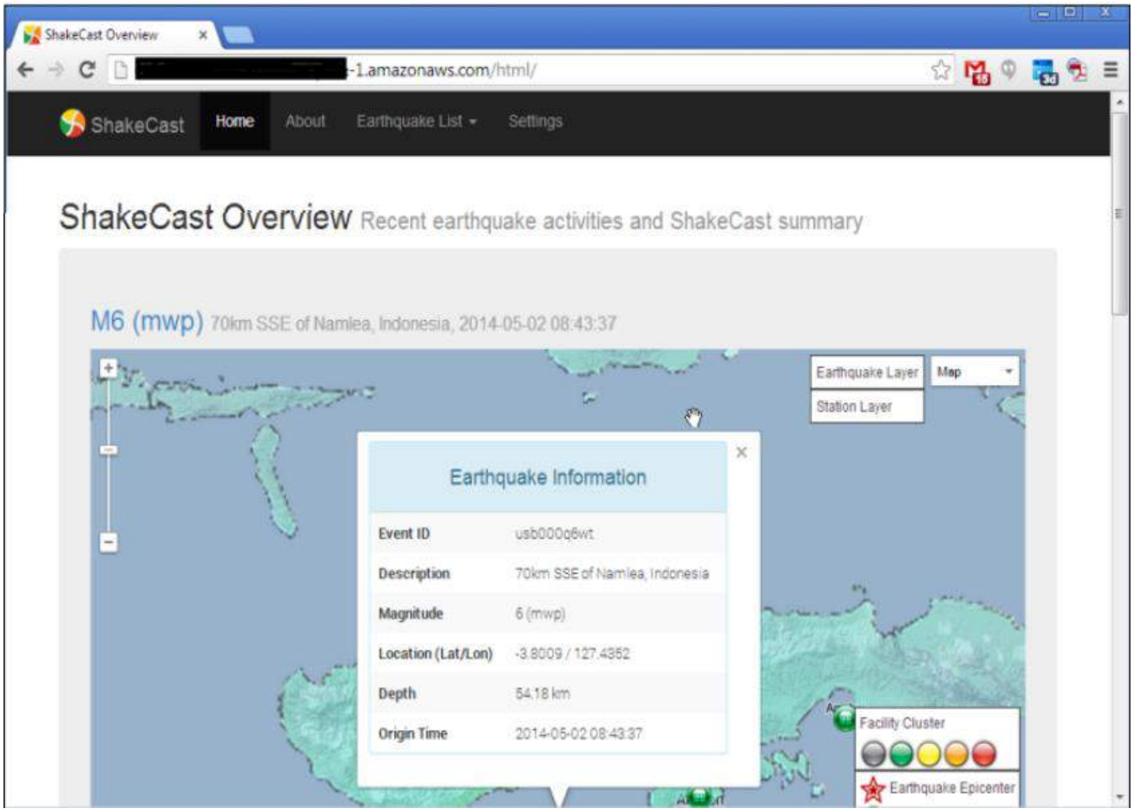

Figure 1. The ShakeCast system developed as part of the US Geological Survey (USGS) Earthquake Hazards Program is a cloud-based notification service showing shaking levels at user-selected facilities. Caltrans proposed a similar approach to flood alerts for state transportation assets.

Figure 2. Along with having one of the more advanced systems combining state hydrologic models, bridge instrumentation, and asset databases to inform flood response, Iowa DOT is also a proactive user of social media for public outreach.

While outside the scope of this document, it is worth noting that such tools can also be readily enlisted to support climate adaptation planning. There is a high level of consensus that episodes of extreme weather phenomena will increase in frequency and intensity (National Climate Assessment, 2014; Intergovernmental Panel on Climate Change [IPCC], 2014). Disruptive weather events are already rising in the Midwest and Northeast. States nationwide have experienced events such as the multiple once-in-500-year floods over short time frames, and a few off-the-charts 1000-year floods (e.g. NWS, 2013). Changing patterns in precipitation, wind, temperature, sea level, and groundwater are all potential challenges to safe and cost-effective management of roads and highways, even presenting divestment questions in some cases. However, the increase in heavy rainfall and flooding are a particular challenge faced by many DOTs and these challenges will be increasingly manageable with the application of the latest forecasting and communications technologies.

Figure 3. Louisiana Department of Transportation and Development uses an enterprise GIS, which has been used to inform emergency management activities, the Louisiana Emergency Management Plan, and various mapping applications. The application above shows users their evacuation route options.

1.1 Project Objectives

This project will identify current DOT methods and a potential framework for incorporation of more data in light of the many flooding issues for transportation. These include data management and procedural needs. To support the overall project goals, this technical memorandum will investigate tools, methods, and models that address the following issues:

- Efficient prediction and identification of expected onset, location, impacted infrastructure, types, and scale of events.
- Data deficiencies preventing hazard analysis, such as asset gaps or errors, topology problems, and knowledge limitations about interactions between transportation system components.
- Expanding existing GIS asset management data models to include more data relevant to flood modeling, e.g., elevation for roadways, drainage infrastructure capacity, topographic considerations, etc.
- Elimination of "silos" between recovery and mitigation, which can impede adaptation and resilience.

- Integration of internal DOT communication systems and with cooperating agencies.
- Paradigm shift from project level improvements and engineering to a system/network management approach.

1.2 Flood Sources Considered in This Project

This memorandum is principally concerned with storm-driven flooding:

- Widespread riverine flooding, both for day-long or multi-day events with long lead times as well as flash flooding.
- Coastal events, such as storm surge, leading to widespread coastal flooding.

Isolated or semi-distributed instances of flooding due to failure of flood control may also damage transportation infrastructure. These sources of flooding are also important but have not been explored in depth at this time. Examples include:

- The bursting of water mains
- Debris buildup or ice flows.
- Snowmelt events.
- Dam break or levee breach.

1.3 Known Floodcasting System Needs for DOT Flood Response

Floodcasting frameworks must focus on explicitly addressing DOT decision-support needs, principally the decision of whether or not to close a road during flood conditions, and where to funnel limited mitigation funds. Establishing detours and support for other DOT emergency management functions is also desirable. The technology and data to support these functions are available, and many DOTs have engaged with at least some aspect of available data and methods, as shown in Section 6, Case Studies from State DOTs. These case studies (available in more detail in Section 6) reveal common themes that will enhance usability of flood forecasting systems for the average operator. These themes can be summarized as follows:

1. **Data**: The user should not have to provide unique data on weather forecasts, streamflow, and topography because there are reasonably high-resolution national datasets that can be used as the default. However, the user should have the option to replace national sources with higher resolution local products where available (e.g., topography data).
2. **Asset management**: The tool should easily interface with asset management systems, including the ability to easily update additions and changes to assets. Many DOT asset management systems are currently under development, some in GIS format. Further, while asset management systems are a logical place to include information about asset fragility and vulnerability to flood conditions, there is currently no standard data model for doing so.
3. **Model results**: Users should not be required to expend significant effort interpret forecasting, hydrology, and hydraulics data, as users may include professionals for whom these topics are not their main area of expertise.
4. **Assets monitored by system**: BridgeWatch™™ and similar tools are used to monitor bridge scour at most DOTs, and some of the more advanced floodcasting tools currently in use also focus on bridge and culvert crossings. Flood prediction must move beyond bridge inundation at stream crossings to include roadways running alongside or adjacent to water bodies, as well as considering impacts to Intelligent Transportation Systems (ITSs) and signals, buildings, equipment, and storage areas. However, due to the widespread use of BridgeWatch™ and the importance of scour to safety, integration between BridgeWatch™ and floodcast tools may be desirable.
5. **Accurate flood modeling at ungaged locations**: Flood inundation extents mapped for entities such as the National Weather Service (NWS) currently tie inundation extents to streamflow at a

gaged location; however, it is also necessary to understand flood risk at ungaged locations. USGS regional regression equations may be of use here. The Iowa Flood Information Center (IFIC), which has developed inundation extents statewide, is an implemented example.

6. **Support for both operational and emergency management activities**:
    - Prioritizing decision-making around road class, Annual Average Daily Traffic (AADT), freight routes, and other concerns
    - Identifying neighborhoods or development clusters at risk of being cut off from road access by flooding.
    - Consideration of impacts to critical infrastructure outside the transportation network, such as hospitals and flooded power substations.
    - Assistance planning and communicating detours.
7. **Easy-to-use outputs:** Usable outputs will integrate well with existing DOT and state systems using widely available platforms (e.g., state 511 websites, Wireless Emergency Alerts, the Federal Emergency Management Agency (FEMA) Integrated Public Alert and Warning System and geospatial applications such as Google Earth or ArcGIS Online). Data standards, which are discussed in more depth in the following section, are integral to achieving this goal.

Tools facilitating the above will help meet DOT needs for floodcasting, which will in turn increase the chance for wider adoption of floodcasting systems. Some tools and methods for these goals are already be available and in use, others will require minor modifications, and some will require substantial modification or new approaches. This technical memorandum investigates and summarizes only the types of tools available; their suitability will be explored in the subsequent project document.

2 COMPONENTS OF A REAL-TIME FLOOD FORECASTING DECISION-SUPPORT SYSTEM

To meet the objectives outlined above, the technology and tools currently exist for a flood forecasting system with the components and capabilities listed in Table 1. The most advanced DOTs are beginning to develop systems with many of the components listed in this section, but data limitations and model run times are frequently cited concerns. Systems under development are typically not yet fully integrated in DOT operations and emergency response functions. Both of these issues are discussed in greater detail in the next section. For a simple overview of software resources that are currently available for use in an operational floodcasting tool, please see this report's Appendix B Resources Table.

2.1 Flood Forecasting, Operations, and Response

Table 1 illustrates the basic components of a flood forecasting system tailored for transportation system use. Components are broken into four sections:

- Flood modeling and flood forecasting platforms
- Infrastructure modeling
- Decision-making, communication, and emergency management
- Interoperability

Considerations related to emergency management activities and mitigation planning are discussed in more detail in Sections 2.1.1 and 2.1.2.

Table 1. Flood forecasting system components and capabilities

Flood Forecasting System Category	Component
Flood Modeling and Flood Forecasting Platforms and Data	Precipitation forecasting/forecasting platforms
	Rainfall-runoff
	Discharge and velocity (stream gages and bridge instrumentation)
	Hydraulic analyses: water surface elevations, inundation extent and depths
	Elevation
Infrastructure Modeling	GIS-based asset management and physical infrastructure
	Critical infrastructure outside the transportation network
	Vulnerability/fragility characteristics
	Dependencies, asset connectivity, and vulnerabilities to cascading failures
Decision-Making, Communication and Emergency Management	Prioritization
	Communication
	Automation: Alerts, personnel deployment, dynamic signage, flood control structures
	Integration with DOT and emergency management operations and procedures
Interoperability	Data standards

2.1.1 Floodcasting Use to Support Emergency Management Activities

Without integration into both operational and emergency management procedures, flood forecasting tools are unlikely to improve transportation safety during flood conditions. Potential breakdowns in utilizing a flood forecasting system can occur at the following points, necessitating operational and procedural safeguards:

- **Monitoring**: Failure to monitor conditions leading to flooding.
- **Operational and flood response activities**: Failure to engage in flood response quickly enough or for long enough.
- **Communication**: Failure to communicate sufficiently with DOT personnel, partner entities, and the public.

Figure 4. FEMA's Wireless Emergency Alerts represent an example of automated hazard alert communication.

Automation of some components of flood response activities may be desirable and are feasible. Flood forecasting tool design that automates monitoring, closures, and communications is possible, but DOTs and Transportation Management Centers frequently choose to have checks of automation, such as recommended variable/dynamic sign messages. Automation may prove especially useful for monitoring and communication and recommended actions to post for the public. Automation of some types of closure infrastructure (e.g., such as dynamic signs or railroad-style crossing gates) at vulnerable locations may also be possible. Consequently, deployment of materials and DOT and cooperating personnel to establish (and, in some cases, to enforce) road closures and detours will still be time- and labor-intensive to varying degrees, depending on the severity of flooding. Therefore, it would be advantageous to design flood forecasting tools to alert the appropriate decision-makers with plenty of lead time to mobilize necessary personnel.

2.1.2 Floodcasting and Mitigation Planning

A flood forecasting system can also have a role in supporting certain longer-term planning activities, including:

- **Prioritizing**: As more hazard and vulnerability data becomes available, the information can be used to prioritize mitigation and capital investment planning.
- **Mitigation**: Identifying the locations of high-impact investments, such as design or specifications changes, elevation of critical electrical components (dynamic signs, inundation-sensitive ITS, transformers, generators, etc.) in high-risk areas, and similar activities. Ideally, selection of mitigation strategies is informed by cost benefit analyses.
- **Tracking/monitoring**: Identifying frequently inundated stretches of road, recording the length of time a road is inundated before undermining occurs, and recording damage.
- **Incident analysis and debriefing**: Using data from past flood events and reviewing issues and lessons learned.
- **Climate change adaptation planning**: Changing climate may exacerbate existing problems, so understanding current flood impacts can indicate where to direct adaptation investments. Methods exist to estimate the change in coastal and riverine floodplain extent for various recurrence intervals (Dewberry, unpublished).

3 PRECIPITATION FORECASTING AND INUNDATION MODELING

The hydrology and hydraulics (H&H) components of a floodcasting system involve some combination of the following data and analysis results:

- Elevation data
- Precipitation forecasting/forecasting platforms or data
- Rainfall-runoff
- Discharge
- Inundation extent

In most cases, local information is preferable, but national information or sources may be more consistently reliable, widely accepted, or easily accessed. The focus of the next section is therefore on national data sources, with some discussion of local sources where appropriate.

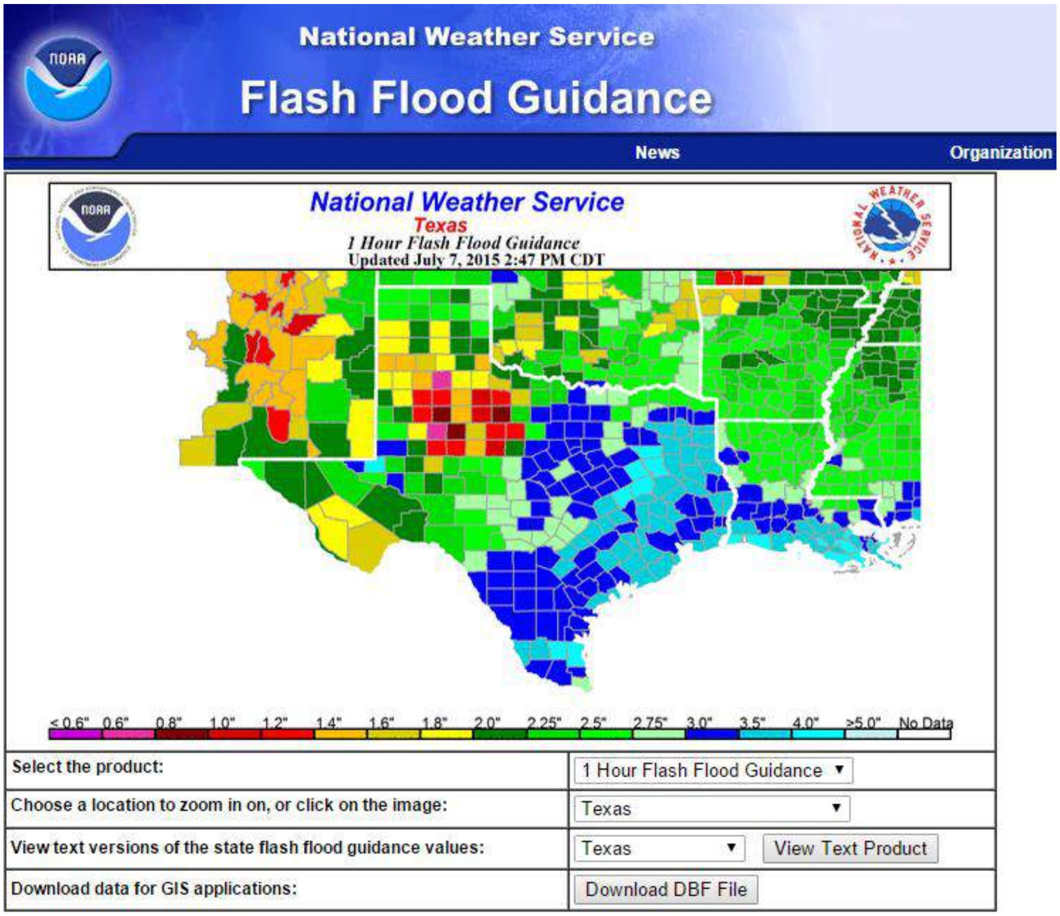

Figure 5. The NWS's flash flood guidance is an example of nationally produced, reputable county-level forecasting data that can support operational preparedness.

3.1 Elevation and Land Use

In this section, elevation of physical infrastructure, specifications for terrain data for use in flood mapping, and aerial methods to track land use changes are discussed. Elevation data pertaining to terrain, DOT assets, and other critical infrastructure are crucial for estimating flood impacts, as is tracking changes to land use, which affect impervious surface and "flashiness" of watersheds. Flashiness reflects the frequency and rapidity of short term changes in stream flow in response to storm events. Streams that rise and fall quickly are considered flashy. This hydrologic change usually occurs in response to urbanization. One measure of flashiness, the R-B flashiness index, may be tracked to assess increase in impervious surface in a watershed over a period of time, particularly the increase in connected impervious surface, which is harder to assess. The National Urban Change Indicator dataset, which shows persistent changes in impervious land cover from 1996 through present, is another valuable method to track changes in impervious surface (FGDC, 2014).

Elevation data can be obtained or supplemented using a number of different methods depending on what is being characterized. Currently, Light Detection and Ranging (LiDAR) is the preferred collection technique for remotely sensed terrain data. Terrain elevations should be updated regularly to account for major development, land use changes, seismic and landslide activity, or similar events. Capturing infrastructure dimensions may require a hybrid of LiDAR and other techniques. Some combination of remote sensing and deployment of survey crews is indicated by the experience of states with operational or experimental flood prediction tools, such as Iowa and Virginia, respectively. These tools are discussed in more detail below in 6. Case Studies from State DOTs.

Supplementary information will sometimes be needed to fully attribute infrastructure assets. For example, the use of as-builts may be appropriate in some instances, but sourcing elevations from as-builts is often time-intensive and should be considered supplementary to remote sensing. An effective standard is for elevation products to comply with FEMA's guidelines for high-quality digital topography. Elevation guidelines for areas of high flood risk recommend an accuracy of up to approximately +/- 24.5 cm as shown in Table 2. It is proposed that this standard be implemented for obtaining key infrastructure elevations as well as for characterizing terrain.

Table 2. FEMA standards for high-quality elevation products used for flood risk mapping and modeling. "FVA" indicates accuracy over open ground and "CVA" indicates accuracy over other land categories. Source: FEMA Procedure Memorandum No. 61 (FEMA, 2010).

Level of Flood Risk	Typical Slopes	Specification Level	Vertical Accuracy, 95% Confidence Level Metric (FVA/CVA; cm)	LiDAR Nominal Pulse Spacing Metric (≤ m)
High (Deciles 1, 2, 3)	Flattest	Highest	24.5 / 36.3	1
High (Deciles 1, 2, 3)	Rolling or Hilly	High	49.0 / 72.6	2
High (Deciles 1, 2, 3)	Hilly	Medium	98.0 / 145	3.5
Medium (Deciles 3, 4, 5, 6, 7)	Flattest	High	49.0 / 72.6	2
Medium (Deciles 3, 4, 5, 6, 7)	Rolling	Medium	98.0 / 145	3.5
Medium (Deciles 4, 5, 6, 7)	Hilly	Low	147 / 218	5
Low (Deciles 7, 8, 9, 10)	All	Low	147 / 218	5

3.1.1 Elevation Data

Ideally, it would be possible to obtain adequate elevation information through remote sensing techniques; however, there are numerous cases where key elevations of transportation features cannot be seen from above, precluding the use of aerial remote sensing tools. A sample set of physical infrastructure assets and the likelihood of obtaining key elevation data through remote sensing tools is shown in Table 3.

Table 3. Using aerial remote sensing techniques to obtain elevation data for transportation and other critical infrastructure

Asset	Key Elevation Data	Likely to Be Obtainable Through Aerial Remote Sensing Techniques?
Road	Crest elevation (at various intervals)	Yes
Bridge	Deck elevation	Yes
	Low chord elevation	No; but may be able to estimate using deck elevation
	Approach road elevation	Yes
Tunnel	Mouth elevation	Possibly
Buildings	Lowest adjacent grade	Yes
	First floor elevation	Possibly
	Sub-grade elevation	No
Signals and ITS	Elevation of vulnerable electrical components Elevation of battery backup	Possibly
Power Infrastructure	Generator and non-submersible transformer elevations	Possibly
Above Ground Utilities	Elevation (at various intervals)	Possibly; asset-dependent
Underground Utilities	Elevation (at various intervals)	No
Power Substations and Transmission Facilities	Lowest adjacent grade	Yes
	Facility elevation	Possibly

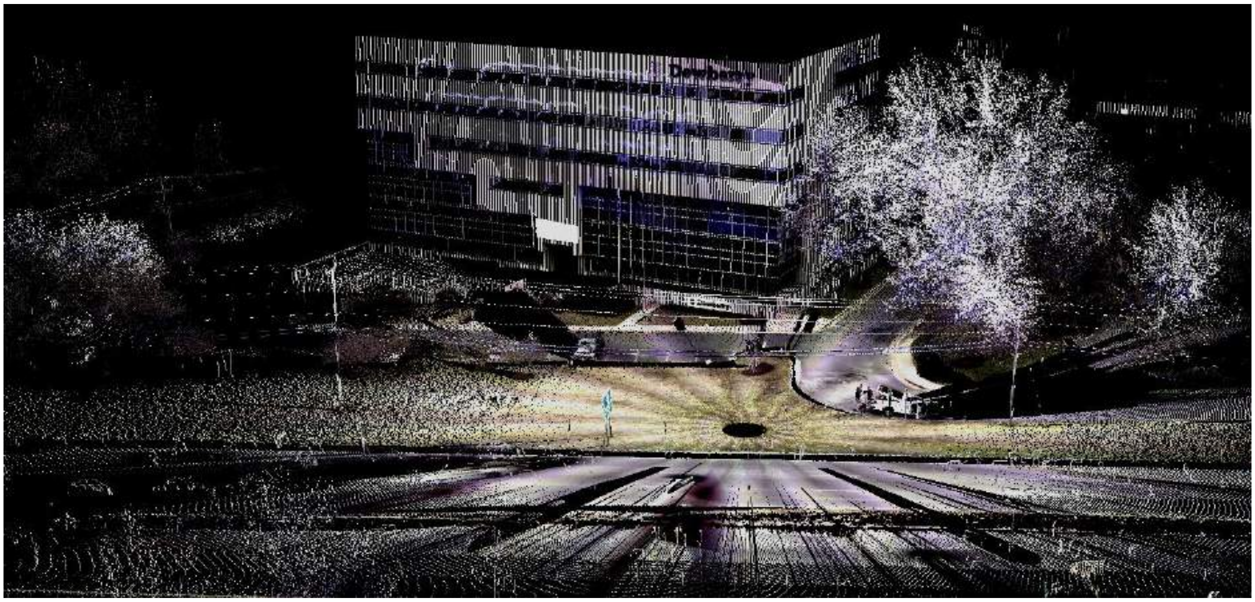

Figure 6. Imagery, dimensions, and elevations obtainable by terrestrial laser scanners, also referred to as terrestrial LiDAR. The black oval at the center of the image is the location of the survey tripod.

Although suboptimal, estimation techniques are likely to be used for some types of assets at lower-risk locations. For example, low chord elevation could be estimated at bridges statewide using remotely sensed elevation estimates of the bridge decks and subtracting an average or type-based approximate bridge deck depth. However, for some sub-grade assets, it may not be possible to use rough estimates at all. Furthermore, at high-priority locations, surveyed data may be preferred. For most DOTs, some combination of remote-sensed, estimated, and field survey-verified elevation data is likely to be employed. Nonetheless, where possible, it is both more cost-effective and consistent to use a single elevation source with well-defined information detailing accuracy and limitations. A number of tools that are available to collect elevation data for transportation and other critical infrastructure assets are summarized in Table 4.

Table 4. A selection of sources for acquiring statewide or asset-specific elevation and land use data

Elevation and/or Land Use Source	Brief Description	Elevation	Large-Scale Land Use Changes	Comments
As-built plans	Paper or digital plans showing post-construction details	Yes	No	Usually only applicable to a single asset or portion of an asset
USGS Point Query Service	Returns point elevations based on input coordinates	Yes	No	Free, quality-controlled national data source
Aerial LiDAR	Dense, accurate elevation datasets useful for terrain mapping	Yes	Yes	Popular for FEMA flood mapping products, including RiskMAP. DOT investment in LiDAR is increasing and has been found to be highly cost-effective (Iowa DOT)
Photogrammetry and satellite	Imagery that can be used to create digital elevation models (DEMs)	Yes	Yes	Publicly available data may not have sufficient resolution or quality for some applications
Pictometry and oblique imagery	Georeferenced aerial imagery, some of which is captured at an angle to provide 360° views	Yes	Yes	Can be useful to compare historical, recent, and post-disaster imagery
Mobile laser scanners	Vehicle-mounted scanners used for mapping corridors	Yes	No	"Street view"-style mapping; best option for areas where many bridges need to be mapped
Traditional survey crews	Land survey teams with tripods, using tie-ins	Yes	No	Single asset; personnel and time requirements may be prohibitive
Terrestrial laser scanners	Tripod-mounted scanner for individual locations	Yes	No	

3.1.2 Land Cover

Many of the tools listed above are also suitable for updating land use and land cover. Land use is a major driver of the timing and magnitude of streamflow through mechanisms like runoff and evapotranspiration. Certain types of land use changes are conducive to increased flooding. An example of human-driven changes that increase runoff is development that expands impervious surface in a basin. Landscape changes that may be natural or human-driven include burn scars, which are the alterations to ground surface and vegetation caused by wildfires and can lead to cascading impacts. Conversely, certain basin-scale practices can also significantly reduce runoff and result in lower magnitude flooding. Two examples are reforestation activities and the supplementation or replacement of elements of traditional gray infrastructure with green infrastructure, including disconnecting impervious surface. Since land use characteristics are a key parameter in modeling runoff as well as inundation mapping, it is desirable to employ remote sensing techniques to obtain this information.

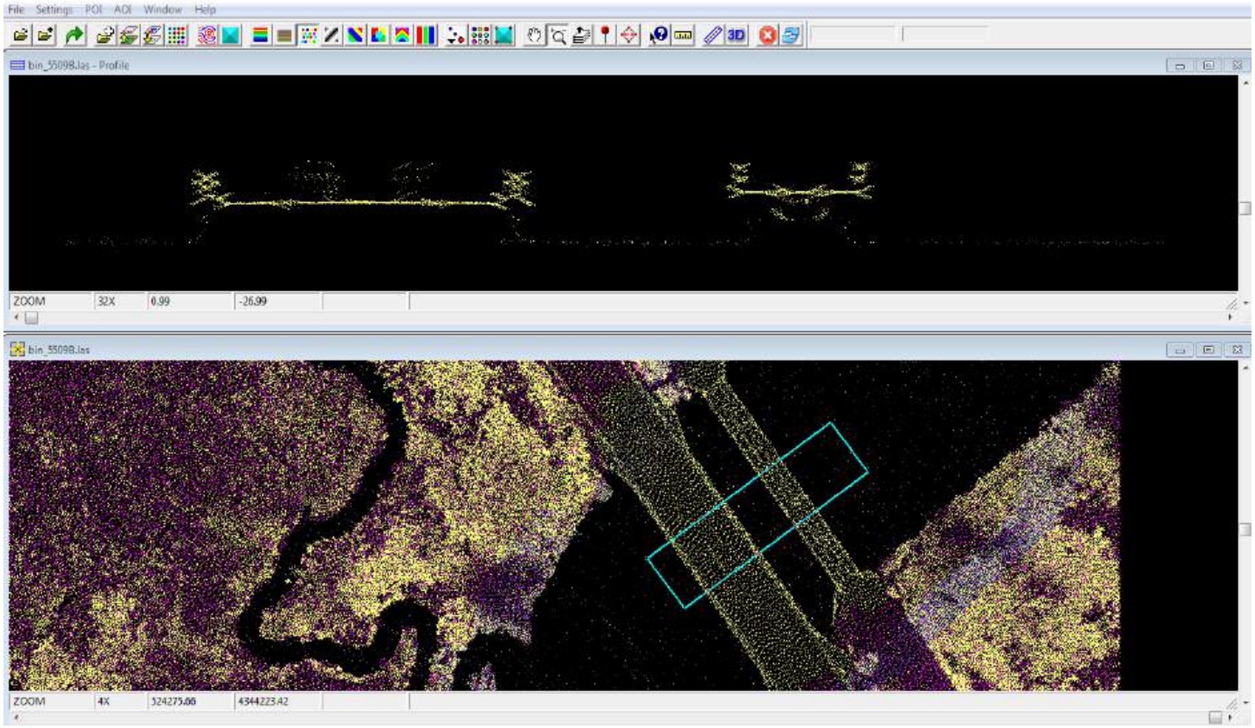

Figure 7. Remote sensing tools are increasingly used for flood risk projects and may also be useful for obtaining transportation asset elevations. Above is an image of a bridge (plan and profile view) as seen through an open source 3D geodata viewer (http://www.fugroviewer.com/) with simple land cover classification implemented.

3.2 Precipitation Forecasting/Forecasting Platforms

Precipitation forecasting sources may be long-range, short-range, or real-time. As the outlook increases (e.g., to 5-7 days), so does uncertainty, because weather is a dynamic and complex phenomenon. Long-range forecasts should always be updated with shorter range updates and real-time verification. Despite this uncertainty, each type of model has strengths:

- Long-range forecasts for use in flood forecasting have an outlook of approximately 1 week and give DOTs the greatest amount of lead time for longer duration flood events.
- Short-range forecasts have an outlook that may range between 1 and 2 days or as few as several hours. These can be used to confirm long-range forecasts and can catch flash flood events that long-range models do not capture.
- Real-time data, or observed values, can be used to confirm or adjust models, and come from sources such as rain gages, radar, and sensors.

Several examples of reliable, national-scale longer-range and shorter-range forecasting sources are shown in Table 5.

Table 5. Examples of long-range, short-range, and real-time forecasting sources

Term	Model	Approx. Spatial Resolution (km.)	Outlook
Long-term	The National Oceanic and Atmospheric Administration's (NOAA) Quantitative Precipitation Forecast Maps	25	1 week
Short-term	National Digital Forecast Database	5	24, 18, 12 and 6 hours
Observation/real-time	NOAA NEXRAD Radar Sites* NOAA Stage IV Precipitation Data	4	Near real-time

*Requires the use of tools that may be cost-prohibitive for many users at this time.

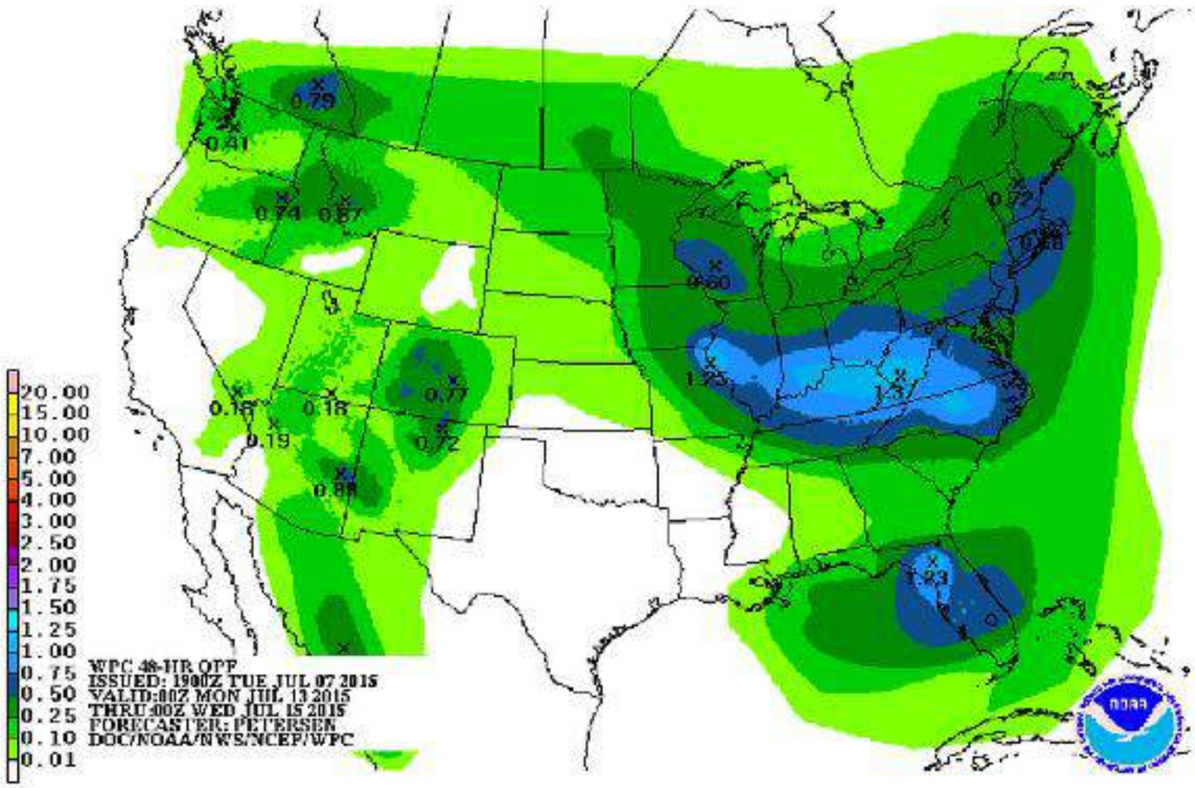

Figure 8. NWS's Weather Prediction Center Quantitative Precipitation Forecast showing estimated 2-day precipitation totals for the 6-7 day outlook period.

3.3 Rainfall-Runoff and Stream Discharge

To facilitate the transition from locally stored, non-standardized digital resources to nationwide, web-hosted geospatial resources, the Federal Geographic Data Committee is advancing a National Water Data Infrastructure (NWDI) with a core set of static and real-time information layers assembled from the best available sources. Although NWDI will take years to complete, readers should be aware of this effort, which will ultimately provide an evolving but significant, high-quality source of information. One of the most exciting outcomes is likely to be a standardized, national source of forecast-based stream discharges developed during the National Flood Interoperability Experiment (NFIE) (Maidment, 2015).

As part of NFIE, a continental-scale hydrologic model estimates stream discharges at the resolution of a National Hydrography Dataset stream segment, which is appropriate for local-scale planning and response. NFIE collaborators also intend to make flood inundation extent and depth grids available. Promising work is being done in this area by the National Water Center (NWC). The NWC, housed at the University of Alabama, is the primary coordinating entity for the NFIE. The NFIE seeks to link four data streams related to hydro-climate to support flood prediction (Maidment, 2014):

- Weather and seasonal climate monitoring and prediction (e.g., NOAA forecast products)
- Land use and land surface (i.e., soil moisture) information with dynamic updates
- LiDAR elevation and geolocation
- Water surface elevation and discharge

Standardized, stable dissemination of the products described above is not yet a reality, so at this time, other national level products coupled with local level inundation estimates, where available, must be relied upon to estimate flood risk based on forecasts. While not exhaustive, several models and data products produced by various entities are shown in the table below. For those with constraints preventing in-house rainfall-runoff modeling, River Forecast Center (RFC) products in combination with NWS Advanced Hydrologic Prediction Service (AHPS) stream gage forecasts and National Flood Hazard Layer (NFHL) or AHPS flood extent products may be more readily accessible resources. These ready-made estimates are also discussed in the following sections.

Table 6. Rainfall-runoff models for use in estimating stream discharge

Approx. Lead Time	Model	Typical Basin Size Modeled
12 hour	NWS Numerical Models (e.g., Sacramento Model and Dynamic Wave Operational Model)	River Forecast Center Basin
Varies	US Army Corps of Engineers (USACE) Institute for Water Resources Variable Infiltration Capacity (VIC)	HUC-4 Basin
1-2 hours	NWS Quantitative Precipitation Estimate for River Forecast Centers	River Forecast Center Basin

3.4 Flood Forecasting Products

Existing river outlook products can also be used to inform flood response planning. The NWS Weather Prediction Center has a number of resources that may be useful, including:

- Significant River Flood Outlook shapefiles or KMLs, which are created once per day with approximately a 5-day outlook.
- Flash Flood Guidance Data shapefiles and .DBF tables, which are updated several times daily.

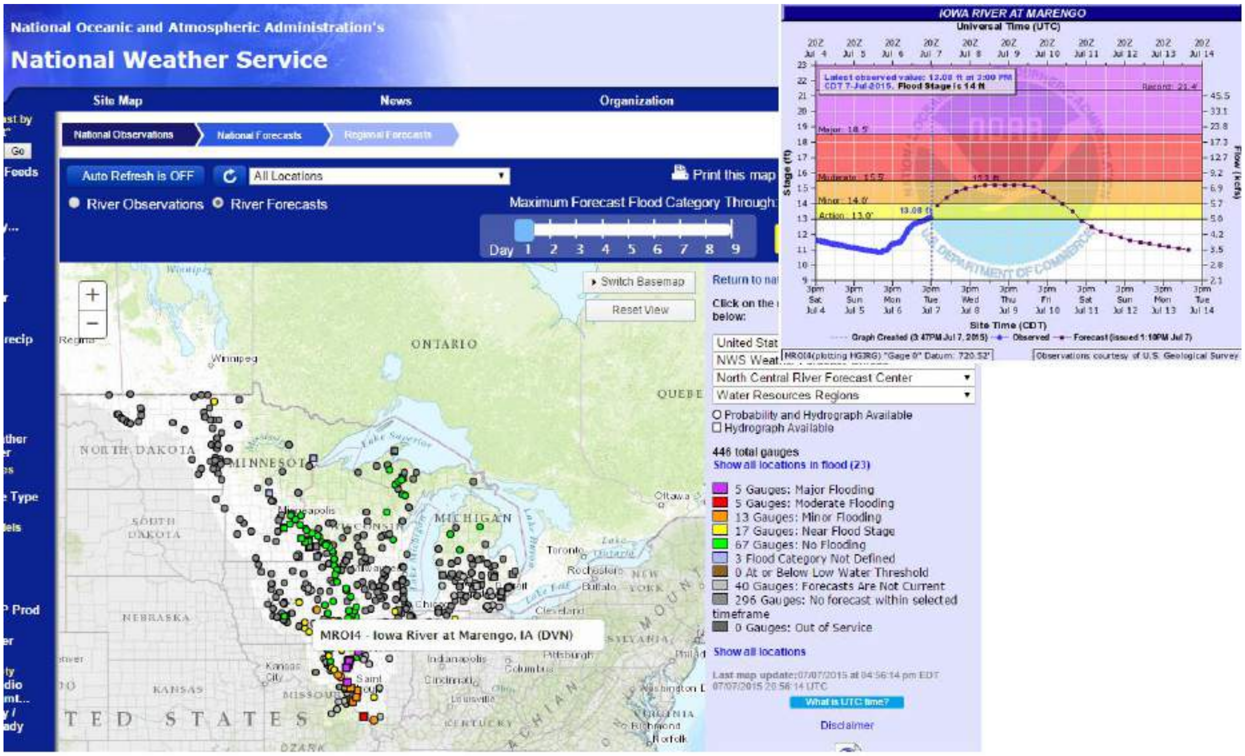

Figure 9. NWS river stage prediction supplied through a regional RFC.

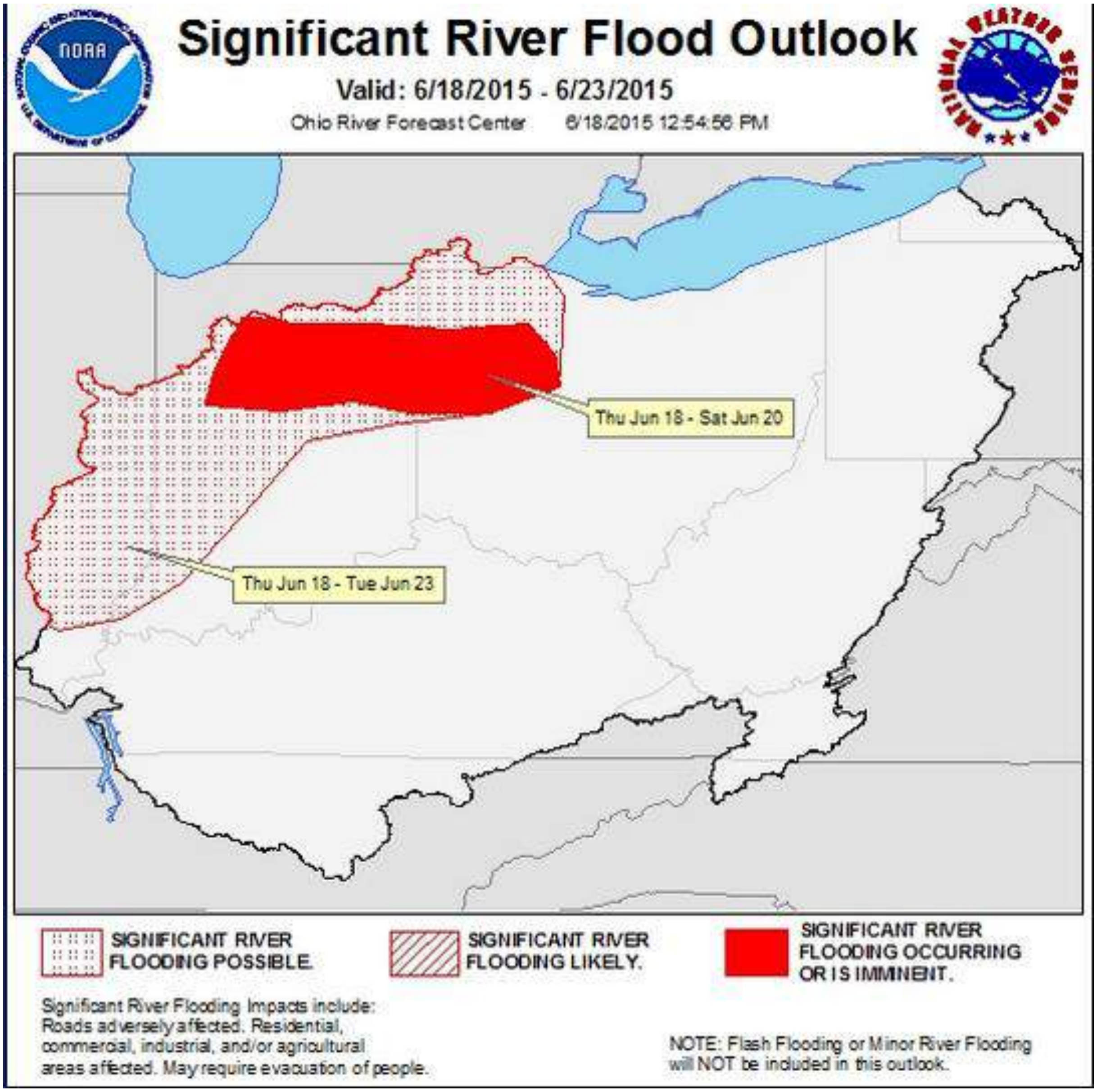

Figure 10. NWS RFC flood outlook product, highlighting basins according to occurring, likely, or possible categories. Small-scale and localized flooding is not included in this estimate, and sub-basin scale resolution required for detailed response is not provided.

3.5 Inundation Extents and Depths

Currently, the most comprehensive national geodatabase of flood inundation extents is the National Flood Insurance Program's (NFIP) NFHL. Approximately 1 million miles of the nation's streams have been mapped for the NFIP, and highly populated areas tend to be well represented, but coverage is not comprehensive. However, the NFHL shows inundation extents only for the low recurrence interval events with regulatory significance for the NFIP, namely the 100-year (1% annual chance) and 500-year (0.2% annual chance) events. Higher-frequency events that result in flooding are not represented. Significant flooding can be caused by 50-, 25-, and even 10-year or more frequent events. Extents and depth grids for all NWS-defined flood stages are available at some locations through the AHPS, but the model development or calibration and flood mapping required to produce similar products for an entire state would be resource intensive, even with automation tools. Ongoing NFIE efforts as well as currently available national sources of flood inundation extents are listed in Table 7.

Table 7. National-scale data sources for flood inundation extents

Inundation Extent Sources	Shows Inundation for	Coverage
NWS Advanced Hydrologic Prediction Service	NWS Flood Stages	Continental United States (CONUS) (partial coverage; ongoing)
FEMA National Flood Hazard Layer	100-year and 500-year event	National (partial coverage; ongoing)
National Flood Interoperability Experiment	Intended: Flood Stage Categories	CONUS (expected, 2015)

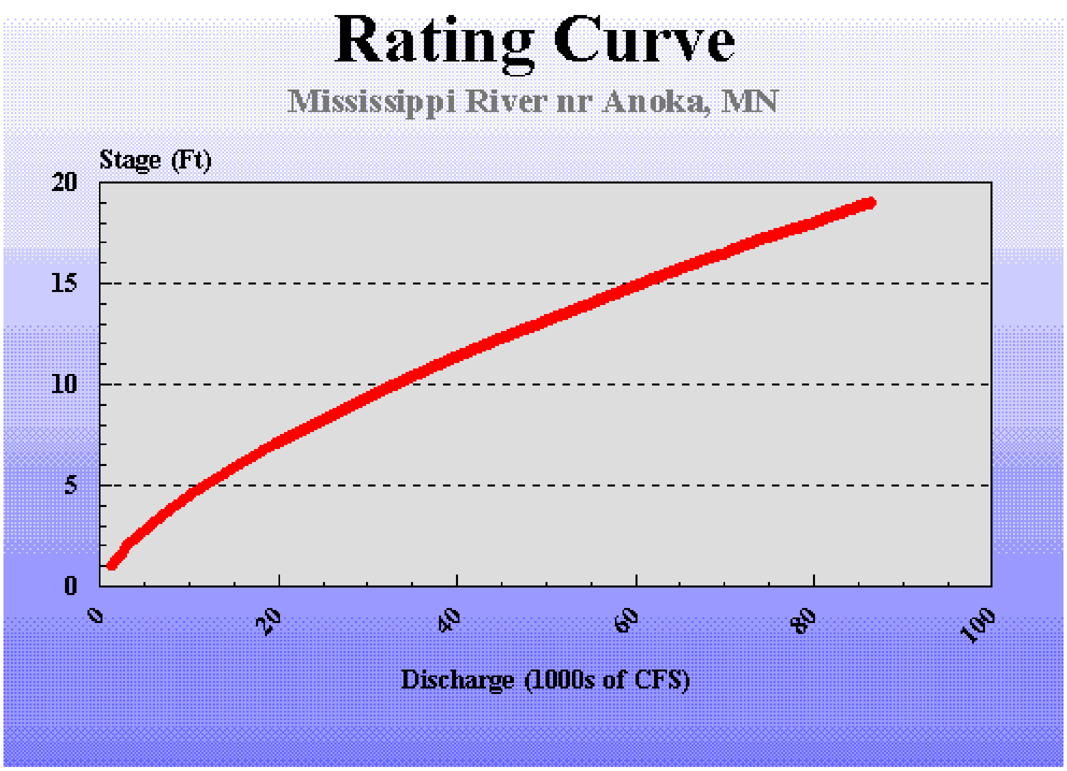

Figure 11. USGS rating curve showing the relationship between discharge and stage of the Mississippi River at a gaged location. Source: NWS's Service Hydrology Manual: Rating Tables and Curves.

Ungaged locations also represent a challenge for inundation extent and depth estimation. In the absence of a stable, continental scale hydrologic model, an option proposed by the NFIE is to use generalized, or regional, USGS rating curves to obtain inundation extents throughout a basin, including both gaged and ungaged locations. Rating curves are developed at gaged locations by USGS to show the relationship between flood stage and discharge. In the flood forecasting context, such an approach would also require developing a relationship between precipitation and discharge, possibly through generalized

USGS regression equations, or derivatives thereof. USGS regression equations consist of a number of parameters describing the basin and climate characteristics most relevant to stream discharge. These or similar techniques could be used to develop inundation extents at ungaged locations, as indicated in Figure 12. This process would also be resource intensive. Data and methods to produce flood inundation extents for any discharge at both gaged and ungaged locations nationwide are an important need.

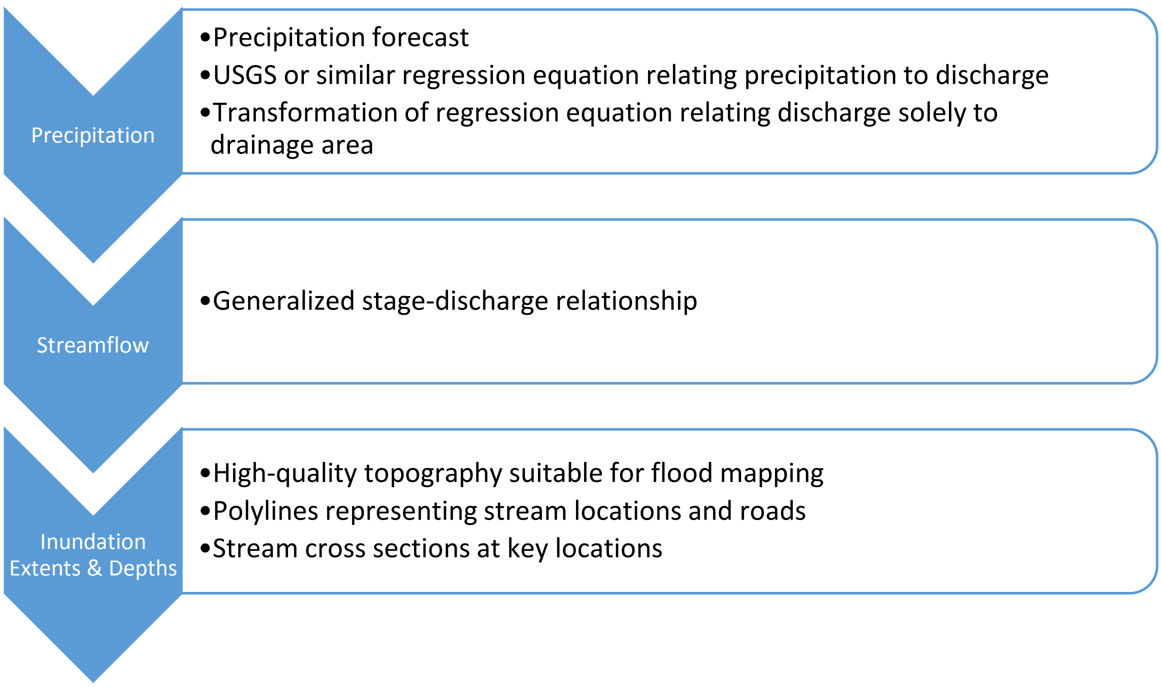

Figure 12. Developing inundation extents and depth estimates from a forecast for ungaged locations at high-priority locations.

4 GIS-BASED ASSET MANAGEMENT AND PHYSICAL INFRASTRUCTURE

Many DOTs are making significant strides toward GIS-based asset management systems. Currently, common challenges with assembling such systems include data gaps and redundancies, synchronization difficulties between different departments, and lack of integration with various management software tools (NCHRP, 2015). However, as the example of Iowa DOT shown in the Section 6.1, indicates, a full linear referencing system (LRS) and high-quality elevation data for roadways offer significant advantages for flood risk planning and response. Many NCHRP projects have provided invaluable guidance on developing and using a GIS for transportation, or GIS-T.

This need to integrate asset data from many DOT functional areas was first identified in NCHRP Report 359 (1993), and further work on the subject includes:

- NCHRP 20-27(2) (1997): Development of System and Application Architectures for Geographic Information Systems in Transportation and NCHRP 20-27(3) (2001): Guidelines for the Implementation of Multimodal Transportation Location Referencing Systems. This project set the Location Referencing System standard for US DOTs and was simplified and codified in ISO IS 19148:2012.
- NCHRP 20-47 (2003): Quality and Accuracy of Position Data in Transportation. Discusses and suggests a data error model to evaluate the quality and possible ramifications of positional error inaccuracies introduced to data during acquisition, processing, transformation, and visualization.

- NCHRP 20-64 (2006): XML Schemas for Exchange of Transportation Data. Outlines an XML-based standardized data transfer methodology to improve transportation data exchange. The proposed standard, TransXML, has since been developed and is summarized briefly in Section 5.4, The Role of Data Standards in Communication and Information Exchange.
- NCHRP 08-87 (2015): Successful Practices in GIS-Based Asset Management. Provides examples of successful integration of GIS and asset management systems and uses, such as for data collection, communication, work planning, and disaster recovery.

NCHRP 08-87 is highly relevant to this effort and the following section builds on the project by addressing issues specific to flood risk and hazard identification. NCHRP 08-87 found that state DOT GIS data, overall, tends to be more complete for roads, followed by bridges, tunnels and culverts. Location data for signals, signs, guard rail, DOT-owned electrical infrastructure, sensors/instrumentation, and building facilities are also useful, as is hazard data (e.g., Colorado DOT rockfall data). Geospatial asset information tends to show location data, but is often lacking in other information that can help characterize vulnerability, such as elevation attributes, age, and condition. Data sources, common issues concerning data limitations, and data quality standards are discussed in the sections below.

4.1 GIS Asset Catalogs

Geospatial data gaps regarding asset location are perhaps the single greatest challenge to creating a statewide floodcast model, followed by the elevation attribute challenges discussed above. As discussed below, improving the comprehensiveness of existing GIS databases is a foundational step toward modeling vulnerabilities for both individual assets and the transportation system as a whole. To obtain sufficient information to support flood hazard impact analysis, it is likely that many DOTs will need to supplement their in-house data with other sources. A number of national and local datasets that may be useful are noted in Table 8. As noted above, elevation data sources will also be needed. Table 9 shows common data needs regarding critical infrastructure outside the transportation network.

Table 8. National and local GIS datasets

Sources of GIS Data	Examples
DOT asset management systems	• In-house systems • Commercially available systems, such as Maximo

State-owned GIS data	• DOT-owned shapefiles: point, line, and polygon
	  ○ Roads
	  ○ Bridges
	  ○ Tunnels
	  ○ Drainage systems
	  ○ Retaining walls
	  ○ Sound walls
	  ○ Building assets
	  ○ Lighting
	  ○ Signs, signals, and ITS
	  ○ Power (e.g., backup generators, transformers)
	  ○ Closed Circuit Television (CCTV), Road Weather Information Systems (RWISs), and other monitoring technologies
	  ○ Flood barriers and gates
	  ○ Pumps and pump stations
	• Georeferenced computer-aided drafting (CAD) datasets

Sources of GIS Data	Examples

Cooperating Agencies and Entities	• GIS files from local, county, and key private stakeholders
	  ○ Non-DOT roads
	  ○ Parcels
	  ○ Building footprints
	• Data characterizing other transportation modes (e.g., rail)
	• Utilities
	  ○ Water/Wastewater/Stormwater
	  ○ Power
	  ○ Gas
	  ○ Telecom

National data catalogues – transportation	• US Census-based TIGER/line files • Federal Highway Administration (FHWA) Public Use Roads and Parking Lots
National data catalogues – flood control	• Dams • Levees

Table 9. Critical infrastructure outside the transportation network

Sources of GIS Data	Examples
• US Critical Infrastructure density raster • Hazus • State emergency management office • County and local datasets	• Hospitals • Schools • Utilities • Power infrastructure • Fire/police/emergency medical services (EMS) • Drinking water treatment facilities • Wastewater treatment facilities • Emergency operations centers (EOCs) • Evacuation shelters

4.2 Vulnerability/Fragility Characteristics

State DOTs own a great deal of physical infrastructure, such as roads, bridges, buildings, signals, ITS, and power sources, each with their own location, specifications and vulnerabilities. This infrastructure has been estimated to be worth more than a trillion dollars nationwide. Much of this infrastructure has stood for decades, hence DOTs are tasked with managing aging infrastructure with some unknowns about condition and state of repair. Furthermore, the components of transportation networks are intertwined, both with other components within the transportation system and with other systems. An example of the latter case is the reliance of traditional traffic signals on the power grid, which is outside DOT purview. Vulnerabilities to the traffic system fall broadly into two categories:

- Vulnerabilities arising from individual asset characteristics (e.g., location, specification, state of repair)
- System-level vulnerabilities, which arise from interactions *between* assets

The vulnerabilities of a single asset are usually different from those at the system level (Leveson, 2011).

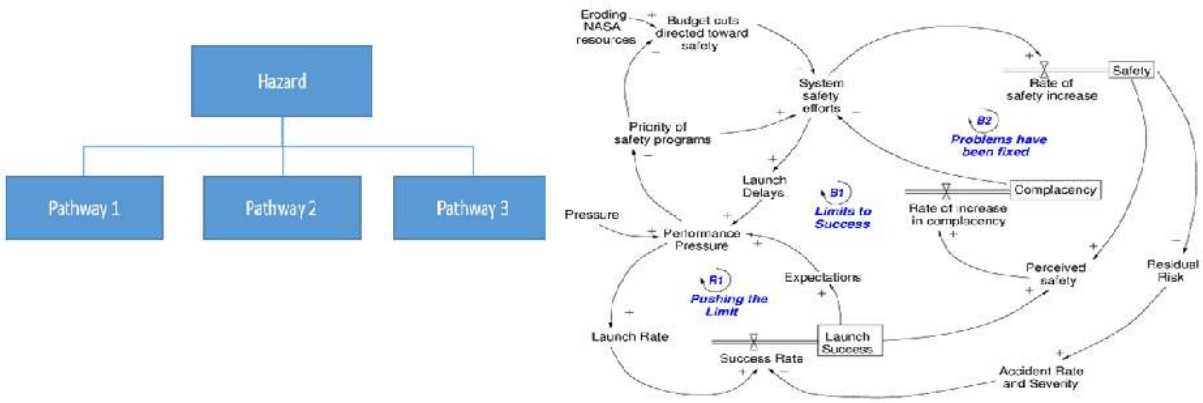

Figure 13. Failure tree for simple, mechanical, linear system following a chain-of-events pathway versus failure mapping for complex systems, which involve a large number of components and interactions characterized by feedback loops. The latter diagram is more analogous to transportation systems. Source: sunnyday.mit.edu/safer-world/refinery-edited.doc.

Even so, vulnerabilities can be difficult to characterize at the asset level as well as the system level. A significant data limitation for flood impact analysis is whether DOTs have information about how assets within the transportation network are affected by heavy rainfall or flood conditions. Without this information, GIS-based analyses are limited to intersections which, at best, incorporate elevation data. To perform the intersection, rainfall or streamflow would be used to map flood extents, and any assets within the inundation boundary are considered impacted. This approach, impacted/not impacted, is very binary, whereas asset responses to hazard conditions often degrade along a continuum or stepwise based on factors such as elevation of key electrical components.

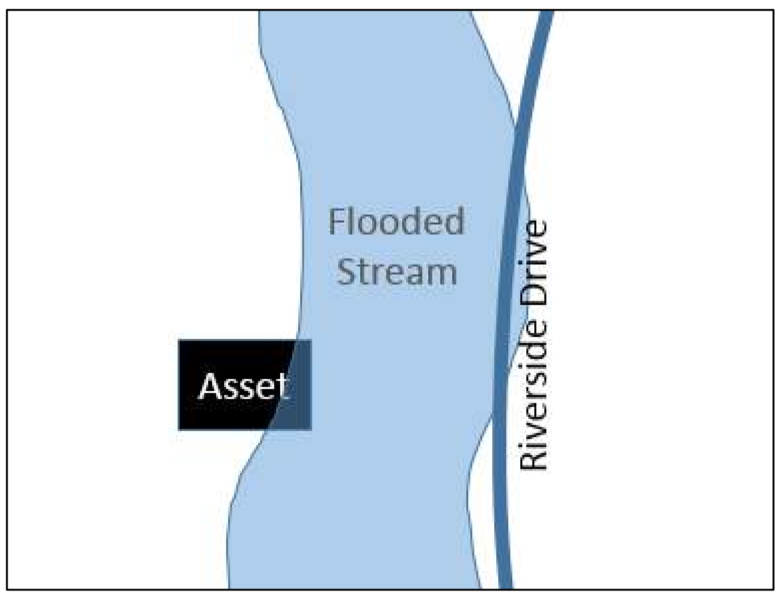

Figure 14. The intersection of the flood inundation polygon with building and road assets indicates likely impact, but without elevation data for the assets, it is difficult to determine the severity of the impact.

Vulnerability can be better assessed when detailed records of asset performance are available or can be inferred from design specifications, allowing the construction of fragility curves related to flood depth for a given asset. Fragility curves for floods show how an asset will function over the range of flood conditions the asset will be exposed to. Compared to the intersection analysis, depth-damage information provides a more accurate understanding of when assets are likely to fail. Loss estimation software such as FEMA's Hazus is a potential source of depth-damage curves for some transportation assets.

The ideal location for information about asset sensitivity to flood conditions is an asset management system with a GIS component. GIS-based asset management information can be used both in real-time flooding applications and to address long-term planning needs, tracking risk areas, maintenance, and progress toward adaptation or remediation of risks. A number of DOTs are using their asset management systems to collect information about flood vulnerability and are discussed in Section 6, Case Studies from State DOTs. Readers will note that this information is currently being used for long-term planning or flood response using information about past events more often than it is being used for real-time flood modeling and response.

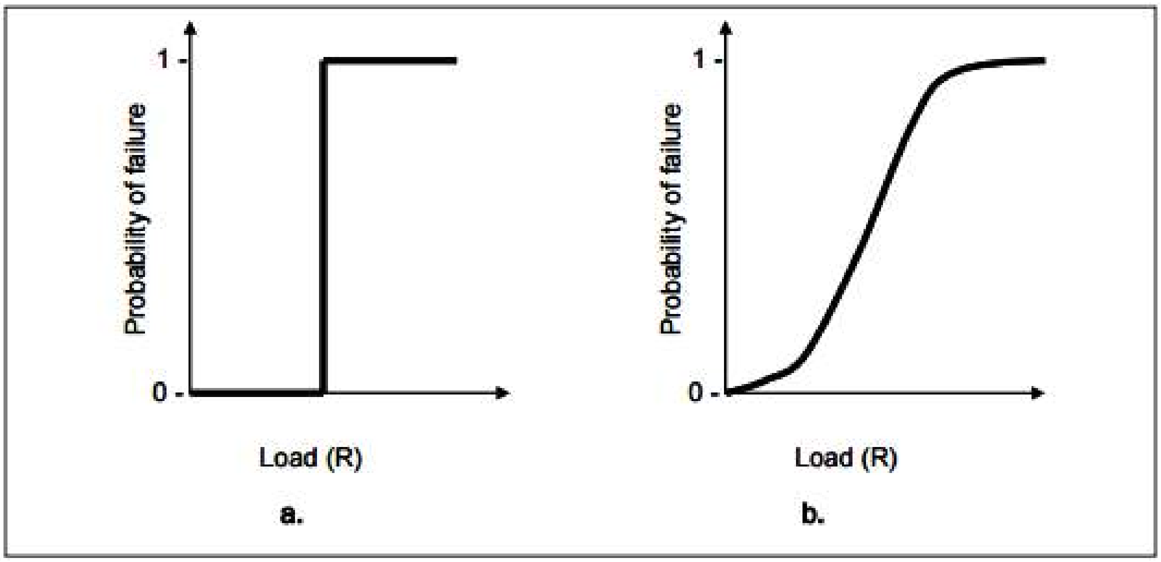

Figure 15. Examples of fragility curves for a) a well understood or brittle system and b) a poorly understood or elastic system. Source: Schultz et al., 2010.

4.3 Dependencies, asset connectivity, and vulnerabilities to cascading failures

Transportation systems are complex (rather than linear) systems composed of spatially distributed networks with interactions both within and outside the network. Flood-related vulnerabilities can therefore affect the functioning of a single asset, and that effect can have ramifications for the wider transportation network. System-level vulnerabilities become increasingly difficult to diagram and understand when systems combining physical infrastructure, computers, and human decision-makers come into play. Depending on the degree of asset connectivity, failure of one asset can affect a number of other assets as well as overall system function. This condition is known as a cascade failure. Before the event, addressing system-level vulnerabilities can improve the overall resilience of the transportation network; after an event, pinpointing the source of a cascade failure can enable faster recovery.

Most hazard-related vulnerability studies of physical infrastructure focus on individual assets or a network of assets of the same time. A relevant example of the latter is re-routing analyses for road networks. Work in the field of system vulnerability and infrastructure cascade failure, which considers interactions across asset types at the system level, is much less mature. Agent-based and network-based analyses are the most common, and network-based approaches have gained prominence over the past decade. Overall, analysis of complex systems involving the built environment are lagging behind the software and aerospace engineering fields. Fortunately, the same methods, which rely on techniques like Bayesian network statistics, are available to model risk to physical infrastructure (Frey et al., 2012; Bensi et al., 2011), although the data and cross-disciplinary collaboration needs are substantial. One example of leading-edge work on systems vulnerability in physical infrastructure is the Strategic Environmental Research and Development Program (SERDP) study of Norfolk Naval Base's vulnerability to sea level rise (Burks-Copes et al., 2014). Failures were defined as incidents interfering with the base's central missions and failure pathways were constructed using those central missions as an anchor point. Notably, this study did *not* include the base's road network, which was being studied separately at the time.

Extending this type of analysis to state transportation networks would be very useful, but several criteria must be met before it is possible to do so:

1. DOTs and other transportation owners must have GIS-based asset information that is reasonably comprehensive, describing the type of asset, location, elevation, and other specifications relevant to the hazard (e.g., culvert capacity).
2. Asset GIS data must have enforced topology rules. Topology rules, such as "line must not overlap" (i.e., for a stream or road) govern the relationships of features. Topology rule enforcement is important for achieving the data quality necessary for modeling. This is discussed in greater detail in the paragraph below.
3. Historical incidents should be reviewed and hypothetical if-then scenarios should be discussed to identify physical and computer-sensor network interconnectivity. Dependencies and failure pathways related to the hazard of interest should be mapped.
4. Fragility curves should be developed for assets exposed to the stressor of interest (e.g., using the Hazus software program).

Modeling cascading failures will continue to be a significant challenge compared to understanding the vulnerabilities of individual assets in the transportation system. Each of the listed items above are likely to represent a new or increased investment in DOT data management. Therefore, for the majority of DOTs, cascade failure modeling may not be feasible at this time. Further, given the relative newness of applying complex systems analysis tools to physical infrastructure, it is reasonable to allow the field to mature.

As an interim goal, it is desirable that DOTs at least aim to complete the first two items (a reasonably complete asset database with enforced topology) on the above list to accomplish meaningful real-time flood mapping. DOTs can also take a less comprehensive but potentially more manageable route by assigning criticalities to assets. Criticality is a subjective measure of how important an asset is to overall system functioning, often assigned on an arbitrary scale based on expert domain knowledge within an organization (e.g., FHWA, 2011). While not suitable for mapping system interactions and potential feedbacks, this approach can streamline identification of many key assets within the transportation network.

4.4 Prioritization

Asset mapping as well as flood inundation mapping are, at best, dynamic efforts requiring continuous updating. As noted above, repair and new construction continually add to the asset catalogue and changes to land use, both natural and human-caused, alter hydrologic conditions. Furthermore, transportation and other critical assets are numerous and highly distributed throughout each state. Consequently, some DOTs may choose to implement guidelines for prioritizing updated mapping of certain streams and roads. Ideally, prioritization will take place in cooperation with emergency management personnel. Beyond organizing road closures and detours during a flood event, FEMA defines a number of emergency support functions (ESFs) for DOTs (FEMA, 2013a), particularly in ESF #1 – Transportation. State emergency management plans include ESF #1 and list DOTs as the primary agency with a number of supporting agencies and defined tasks that fall under this annex. Typical operational and emergency management functions for DOTs are shown in Figure 16. During flood events, DOTs may be coordinating with state, county, local, and national entities; communication is a therefore a necessity and is addressed in greater depth in Section 5.

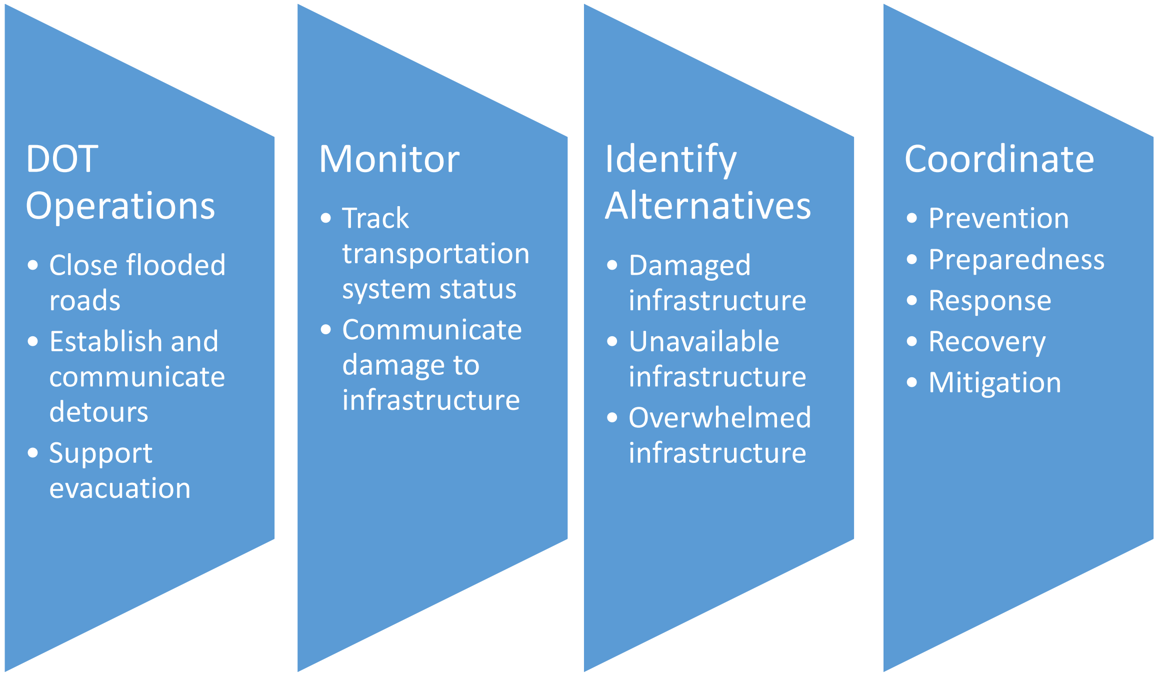

Figure 16. DOT operational and FEMA-defined emergency management functions (Monitor, Identify Alternatives [i.e. for passenger and freight travel, evacuations, etc.], and Coordinate).

Operationally speaking, DOTs note that the following characteristics help determine prioritization during a flood event that may be affecting multiple locations (TRB Annual Meeting, 2015):

- Functional class (e.g., road is part of the national highway)
- Route provides access to critical infrastructure such as a hospital, fire, police, or EMS
- Designation as a major freight route
- AADT > 10,000
- Location is experiencing flooding more severe than, for example, the 25-year event
- Detours are greater than 20 miles
- Water is deeper than a certain level, e.g., 1 ft.
- Designation as an evacuation route

The TRB Annual Meeting panels (2015) also revealed that, from an emergency management perspective, many of these same issues are important:

- Will flooding impact access to hospital facilities, fire and rescue, police, etc.?
- Does flooding hinder access to shelters (e.g., stadiums or schools) or emergency management staging areas?
- Can people access evacuation routes?
- Are residences affected by flooding?
- Are power substations likely to be impacted, and what are the implications for signals, dynamic message boards, communication, etc.?

EOCs will also have specific questions about how many houses or people are impacted, which roads are impacted, and to what depth (North Carolina Department of Emergency Management, 2013). The location of vulnerable populations that may need special assistance during evacuation is also a concern. These questions represent overlapping areas of concern between transportation and emergency management. DOTs tend to have more information about and monitoring for high-priority locations, but it is desirable to address statewide hazards in a systematic way. Tools answering emergency management-focused questions, along with showing impacts to bridges and roads, would be a valuable contribution to flood response efforts.

5 COMMUNICATION, INTEROPERABILITY, AND DATA STANDARDS

Communication issues that arise with flood forecasting vary depending on timing and audience. Issues that arise early in the emergency response process are different than those that take place during cleanup and recovery. There are also different considerations depending on from where and to whom information is being communicated. As shown in Figure 17, two-way information flows occur between people, software, and infrastructure. An overall discussion of typical information needs and potential technologies related to flood response follows. During the survey phase, additional concerns and needs may emerge.

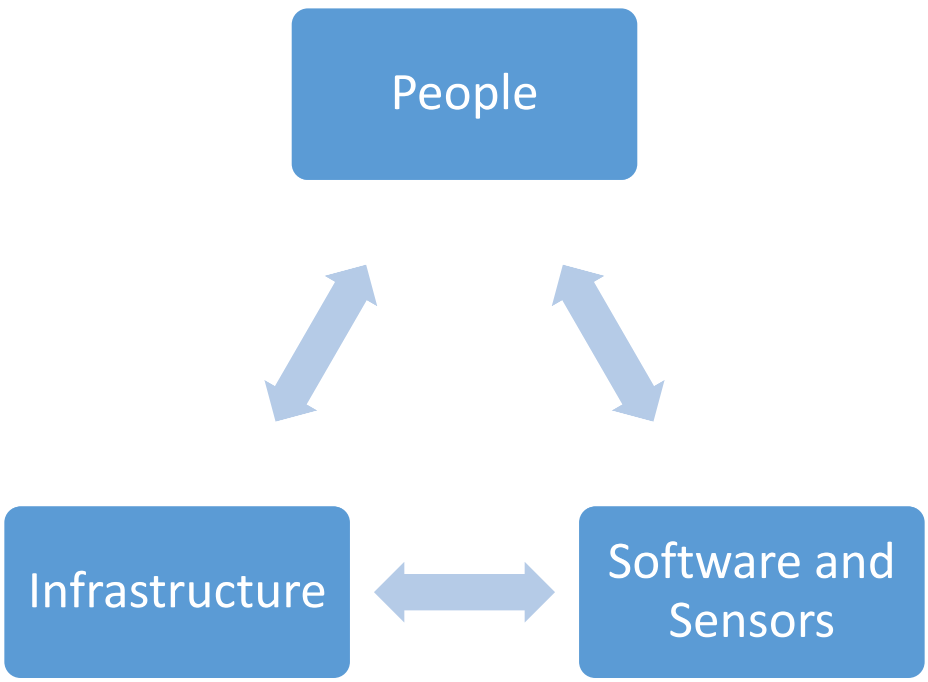

Figure 17. Two-way flows of information take place between people, software, and infrastructure (either through sensors or eyewitness reports) during a disaster event.

Information flows through a wide range of channels within and across institutional hierarchies. Channels include traditional telecommunication (telephone, television, radio); social media; DOT and emergency management software; and innumerable sensors, some of which are static (e.g., stream gages, RWIS) and some of which are mobile (e.g., smartphones and tablets, Global Positioning System [GPS], aerial photogrammetry). DOT personnel; cooperating agencies; local, county, or national entities; and the public may be sending or receiving information at any given time. Communication tools are used to enhance situational awareness, coordinate response activities, and execute specific actions. Given the large number of channels and users, it can be desirable to employ automation techniques to facilitate communication to appropriate audiences and software platforms.

5.1 DOT Internal Information Needs

The real challenge of flood forecasting tools is to integrate each of these data streams and to ensure that usable information is received by the appropriate audiences. Much like how an EOC coordinates state flood response efforts, floodcasting tools can integrate and disseminate information needed to support those efforts before, during, and in the aftermath of an event. Some of that information will come from field crews, in which case allowing real-time or administrator-approved updates to geospatial features such as inundation extents, road closures, and detour information may be desirable. Traditionally, information exchange will be input manually after coming into a central location via phone or radio, but it is also possible for field crews to use tablets and mobile devices to update the geodatabase themselves. Multi-user editing functionality is possible through tools such as the open source GeoServer, and proprietary platforms such as ESRI's ArcSDE (spatial database engine) technology.

Aside from needing to examine a great deal of hazard, asset, and response data when available, DOTs have numerous responsibilities during an emergency or disaster, some of which necessitate close coordination with a number of state, county and local, and national entities. The most common entities with which DOTs need to communicate before, during, and post-event, are listed in Appendix A. Communication may be top-down, bottom-up, or between partner agencies. Common questions that are internal to a DOT are shown in the following tables, along with examples of technologies or methods that can facilitate necessary exchanges. Tables in this and the successive sections dealing with state and local authorities as well as the public are organized according to response phase: planning/early warning, response, and early recovery.

5.1.1 Pre-Event

One-click or automated communication tools can help streamline efforts for DOTs to get the word out internally, to partner agencies, to infrastructure owners, and to the public.

Multi-media integration of floodcast advisories across the most commonly used platforms, including state 511 and other mobile mapping applications, is highly desirable. Additionally, crowd-sourcing can provide valuable real-time updates to flood extents, incidents, and other information. Both of these issues are discussed further in Section 5.3. Although not discussed here, DOTs may also wish ensure that traffic management plans are adequate.

Table 10. DOT internal information needs pre-event

Planning/Early Warning	Technologies and Methods
Where will it flood?	• The forecasting and H&H module of a floodcasting system • The GIS-based asset catalogue with the floodcasting system
When will it flood?	
How deep will flooding be?	
Which assets are at risk?	
Are power outages expected?	• Inundation extents estimated by the floodcasting system • Discussion or alerts (e.g., automated text message) to utility owners or facility owners
Emergency management: Are impacts to other critical facilities (e.g., power utilities, hospitals/EMS/police, evacuation shelters) expected?	
What are our priorities?	• Offline discussion at DOT
Who do we need to contact?	• Notification tree • Automation via text message, Twitter, and other social media
What are our expected staffing needs?	• Offline discussion at DOT • Automated notification of staff via text message

Wisconsin, Missouri, and North Carolina are examples of three states with strong social media presences, including some automation. Washington State DOT has invested in a social media presence as well. Social media have proven to be valuable communication tools during flood events. North Carolina DOT uses social media to communicate about road closures, noting:

> We started using social media in 2009 in the hurricane season as a way to push out traffic and road closure information during the hurricanes and big storms that we have in North Carolina. We created 16 dedicated Twitter feeds to hook into our traffic information management system feeds that we already had available on our website. We were pushing out the same alerts via TIMS [Traveler Information Management System] Twitter account. We found that during hurricanes, a lot of people lose power and can't get on the Internet, but they've got their cell phone charged, and more likely than not, that cell phone is a smartphone, so they wanted to get the information through Twitter. (Schell, 2012)

5.1.2 Response

As discussed in Section 4.4, the DOT will have a number of different functions during flood response. Real-time intelligence may come partly from sensors, but a distributed network of personnel in the field will be a critical information source. Information will also come in through crowdsourcing, particularly via social media and phone calls. Table 11 notes many of the questions and information channels relevant to response. For the purposes of this section, groups with a close partner role and open line of communication with the DOT, such as state troopers, are considered part of the team internal to the DOT. Crowdsourcing, although public-driven, is also noted. Public needs and communication technologies are considered in greater detail in a later section.

Table 11. DOT internal information needs during flood response

Response	Technologies and Methods
Which roads, tunnels, etc., are closed, and which still need to be closed?	• Floodcasting event tracking module • Automated list updates to field crews by e-mail, text, or web • Field crew updates submitted by phone, text, or multi-user geospatial editing • Updates coming from local and county personnel via phone, text, or radio • Updates coming from other transit agencies or critical infrastructure owners via phone, text, or radio • Automated or remotely operated gates and floodwalls
Which roads need to be re-opened?	
What is the status of transportation assets owned by other entities, and how will they affect the DOT?	
What is the status of critical infrastructure owned by other entities, and how will this affect the DOT?	
How do the modeled flood impacts compare to ground truth?	• Analyst updates to floodcasting inundation extents • Bridge sensors and stream gages • RWIS stations • Updates coming from field crews via phone, text, radio, or multi-user geospatial editing • Updates coming from local and county personnel via phone, text, or radio
Where is there damage?	• Floodcasting event tracking module • Updates coming from field crews via phone, text, radio, or multi-user geospatial editing • Updates coming from local and county personnel via phone, text, or radio
Where is there debris?	
Where are there traffic incidents?	• Floodcasting event tracking module • Updates coming from field crews via phone, text, radio, or multi-user geospatial editing • Updates coming from local and county personnel via phone, text, or radio • Updates coming from the public via phone, web, or social media
How well are detour routes working?	• Updates coming from field crews via phone, text, radio, or multi-user geospatial editing • Updates coming from local and county personnel via phone, text, or radio • Updates coming from the public via phone, mobile applications, web, or social media • Traffic models

Response	Technologies and Methods
What do we need to communicate to partner agencies other stakeholders about issues such as: • **Closures** • **Detours** • **Traffic** • **Incidents**	• Automated text alerts • Tweets and other social media • Web, e.g., 511 websites • Dynamic signs • Sharing the floodcasting display with partner agencies
Is staffing adequate?	• Offline discussion at DOT

5.1.3 Early Recovery

Early recovery occurs when assets in the transportation network are cleared and re-opened and damage is assessed. After closures have occurred and asset condition is determined to be satisfactory, the asset can be re-opened for use. In other cases, debris, which can affect roads, bridges, culverts, highway drainage systems, and other assets, will need to be removed before the asset can be placed back in service. Some assets will require inspection for damage, and for major events, this work can be extensive. In all cases, geospatial record-keeping will also be important to help DOTs prioritize issues and can facilitate debriefing and sessions to discuss lessons learned, preparation for future events, and applications for post-disaster or mitigation funding.

Table 12. DOT internal information needs during early recovery

Early Recovery	Technologies and Methods
How long was infrastructure inundated?	• The forecasting and H&H module of a floodcasting system • Event records in the floodcasting system • Bridge sensors and stream gages • RWIS stations • CCTV • Aerial/satellite imagery
How severe is the damage?	• Floodcasting event tracking module • Updates coming from field crews via phone, text, radio, or multi-user geospatial editing • Geo-tagged photographs • Photogrammetry; aerial/satellite imagery
Where do we need more information?	
Where has damage or debris been repaired/removed?	
What are the repair and cleanup priorities?	• Prioritize according to asset criticality to the system, personnel availability, etc. • Offline discussion at DOT
How many personnel are needed to handle damage and debris?	

Depending on the impact of the event, the state may pursue a Presidential Disaster Declaration. Transportation system damage falls under the "Public Assistance" category and to support the declaration, the DOT will need to prepare certain information for FEMA's preliminary damage assessment (PDA) process. Identifying damaged locations, geo-tagged photographs, and documents estimating rough quantities are examples of basic background information that will support the PDA (FEMA, 2015); emergency work needs should also be identified. In the latter case, fly-overs may be required where large or inaccessible areas are concerned. For more issue-specific information and guidance regarding the early recovery process, please see resources such as NCHRP Report 781, A Debris Management Handbook for State and Local DOTs and Departments of Public Works. As a centralized repository for the status of the transportation system related to the flood event, a floodcast system can support these efforts.

Following identification of damage sites, PDA teams consisting of both FEMA and state representatives will visit the sites, and the DOT will likely have coordinating and support roles. If emergency work actions are needed, information about costs and quantities are needed to support requests for expedited funding following a disaster declaration (FEMA, 2013a). The state will then develop final damage reports and enter project worksheets into FEMA's Emergency Management Mission Integrated Environment (EMMIE). In some situations, such as post-Sandy, other federal agencies may become involved, such as the Federal Transit Administration (FTA) (FEMA, 2013b). During Superstorm Sandy recovery, damage reports were developed through FTA according to FEMA guidelines.

5.2 DOT Communication with Emergency Management and Other Partner Agencies

Although not all flood events will result in governor-declared states of disaster or emergency and use of the state's emergency management plan, widespread flooding, such as the April 2015 floods in Kentucky (Patton, 2015), often does. State emergency plans often include a transportation annex, which typically expands DOT roles to include monitoring, the provision of transportation alternatives, and a coordinating role in response and mitigation. In cases where the state emergency plan is activated and an EOC is established, DOTs will work closely with EOC personnel. Once activated, EOCs may already have their own web platforms in place, such as Web EOC, Emergency Responder, and E Team. Ideally, floodcast tools will interface with EOC tools, improving information exchange. Both before and after the EOC is activated, as well as during early recovery, DOT floodcast systems could offer a streamlined pathway to improve the situational awareness of emergency management and other cooperating agencies. These issues and techniques are outlined below.

Local and county authorities may have significantly fewer software and monitoring resources, but will often be the first to decide that a road needs to be closed or re-opened. Operationally, for maximum effectiveness, close coordination will need to occur at the state and county level. Additionally, a large number of public safety, fire, and EMS personnel come from the local and county level. Observations, updates, and first responder activities may all be appropriate to log in a floodcasting system, and this group may be well-qualified to do so.

5.2.1 Pre-Event

If an EOC has not yet been established, DOT floodcasting tools may principally be used to summarize information for the State Emergency Manager as well as for emergency management officials at the local and county level. Pre-event flood warnings that indicate widespread flooding can provide important situational awareness for emergency management personnel, allowing decision-makers to anticipate potential staffing needs and resources. Predictions of whether and when population centers, shelter areas, and evacuations routes may be affected can apprise emergency managers of likely logistical needs. Pre-event, it is desirable that the floodcasting system has sufficient data to serve as a one-stop source for preparation.

Table 13. DOT-partner agency communication needs pre-event

Planning/Early Warning	Technologies and Methods
Where will it flood? **When will it flood?** **How deep will flooding be?** **Will evacuation routes be flooded?** **Will residences be flooded?** **Will roads/other transportation modes be affected?** **Will non-DOT transit be affected?** **Will other critical infrastructure be affected?**	• Floodcasting system datasets and analysis results, including: ○ The forecasting and H&H module of a (showing inundation extents and flood depths) ○ The GIS-based asset catalogue with the floodcasting system ○ Other transportation modes and the critical infrastructure catalogue ○ Building footprints ○ Demographic analysis such as Social Vulnerability Index (SoVI) (Cutter, 2010) • Automated alerts and updates to emergency managers through text message, e-mail, or other means

5.2.2 Response

Once the EOC has been established, response activities will be divided somewhat, with the DOT focusing on transportation issues and the EOC taking a broader view. The EOC will provide direction on issues such as evacuation support but may also benefit from using the floodcast tools to estimate emergency prevention activities (e.g., sandbags), evacuation, and rescue needs. Up-to-date information about road closures, especially potential impacts to evacuation routes, will be critically important. Again, floodcasting tools can serve to consolidate much of this information in a single location.

Table 14. DOT-partner agency communication needs during flood response

Response	Technologies and Methods
Where is flooding? **How deep is flooding?** **Who needs evacuation, rescue or other support?** **Which roads are closed, and what are detour options?** **What is the status of transportation infrastructure (including non-DOT)?** **What is the status of other critical infrastructure?**	• Floodcasting system datasets and analysis results • State 511 websites • Automated alerts and updates to emergency managers through text message, e-mail, or other means • Wireless Emergency Alerts, FEMA's Integrated Public Alert and Warning System • Social media • Updates coming from other transit agencies or critical infrastructure owners via phone, text, radio, or multi-user geospatial editing

Response	Technologies and Methods
Where are support personnel deployed, and where else do they need to be deployed?	• Floodcasting system datasets and analysis results • Web EOC or other EOC decision-support software • Offline discussion

5.2.3 *Early Recovery*

Depending on the impact of the event, the EOC, emergency management, or other state coordinating officers may continue to have extensive interaction with the DOT. The state will coordinate interactions with relevant federal entities and will have a role in post-disaster damage assessment. As noted in Section 5.1.3, disaster declarations and preliminary damage assessments, as well as work plan development, are integral to securing post-disaster Public Assistance funds. Numerous questions specific to the event will be raised beyond what is noted here, but information needs common to early recovery that can be provided by DOTs to state officers are indicated in Table 15. At the local and county level, emergency management personnel may also have a role in data-gathering.

Table 15. DOT-partner agency communication needs during early recovery

Early Recovery	Technologies and Methods
Which roads have been re-opened?	• Event records in the floodcasting system • Offline communication with DOT personnel • Site visits, photography, quantity estimates, and documentation
How long were assets inundated?	
Where are high water marks?	
What type of support does DOT require for cleanup/repair?	
What type of support do local authorities need for cleanup/repair?	
Are there any emergency repair needs?	

5.3 DOT Communication with the Public

Particularly in the age of social media, DOT-public communication takes place at a high volume. As noted above, DOTs are increasingly engaging citizens through media like Twitter in an effort to be transparent and responsive. Communication does not originate solely with the DOT; it is often initiated by the public seeking information about specific concerns or notifying the DOT of problems. Indeed, the public is considered a partner in some respects, given that motorists may very likely notice problems before DOT personnel. States commonly have phone lines and web forms for the public to report issues such as road damage and guard rail repair needs. During a flood event, the volume of these incoming reports may be heavier than usual and dedicated staff may be necessary to integrate (and potentially validate) incoming information into a floodcasting system.

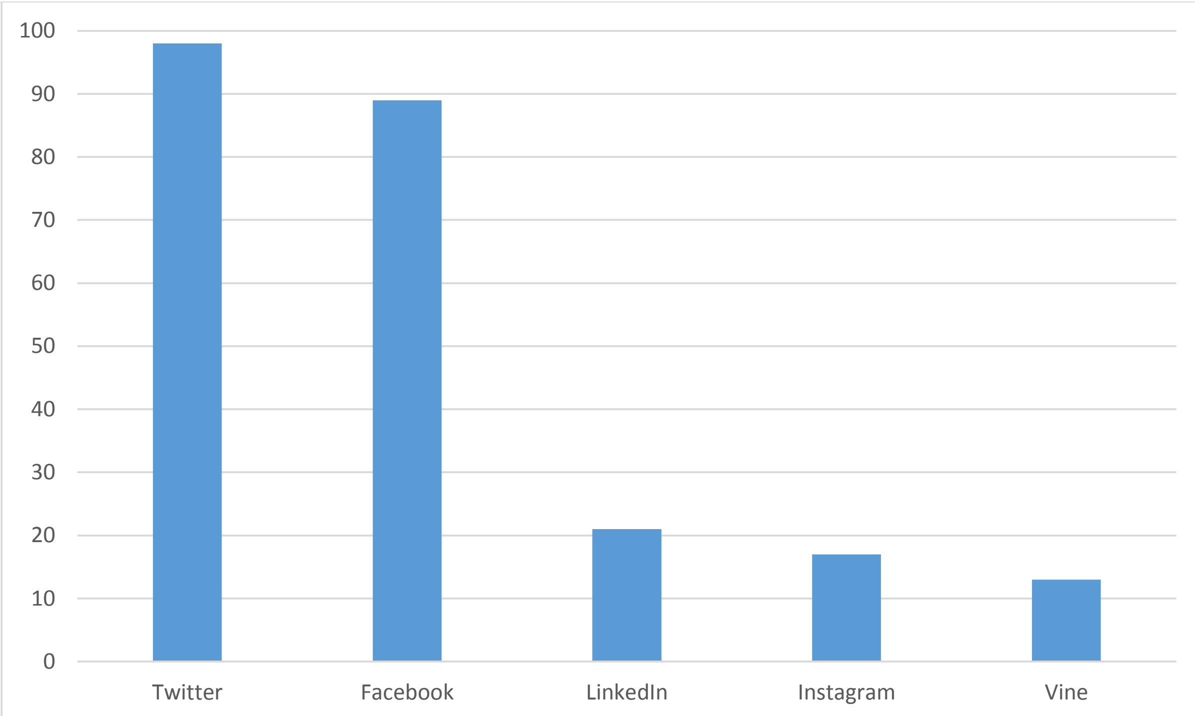

Figure 18. Percentage of DOTs using various forms of social media (2014).

5.3.1 Pre-Event

The information needs of the public prior to an event are generally modest, and will typically not involve much response from the DOT. The main objectives of pre-event communication are to advise the public of the upcoming event and to remind the public about roadway safety during floods, i.e., observing closures and detours. Depending on whether the predicted flooding is several days out or is due to expected flash flooding, lead time may range from days to hours. Once initial decisions have been made about planned closures and detours, that information can be conveyed through multiple avenues, as noted in Table 16.

Figure 19. Percentage of DOTs offering mobile-friendly information (2014).

Table 16. Public communication needs pre-event

Planning/Early Warning	Technologies and Methods
Will roads I use be affected? **When will they be affected?** **What are my detour options?**	• Automated messages from the floodcast system, such as location-based text alerts • Traditional media, such as radio and television and newspaper (if there is significant lead time) • Social media • 511 websites and phone lines • Incorporation into common web-based and mobile navigation applications

5.3.2 Response and Early Recovery

Unlike the sections dealing with DOT, state, and local authorities, this section merges the response and early recovery issues, since in both cases, the public's focus is on the central question of usability. Motorists rely on the functionality of roadways, functioning signals, and other transportation assets for many of their daily activities and are highly attuned to issues with the routes they frequent. While the public will need to know about closures and detours, they will also be an important information source about roadway conditions. This can be a rich source of real-time data, as the public tends to be highly invested in functioning roads and sensitive to any disruptions. It is expected that during response and early recovery, motorists may contact DOTs to report any of the following:

- Debris, including the need for tree removal
- Damage to roads, bridges, and culverts

- Problems with highway drainage systems
- Malfunctioning signals
- Sign replacement needs

Information needs and supporting technologies are listed in the table below. Readers will note that information is communicated via two-way exchange, which, particularly during power outages, are often accomplished through mobile phone technology.

Table 17. Public communication needs during flood response and early recovery

Response and Early Recovery	Technologies and Methods
Which roads are closed, and what are detour options? **What are road and other transportation asset conditions?** **What are traffic conditions?**	• Automated messages from the floodcast system, such as location-based text alerts • Traditional media, such as radio, television and newspaper • Social media • 511 websites and phone lines • Incorporation into common web-based and mobile navigation applications

While outside the scope of what a flood forecasting tool can provide, it is worth noting that injuries and fatalities will still result if motorists bypass road closures, which they sometimes do. This is a separate issue from designing a good flood forecasting model, which assists DOT staff in closing flooded roadways in a timely fashion. Motorists bypassing closures may do so for a number of reasons, such as perceiving a lack of available detours, time pressure, or overreliance on map applications (e.g., Las Vegas Review Journal, 2015), or belief that a closure is unnecessary. Preferred solutions would not put staff or personnel from DOTs or partner entities at risk. Education about flood risk to motorists is a noteworthy option (e.g., the NWS's "Turn Around, Don't Drown" campaign). Less desirable and more likely to put personnel at risk are after-the-fact interventions, such as interception of the motorist en route, or, as a final option, rescue activities.

5.4 The Role of Data Standards in Communication and Information Exchange

Data standards provide templates for the organization and dissemination of machine-readable digital data. This crucial piece of data management ensures that data can be consumed by the majority of web platforms and GIS systems in use by decision-makers. Standardization of this type is essential for internal communication with field crews as well as cross-entity collaboration, especially at the state, regional, or national level. Very high resolution, accurate data that cannot be read or requires significant manipulation prior to integration with web-based services used to support decision-making is of limited use during emergency events. Standardization can significantly streamline the number of steps required when coupling models together and when integrating flood forecasting tools with emergency management, traffic notification, and other tools used by the transportation agency and cooperating entities. For optimal functionality, determining interoperability requirements and data standards for software are critical.

Examples relevant to this project include the following:

- **WaterML2** (Water Markup Language) is described as providing a systematic way to access water information from point observation sites.
- **RiverML** (River Markup Language) is a proposed language to standardize the description of river hydrology and hydraulic characteristics (e.g., river channel and floodplain geometry, flow

characteristics) for use in web applications. RiverML is a joint effort involving Consortium of Universities for the Advancement of Hydrologic Science, Inc.'s (CUASHI) HydroShare development team, the Open Geospatial Consortium Hydrology Domain Working Group, and the developer community (Jackson et al., 2013).

- **CityGML** (City Geography Markup Language) is an open data model developed for the storage and exchange of virtual three-dimensional city models.
- **TransXML** (Transportation Extensible Markup Language) is a data model developed to store transportation-related information, including:
  - Geometric roadway design
  - Bridge design and analysis
  - Construction progress
  - Crash reports
  - Highway information safety analysis
- **InfraGML** (Infrastructure Geography Markup Language) is a proposed standard that is still in the public comment period as of this writing. This standard is being developed with the intent of facilitating integration with CityGML and TransXML. The intent is to create a markup language to describe land parcels and the built environment, starting with:
  - Alignments/roads
  - Survey
  - Land parcels
  - Modules for other areas with identified needs, such as pipe networks, may also be added to InfraGML

6 CASE STUDIES FROM STATE DOTS

Existing flood planning systems can include coastal and/or riverine modules. Around the country, these systems, where they exist, exhibit varying levels of sophistication. Higher levels of sophistication and maturity exist in areas that have seen damaging events (e.g., New York State) and have extensive asset catalogues (e.g., California).

A recurring theme is the need for high-quality elevation data and relatively comprehensive asset location data; without knowing where and at what elevation assets are, it is difficult to predict and prioritize necessary response activities. In addition to real-time flood support, some systems are often being used to support mitigation and climate adaptation planning. Other states are involved in efforts that are noteworthy for various reasons. For example:

- **North Carolina** documented a number of valuable emergency management experiences and lessons observed.
- **Iowa** has some of the best validated short-term decision-making based on stage-discharge and a promising methodology for understanding stage-discharge and developing inundation extents at ungaged locations.
- **Virginia** has one of the more advanced examples of modeling transportation network impacts from forecasted precipitation.

While there are a number of different ways that this section could be organized, the number of examples presented seemed best served by prefacing as shown above and then organizing alphabetically by state.

6.1 Iowa

Real-time flood modeling is dependent on good terrain data, because topography dictates flood extents. Robust GIS data characterizing transportation assets is also crucial, and Iowa DOT is one of the few states with a full LRS on all public roads (IOWA DOT, N.D.). In the US, a 30 meter National Elevation Dataset is available everywhere at http://ned.usgs.gov/Ned/about.asp. Iowa has invested in statewide LiDAR data, and in states like Maryland, coastal and floodplain LiDAR data, which correspond to high-hazard areas, is available.

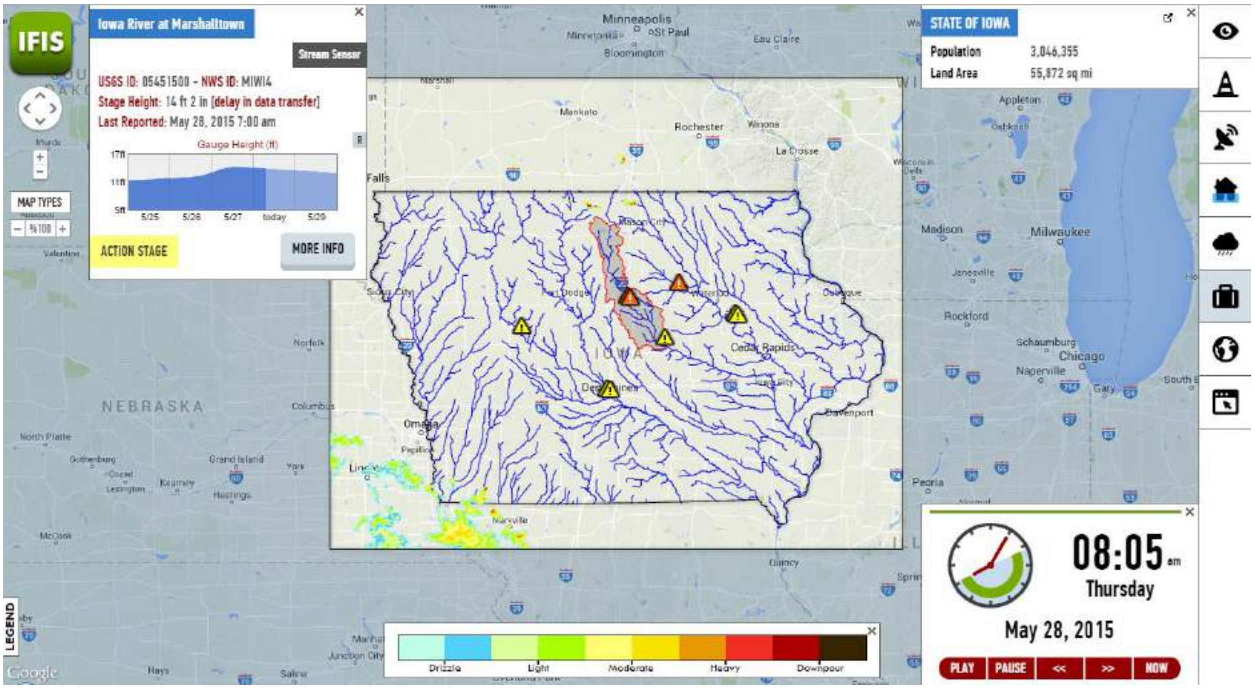

Figure 20.

The state of Iowa has one of the more sophisticated flood warning systems in place in the U.S. After the state experienced a month-long period of flooding in 2008 affecting most rivers in eastern Iowa, the state funded the new Iowa Flood Center (IFC; ifis.iowafloodcenter.org). The IFC has developed the Iowa Flood Information System (IFIS) as a one-stop web-platform with flood maps for Iowa communities, weather maps, and both real-time and anticipated (5-day and seasonal) flood conditions. The DOT also took action to improve flood prediction and response, and decided to move beyond the standard BridgeWatch™ tools through activities such as:

- Capturing LiDAR elevation at +/- 8 inches vertical resolution for the state, including elevation data for infrastructure, such as I-680 (all survey control points were lost during the floods) and the levee system.
- Understanding long-term and recent-term trends for floods and high flows (with USGS).
- Ensuring high-quality stage-discharge data at gaged locations and working with the University of Iowa's new hydrologic model to develop models for stage-discharge relationships at ungaged locations (Demir et al., 2015)
- Developing evacuation procedures and routes and working to get signage in place for the future.

Iowa DOT emphasizes how useful good stage-discharge data is for short-term flood response: during recent flooding of the frequently overtopped I-80, the DOT has been able to predict the need for closures 2 to 3 hours in advance and with +/- 0.5 ft accuracy (TRB Annual Meeting, 2015). Iowa is also a leader in multi-platform communication, leveraging 511 systems, e-mail, Twitter, and other subscription services to disseminate flood information (IDOT, 2013). On the climate adaptation front, Iowa DOT is performing climate modeling to understand potential changes in streamflow patterns and may use that information to influence the sizing of bridges and culverts (TRB, 2015)

6.2 Maryland

Maryland State Highway Administration (MD SHA) is motivated by flooding and projected sea level rise to understand their flood risks. MD SHA has logged road closures through its transportation network during past events to help prepare for flood response during upcoming events. Some state DOTs, such as Ohio and Maryland, also have complete inventories of their hydrologic infrastructure. The analysis utilized road closure coordinates from Coordinated Highways Action Response Team (CHART), creating a GIS map labeled by category for the type of road closure such as high water, debris, winter precipitation, or other type of incident. MD SHA has used this data for highway system and individual asset vulnerability assessment and in emergency operations.

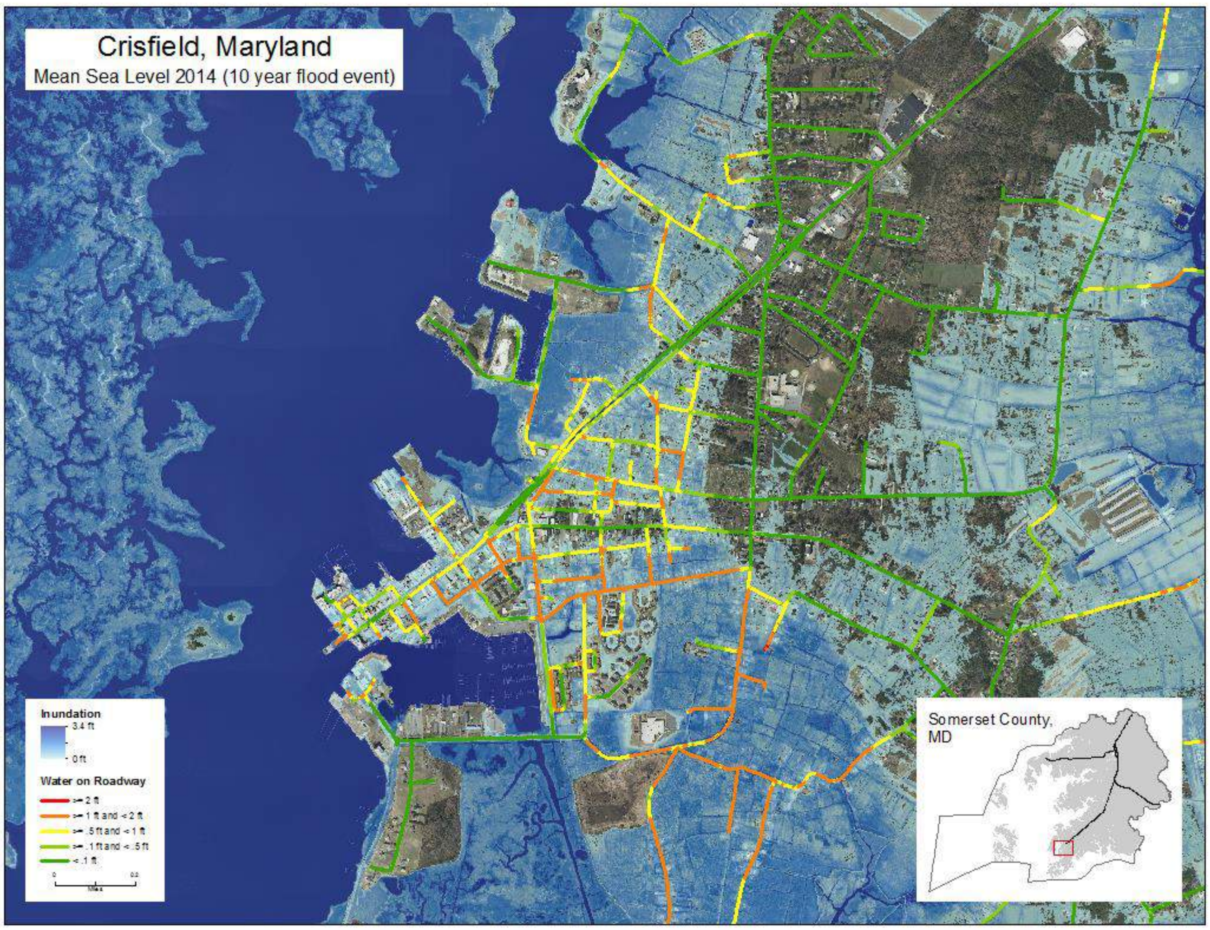

Figure 21. Maryland SHA coastal hazard assessment for 10-year flood using GIS data.

For instance, during Hurricane Sandy in October 2012, the state emergency management agency used the 2011 road closure data layer in a geographic data mapping system called Osprey to combine many other data layers and identify potential hazards. The Osprey system used historical data on traffic and road closures collected by MD SHA to help improve storm response. MD SHA is also beginning to look at the costs of road closures (from an operational perspective) and how the reoccurring closures impact the agency and the transportation system. They began a task to evaluate damage coefficients in Hazus modeling. The state also has very high resolution LiDAR data, which is +/- 3 inches vertical resolution along the coasts.

6.3 Massachusetts

Massachusetts DOT (MassDOT) identified and documented information on the drainage impacts of heavy rain and storm events in their asset management system, Maximo. MassDOT also collected information on the potential causes of damages due to flooding. The causes cited, in descending order, were insufficient drainage, flooding water body, low elevation/high water table, high tides, debris clogging, beavers, and runoff from development.

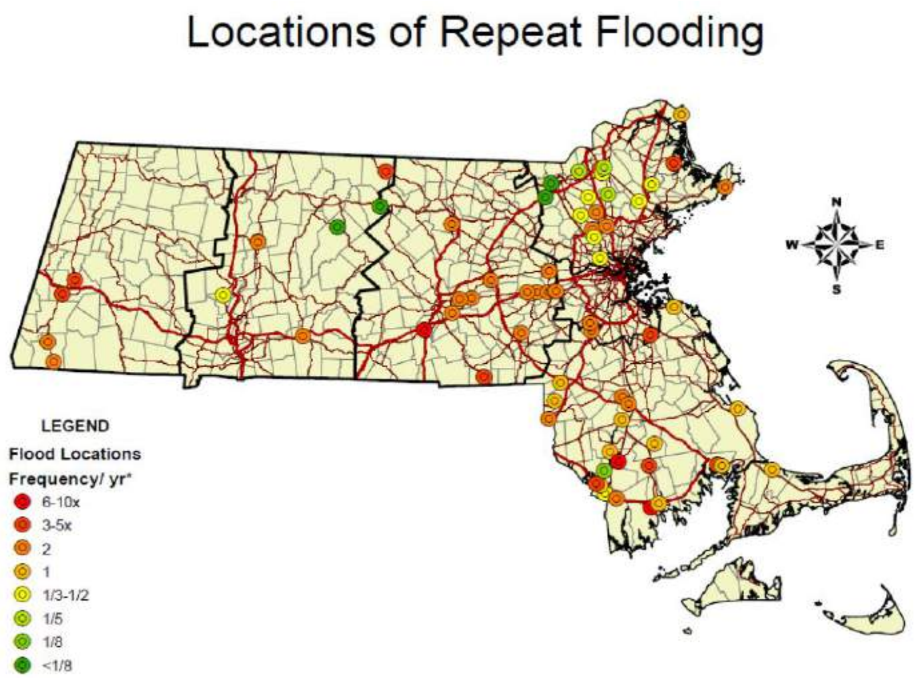

Figure 22. Locations and frequency of repeat flooding in Massachusetts.

MassDOT mapped locations of repeat flooding, as shown in Figure 22, and is collecting current information. MassDOT's adaptation strategies include completing mapping of culverts in its Maximo infrastructure management system, identifying design fixes, and prioritizing maintenance.

6.4 New York

New York State DOT (NYSDOT) conducted a similar statewide assessment for use in long-term planning. Staff knowledge collection involved 60 residencies (at least one staff person from each) in addition to 5-10 regional staff from each of the 11 regions plus a project management and GIS headquarters team. NYSDOT focused on mapping roads, bridges, and culverts that are most vulnerable to past and future flooding conditions. In New York State, both coastal and inland flooding is increasing, brought on by climate change. Like Washington State DOT (a participant in FHWA's climate change adaptation pilot program), NYSDOT asked staff to identify and weigh the severity of impacts in case of long-term closure of state highways.

In the future, NYSDOT will also consider local roads where included on the NHS+ system or where local roads and bridges may be utilized as detours. NYSDOT headquarters staff kicked off the project by developing GIS coverage showing relationships of roads, bridges, and culverts with natural and socioeconomic resources. These maps helped provide regional staff with information that would help weigh the severity of impacts in case of closure of an asset. Considerations included safe traffic rerouting, emergency preparedness, and access to critical socioeconomic resources.

In addition to valuable flood vulnerability data collected in their asset management system, NYSDOT is working on real-time and future flood issues. The state is in the process of establishing a new Upstate New York Flood Warning System, encompassing three watersheds in 27 upstate counties where flooding has long been a recurring problem. The flood warning system will use weather forecasts, precipitation gages, and newly installed and existing stream gages. The system will result in more precise flood warnings that will include timing of peak water levels, and projected flood inundation via online maps.

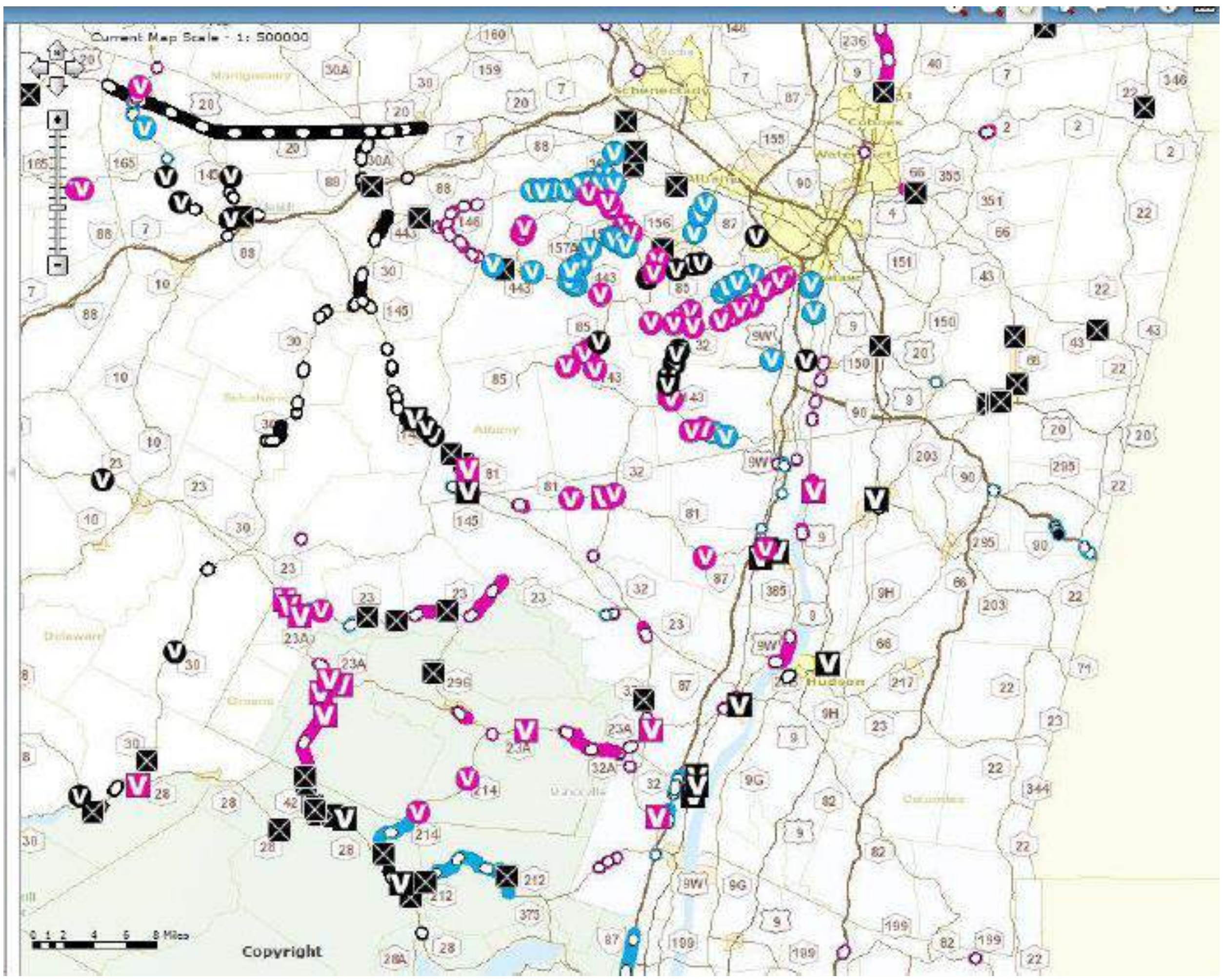

Figure 23. NYSDOT GIS-based vulnerability assessment, grouped by asset class, e.g., culverts, bridges, roads.

Real-time flood monitoring is augmented by the use of “nowcasting” forecasts performed at the City University of New York’s NOAA Cooperative Remote Sensing and Technology Center (NOAA-CREST), although NYSDOT notes that a non-trivial amount of flood monitoring is still manual, occurring when people visit a stream (TRB Annual Meeting, 2015). Improved sensors are also being used: New York State is installing a Mesonet system consisting of 125 sophisticated interconnected weather stations to provide real-time monitoring of surface pressure, wind speed and direction, temperature, rainfall, radiation conditions, soil moisture, and temperature. This information can be used to help identify threats to roads, bridges, and the electric system. In addition, NYSDOT is supporting USGS research to upgrade its StreamStats tool for New York State and expand it to allow calculating stream flows for projected rainfall trends under different climate scenarios. The tools are rapidly developing to provide excellent real-time flood modeling for the state's transportation network, as well as support for long-term planning needs.

6.5 North Carolina

In many states, DOTs may not be the main owners of flood information systems, underscoring the need for such systems to facilitate coordination between DOTs, emergency management, and other cooperating entities. The state of North Carolina houses its real-time flood mapping activities within the Division of Emergency Management. The system, called the Flood Inundation Mapping and Alert Network (FIMAN), has one of the most robust flood warning systems for surface transportation in the country and reflects post-Hurricane Floyd efforts to improve flood forecasting. FIMAN produces maps in real-time that depict areas of inundation, as well as flood forecast maps that show areas that are expected to become inundated hours and days into the future. The inundation maps use Integrated Hazard Resource Management data (building footprints, finished floor elevations, and mobile LiDAR of 4,000 miles of coastal roads) to run a series of flood depth overlays to identify infrastructure at risk. The system also uses real-time data from USGS stream gages, including new gages funded by the project as well as NWS forecasting products.

View Current Gage Info.

Date	Time	Forecast Gage Ht	
12/19/07	1300	88.74	
12/19/07	1900	89.0	
12/20/07	0100	90.5	
12/20/07	0700	91.1	
12/20/07	1300	92.0	
12/20/07	1900	92.8	
12/21/07	0100	93.5	
12/21/07	0700	92.6	
12/21/07	1300	92.1	

Figure 24. North Carolina's FIMAN system shows the forecasted water surface elevation at a gaged site over several days.

6.6 Oregon

Most US DOTs use BridgeWatch™ or similar software to track bridge scour, but BridgeWatch™ is solely applied to individual bridge assets and is not intended for agency-wide flood response support at roadways that cross or are adjacent to water bodies. A single-asset system of this type is "point-based," focusing on the vulnerability of individual assets, rather than network-based, and does not consider wider impacts of asset failure on the infrastructure system. In order to obtain more comprehensive decision support, a number of DOTs use custom systems to monitor flood risk at vulnerable points. Oregon DOT (ODOT) is one such example.

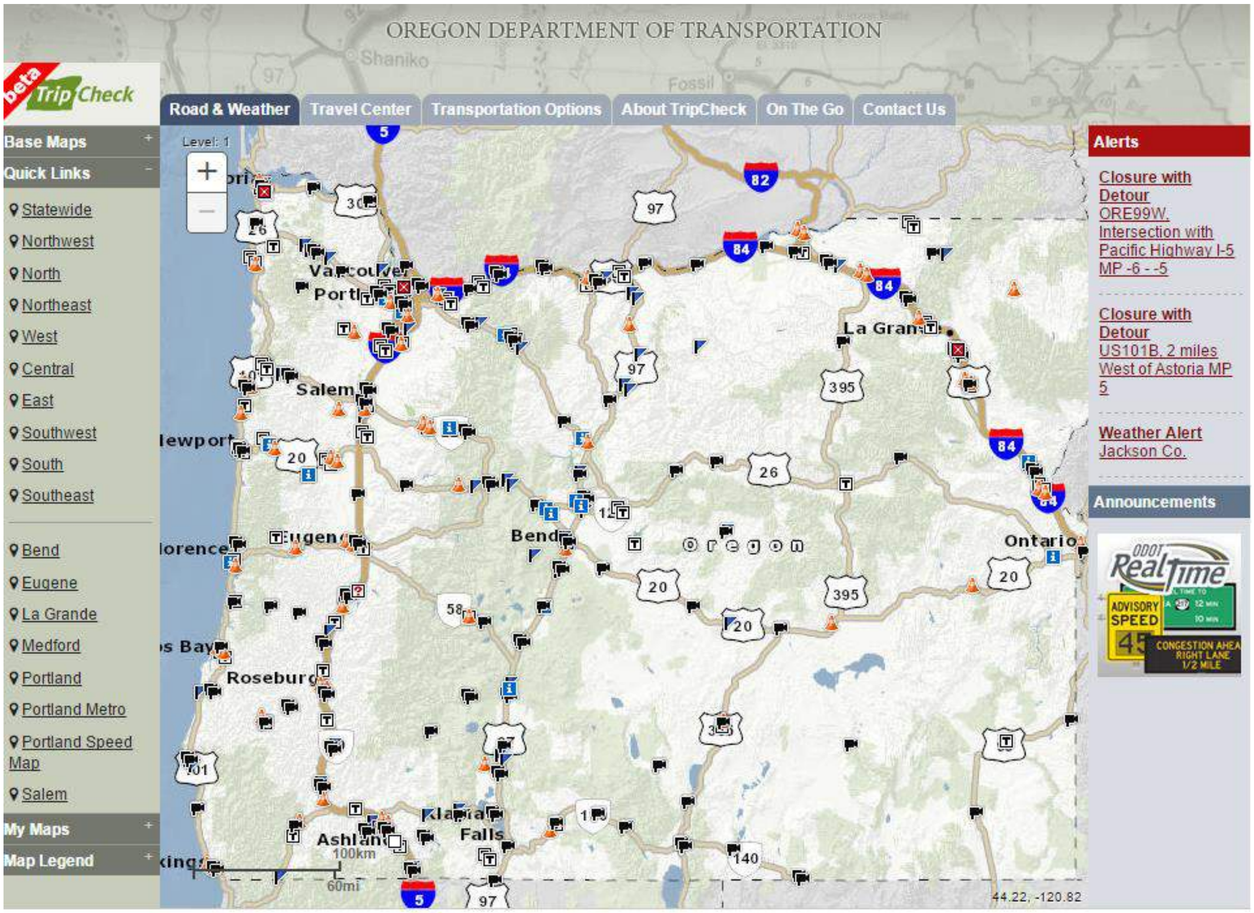

Figure 25. GIS-based ODOT TripCheck is a public-facing application with information on detours, road closures, weather conditions, and other travel information.

ODOT is focusing on landslide risk and flood warning in the northwestern part of the state, developing an ArcGIS web-based application, mapping highway vulnerabilities and hot spots, developing study corridor and site selection criteria, and preparing a range of site-specific adaptation options. ODOT does not do inundation mapping; its hydrological models are based on simple regression models available through USGS. The most important challenge for these systems is finding stream gages in the same basin as the bridge to be monitored. ODOT has installed an ultrasonic water level sensor on one bridge, using the same technology that USGS uses for stream gages. This sensor transmits via satellite and allows ODOT to look at actual water levels in real time. The sensor cost around $3,000 plus a monthly maintenance fee for the satellite system and data server.

6.7 Virginia

A noteworthy transportation-focused flood forecast model was piloted by Virginia DOT (VDOT). After Hurricane Irene, VDOT pursued the construction of a model to better predict flood threats with more lead time. Flooding in the state can make certain areas impassable and/or divided from emergency services. VDOT's Regional River Severe Storm (R^2S^2) model required a serious data collection effort by field crews with surveying equipment in order to get low bridge chord elevations and culvert dimensions. Despite the data collection required, the model has many advantages:

- Can use actual rainfall data from real storms in addition to predefined discharge data.

- Uses county GIS data for land use values instead of assumed values. The model can be updated whenever counties update their GIS data.
- Automatically integrated with GIS, enabling quick turnaround of results during extreme storm events, and possible integration with the Virginia 511 system.
- Analyzes hundreds of bridges at once.
- Takes into account the effect of each structure on the system as a whole, allowing the DOT to study how one bridge, or structure, influences other structures nearby (rather than just study individual bridges).

Though model runtime is slower than VDOT would like (Scott, pers. comm. 2015), R^SR^2 is thought to have more realistic results than the Hydrologic Engineering Centers River Analysis System (HEC-RAS), which is known to be a very conservative model that may cause designs to lean toward larger, more expensive bridges. VDOT piloted the model in one region and is now expanding it for other districts. There is also desire to integrate the model into other applications, such as state emergency management functions.

Table 18. Comparison between Virginia DOT model and HEC-RAS

Element	HEC-RAS	R^2S^2
Rainfall	N/A (discharge)	Natural events
Watershed	Site specific	Regional
Land use data	Assumed values	County GIS
GIS integration	N/A	Fully integrated
Effort	Labor intensive (one-at-a-time)	Computer intensive (all-at-once)
Global influence	One structure at a time	Almost 500 structures
Quality of estimate	Very conservative	Realistic

Source: Virginia DOT

7 CONCLUSIONS

Flood prediction must move beyond bridge inundation at stream crossings, which is a fairly common exercise at DOTs. Most US DOTs use BridgeWatch™ or similar software to track bridge scour, but this type of software does not capture flooding impacts to the transportation network as a whole and has limited application in widespread flooding where cooperation with emergency management personnel is likely. Other at-risk assets include roadways running alongside or adjacent to water bodies, ITS and signals, buildings, equipment, and storage areas. Expected or current impacts to non-transportation critical infrastructure and assets owned by other transit agencies are also important knowledge.

7.1 Summary of Current Needs

Major data limitations for DOTs interested in flood vulnerability assessments in response to forecasts commonly include:

- Incomplete asset catalogues with only partial migration to GIS.
- Lack of enforced topology rules in GIS-Ts.
- Missing elevation attributes.
- Limited information about asset sensitivity to hazards and system connectivity.

Some of these issues can be remedied through supplementing with or extracting information from state or national datasets (e.g., elevation data), but other elements can only come from in-house sources. To maximize the functionality of floodcasting systems, it is recommended that DOTs prioritize improving GIS data quality. DOTs such as Iowa have found LiDAR data to be extremely valuable with benefits substantially exceeding investment costs (Claman, 2015).

Automation is both possible and desirable to handle the tasks of monitoring and communication across a distributed network of assets and response personnel. Floodcasting systems could be used to interface with state 511 systems and mobile mapping applications and to support recovery activities after the fact. Getting warnings out early and through as many mediums as possible, such as FEMA's Integrated Public Alert and Warning System, increases the chance that flood fatalities will be avoided. It is also valuable to assign personnel to sift through the high volume of information coming into the DOT from the public and local officials, much of which can be captured in a floodcasting system and will be crucial for situational awareness. Motorists are frequently the first to notice roadway or other asset conditions that required DOT attention. Information tailored to support coordination with partner agencies and the state EOC is also desirable: DOTs may be focused on asset protection, but partner emergency managers need information concerning the estimated number of houses that will be affected, which roads, and the depth of flooding

7.2 Promising Systems Used by State DOTs Today

Overall, the development of a floodcasting framework represents a promising improvement to the existing DOT planning and response toolkit. Some states, such as Iowa, have fairly advanced flood warning systems implemented statewide, and others, such as California and New York, have very good transportation asset characterization data and perhaps some degree of real-time or forecasting systems in place, but typically, flood forecasting systems and transportation asset networks are not well-integrated. Although Virginia's system is a pilot that does not yet cover the state, it is one of the most advanced examples of integration at this time. The Virginia pilot and the review of promising technologies and methods in this memorandum note that it is likely feasible to establish or improve integration of flood forecasts with decision-making related to transportation systems for most states, although near-term improvements in available datasets related to flooding and transportation assets may facilitate efforts of this type.

7.3 Future Uses for Floodcasting Systems

Long-term floodcasting systems may have a number of applications beyond preparation and response. Many of these applications are outside the domain of transportation planning that DOTs are most concerned with but could be important for other types of planning at the state and local level. Records from flood events captured within the floodcast system can shorten recovery timelines and may be useful in the mitigation grant application process. Floodcasting systems may also have a role in predictive analysis based on changing land use, indicating where problems due to development (e.g., possible repetitive loss properties) are likely to arise over time. Finally, as climate scientists hone the methods needed construct individual precipitation events from Global Circulation Model scenario projections, floodcasting systems may have a role in climate adaptation planning for the transportation context.

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ABBREVIATIONS AND ACRONYMS

AADT	Annual Average Daily Traffic
AHPS	Advanced Hydrologic Prediction Service
Caltrans	California Department of Transportation
CCTV	Closed Circuit Television
CONUS	Continental United States
DEM	Digital elevation model
DOT	Department of Transportation
EMS	Emergency medical services
EOC	Emergency operations center
FEMA	Federal Emergency Management Agency
FHWA	Federal Highway Administration
FIMAN	Flood Inundation Mapping and Alert Network
FTA	Federal Transit Administration
GIS	Geographic information system
GIS-T	Geographic information system for transportation
H&H	Hydrology and hydraulics
HEC-RAS	Hydrologic Engineering Centers River Analysis System
IFS	Iowa Flood Center
ITS	Intelligent Transportation System
LiDAR	Light Detection and Ranging
LRS	Linear referencing system
MassDOT	Massachusetts Department of Transportation
MD SHA	Maryland State Highway Administration
NCHRP	National Cooperative Highway Research Program
NFHL	National Flood Hazard Layer
NFIE	National Flood Interoperability Experiment

NFIP	National Flood Insurance Program
NOAA	National Oceanic and Atmospheric Administration
NWC	National Water Center
NWS	National Weather Service
NWDI	National Water Data Infrastructure
NYSDOT	New York State Department of Transportation
ODOT	Oregon Department of Transportation
PDA	Preliminary damage assessment
R^2S^2	Regional River Severe Storm model
RFC	River Forecast Center
RWIS	Road Weather Information System
TRB	Transportation Research Board
USACE	US Army Corps of Engineers
USGS	US Geological Survey
VDOT	Virginia Department of Transportation

APPENDIX A ENTITIES TRANSPORTATION AGENCIES WILL COMMONLY COMMUNICATE WITH DURING FLOOD EVENTS

	Local and County	State and Regional	Federal Government
Preparation and Response	• Public Safety • Fire • EMS • Hospitals • City, Town, County and Tribal Officials • Local Emergency Manager • Schools • Shelter Locations • Military Bases • Transportation Authorities • Private Sector Entities	• Emergency Management/EOC • Rail • Bus • Aviation/Civil Air Patrol • Turnpike • Tunnel • Ports • Public Transportation • Governor's Office • State Police • Public Health • Environmental Services • Water, Wastewater, and Stormwater • Fish and Wildlife • Natural Resources • Economic Development • Human Services • Liaison Agencies to the Military • Power and Energy • National Guard	• FEMA • USACE
Recovery	• Academia • City and Regional Planners • Community Councils • Conservation Commissions • Private Sector Entities • Tribal Authorities • Residents	• Hazard Mitigation • State Floodplain Manager • Agriculture • Climate/Environment • Natural Resources • Water, Wastewater, and Stormwater • Housing and Community Development • Business and Economic Development • River Basin Commissions • Power and Energy • Public Works	• NOAA - NWS • USGS • USACE • FEMA • US Environmental Protection Agency • US Fish and Wildlife Service • Natural Resources Conservation Service • US Department of Agriculture

APPENDIX B RESOURCES TABLE

The resources in the tables below represent effective data, tools, and methods for supporting flood forecasting. Resources are predominantly:

- National in scope
- Are produced or made available by a federal agency
- Open source

Exceptions include useful ESRI, Bing or Google products that are very common or do not have federally distributed counterparts. Resources are marked as web download (e.g. through data portal or ftp) versus API/WMS. In the table below, the former is usually shown hyperlink, valid at the time of writing, while the latter's API name is listed. Please note that those resources available through APIs typically also have downloadable versions of their data available through websites, although solely the API version is listed here since it is the preferred format.

Resources are graded as follows:

A. It is recommended that this product be included in a floodcast tool suite.
Product is comprehensive, with national coverage (or the equivalent for, e.g., coastal processes). Resolution, refresh rate, and/or accessibility of data may be suboptimal for local-level decision-support, but no better product with national coverage currently exists.

B. It is recommended that this product be included in the floodcast tool suite, but data gaps should be clearly understood, and, where available, higher-resolution or more complete data sets should be used to supplement this product.
Product provides an important supplement to more comprehensive data sets available either in this list or in-house (e.g. US Tiger line transportation data gets a "B" because DOTs would ideally have more info available about their own assets) OR product would receive an "A" grade if it were nationally comprehensive (The NFHL gets a "B" because coverage is not comprehensive, yet). In the latter case, "B" products may represent ongoing projects at the federal level or critical research needs. Resolution and refresh rates are not taken into consideration and may be higher or lower than an "A" graded product.

C. Product may have significant limitations and is not a preferred source of data.
Product provides information that may be useful to users in some instances, but that usefulness needs to be evaluated on a case-by-case basis (for example, where high-quality, in-house data on elevation is missing, the USGS Point Query Service may provide useful elevation estimates), OR product is not easily used for operational decision support (e.g. some NHC storm surge products which don't provide real-time or storm-specific runs, but could have a role in supporting mitigation planning).

Table B1. Module: Base Data				
Grade	**Tool, Method or Model**	**Description, Uses and Limitations**	**Data Availability**	**Source**
A	ESRI World Elevation Services	Best publicly available multi-resolution, multi-source elevation data for land and near-shore locations. May be a useful supplement to characterize landscape for use in applications such as H&H modeling.	☐Web ☒API/WMS	ESRI World Elevation Services
A	Base Maps	The most common base maps provide a variety of data which can be used in combination with other national or state data sets.	☐Web ☒API/WMS	e.g. OpenStreetMap API; Google Maps JavaScript API; ArcGIS API for JavaScript; Bing Traffic API. KML layers may also be available.
A	Traffic and Transit Maps	Real-time traffic and transit maps displaying characteristics such as traffic congestion.	☐Web ☒API/WMS	e.g. Google Maps JavaScript API; ArcGIS API for JavaScript; Bing Traffic API.
A	USGS National Land Cover through the National Map	Land cover data has potential uses in H&H modeling and in identifying landscape characteristics that amplify flood risks, such as impervious surfaces and burn scars.	☒Web ☐API/WMS	http://isse.cr.usgs.gov/arcgis/rest/services/LandCover/USGS_EROS_LandCover_NLCD/MapServer
A	US Census Demographic Data	Census-block scale demographic information, including characteristics that can be used to identify socially vulnerable populations, which can be useful information in, e.g. evacuation planning.	☐Web ☒API/WMS	US Census Bureau US Poverty Data

Table B1. Module: Base Data

Grade	Tool, Method or Model	Description, Uses and Limitations	Data Availability	Source
B	Burn Scars	Additional sources of wildfire burn scar data from the US Forest Service and NASA.	☒Web ☐API/WMS	USFS KMLs and GEOtiffs: http://activefiremaps.fs.fed.us/burnscar.php NASA MODIS Burned Area Products: http://modis-fire.umd.edu/pages/BurnedArea.php?target=Download
C	USGS Point Query Service	Returns the elevation of a specified location in meters or feet. May be useful for attributing assets with missing or incomplete elevation data. Vertical and horizontal resolution vary, but are approximately 1.5 m and 10 - 30 m, respectively, which are coarse for use in local-level planning. Best used for rough estimates.	☐Web ☒API/WMS	USGS Elevation Query Service, *or* National Map Elevation Query

Table B2. Module: Forecast Data				
Grade	**Tool, Method or Model**	**Description, Uses and Limitations**	**Data Availability**	**Source**
A	NOAA's Quantitative Precipitation Maps	Expected rainfall, in hundredths of an inch, over specified time periods and spatial extents.	☐Web ☒API/WMS	National Weather Service QPF
A	National Centers for Environmental Prediction High Resolution Rapid Refresh model	Forecasted 15-minute and hourly precipitation at 3-km resolution across the entire United States. This forecast extends out to 15 hours, but the model requires 1.5 hours to run making it an effective 13.5 hour forecast. Model updates every hour.	☒Web ☐API/WMS	http://mag.ncep.noaa.gov/model-guidance-model-area.php
A	National Digital Database	Forecasts for numerous weather parameters, including precipitation, over various time periods. Three to seven-day precipitation forecast products may be especially useful for operational planning.	☐Web ☒API/WMS	National Weather Service NDFD
A	NOAA Stage IV Precipitation Data	A multi-sensor precipitation forecast product produced by the 12 River Forecast Centers in the CONUS. Various time increments are available; hourly is shown here.	☒Web ☐API/WMS	Hourly: ftp://ftpprd.ncep.noaa.gov/pub/data/nccf/com/hourly/prod/
A	NCEP River Flood Outlook	Shows major flooding outlook for one through five days, grouped occurring, likely, or possible categories. Does not predict minor, small-scale, or flash floods.	☒Web ☐API/WMS	ftp://ftp.hpc.ncep.noaa.gov/shapefiles/fop http://www.wpc.ncep.noaa.gov/kml/kmlproducts.php

Table B2. Module: Forecast Data				
Grade	**Tool, Method or Model**	**Description, Uses and Limitations**	**Data Availability**	**Source**
A	Excessive Rainfall	One, two and three-day forecasts of the likelihood that rainfall will exceed flash flood guidance grouped into slight, moderate and high risk categories. Covers the CONUS with 1-, 3- and 6-hour values. Flash flood forecasting is difficult, and risk may be upgraded to moderate or high with very little lead time. Does not consider inundation or main stem river flooding and would therefore be complemented by the NCEP River Flood Outlook product, which does.	☒Web ☐API/WMS	ftp://ftp.hpc.ncep.noaa.gov/shapefiles/qpf/excessive/ http://www.wpc.ncep.noaa.gov/kml/kmlproducts.php
A	NWS Flash Flood Guidance	Flash flood guidance produced by river forecast centers in shapefile format. This product is updated several times daily. Available only at the county level.	☒Web ☐API/WMS	http://www.srh.noaa.gov/rfcshare/ffg_download/ffg_download.php
A	National Hurricane Center Products (Other)	Prototype data actively linked to the NHC, including probabilistic storm surge products which are available when hurricane watches/warnings are in effect. Extratropical products (e.g. Nor'easters) are also available.	☒Web ☐API/WMS	http://www.nhc.noaa.gov/gis/activekml.php

Table B2. Module: Forecast Data				
Grade	**Tool, Method or Model**	**Description, Uses and Limitations**	**Data Availability**	**Source**
B	NOAA NEXRAD Radar Sites	Next Generation, high-resolution radar products covering 160 stations in the US with over 40 weather-related data sets. The WMS is currently hosted by Iowa State and is not intended for use with a high-traffic website. KML/KMZ and other GIS formats are also available directly from the NOAA NEXRAD III Data Catalogue.	☐Web ☒API/WMS	RadMap
B	NWS Watches, Warnings, and Radar	Polygons containing watches, warnings, and advisories at the county or county-equivalent level. Users can determine which types of weather events to receive data for.	☐Web ☒API/WMS	Radar and Watch/Warn Service WMS
B	NOAA NowCOAST WMS	Various OGC-compliant data sets that are available through a web mapping service. Real-time observations, forecasts, warnings and advisories, etc. are listed.	☐Web ☒API/WMS	http://nowcoast.noaa.gov/help/mapservices.shtml?name=mapservices#wwa
C	National Hurricane Center Storm Surge Models	Hypothetical and historical storm surge modeling results and used to estimate potential flooding. Real-time, storm-specific runs are not available at this time.	☒Web ☐API/WMS	http://www.nhc.noaa.gov/surge/meowAvail.php

Table B3. Module: Infrastructure				
Grade	**Tool, Method or Model**	**Description, Uses and Limitations**	**Data Availability**	**Source**
A	National Dam Inventory	Shows US dams over 50 ft. in height with storage capacity of 5,000 acre-ft. or more. These are considered "major" dams and are a subset of the USACE's National Inventory of dams, which includes smaller structures. This data set can be used to enhance awareness of dam locations where failures have the potential to increase flood risk.	☒Web ☐API/WMS	https://catalog.data.gov/dataset/usgs-small-scale-dataset-major-dams-of-the-united-states-200603-shapefile
A	National Levee Inventory	National levee database, showing the majority of levees within the USACE Levee Program. Not all US levees are shown. This data set can be used to enhance awareness of levee locations where failures have the potential to increase flood risk.	☐Web ☒API/WMS	http://geo.usace.army.mil/cgi-bin/wms/nldwms
A	Highway Performance Monitoring System	Spatial file of the nation's highways broken out at the state level. Through lanes, HOV lanes, and tolls are noted, as is AADT. Condition is also noted. 2012 is the most recent version of this data.	☒Web ☐API/WMS	https://catalog.data.gov/dataset/highway-performance-monitoring-system-hpms-national
B	US Census-based TIGER line files	Geographic, governmental and demographic data, along with physical features such as hydrography, transportation, and special land use areas. Current through 2014.	☐Web ☒API/WMS	TIGER Web Apps

Table B3. Module: Infrastructure

Grade	Tool, Method or Model	Description, Uses and Limitations	Data Availability	Source
B	US TIGER Lines: Bridges and Other Transportation	US National Transportation dataset based on the US Census TIGER line files and supplemented with HERE road data. Roads, railroads, trails, airports and other features are included. A good source to complement asset inventories.	☒Web ☐API/WMS	ftp://rockyftp.cr.usgs.gov/vdelivery/Datasets/Staged/Tran/FileGDB101/TRAN_NATIONAL.zip
B	National Highway Planning Network	Approximately half a million georeferenced US roadways within the National Highway System, classified by use (e.g. principal vs. minor arterial). Dataset provided by FHWA.	☐Web ☒API/WMS	NHPN GeoJSON
B	US Critical Infrastructure	Critical infrastructure, emergency facilities and valued assets from agency and national databases such as HAZUS. Data is represented as a density grid, expressing the number of critical facilities within a 1 mi radius of each 100 m cell.	☐Web ☒API/WMS	ESRI WMS: http://www.arcgis.com/home/item.html?id=552c3af5f6684f7d8b64d81a1581f5ed
C	HAZUS	Hazus is a nationally applicable standardized methodology to estimate potential losses due to hazards. The database containing loss estimates for transportation assets, including bridges and roads, may be useful in mitigation planning.	~~☐Web~~ ~~☐API/WMS~~	Not available as a standalone download or WMS. This is a component of an Access database. See: https://www.fema.gov/hazus-software

Table B4. Module: Inundation Estimates				
Grade	**Tool, Method or Model**	**Description, Uses and Limitations**	**Data Availability**	**Source**
B	National Weather Service Advanced Hydrologic Prediction Service	Ongoing, frequently updated project of the NWS. Data availability varies and is only offered at gaged locations. Shows current and projected river stage as an image marked with the NWS flood categories. Where available, also shows inundation estimates. Best national source for inundation and depth grid estimates for various flood stages. Currently does not include a future precipitation component, only observed past precipitation.	☒Web ☐API/WMS	Hydrographs: e.g., http://water.weather.gov/resources/hydrographs/avon6_hg.png Shapefiles, KMZs or PNGs: e.g., http://water.weather.gov/ahps2/download_gauge.php?wfo=cle&gage=kilo1
B	Federal Emergency Management Agency National Flood Hazard Layer	Labeled flood hazard zones, flood control structures, and other information related to the National Flood Insurance Program. 100-yr and 500-yr floodplains may be a useful supplement to NWS AHPS flood inundation extents.	☐Web ☒API/WMS	REST or OGC: http://hazards.fema.gov/gis/nfhl/rest/services

Table B5. Module: Sensors

Grade	Tool, Method or Model	Description, Uses and Limitations	Data Availability	Source
A	USGS River Gage Stage Data	USGS stream gages, with readings taken in 15 minute increments and transmitted hourly. Useful near real-time check against NWS stream predictions and other forecasting products.	☐Web ☒API/WMS	USGS Instantaneous Values Web Service
A	NOAA Tidal Gage Data	Tidal gages with readings taken in 1-minute increments and made available immediately. Intended to support such diverse uses as tsunami detection, warning and mitigation. Useful real-time check against storm surge model estimates.	☐Web ☒API/WMS	CO-OPS API For Data Retrieval
A	NWS MADIS	Fine-scale meterological readings updated every 15 minutes and transmitted hourly. Contributed by NOAA and other entities, including 33 states' Department of Transportation RWIS sites. Atmospheric, pavement, and water level data is reported. Useful real-time check against precipitation, inundation and other forecasts.	☐Web ☒API/WMS	NOAA MADIS
B	NOAA High Frequency Coastal Radar	Coastal-ocean surface current and wave information out to 300 km from shore. Data comes from many different institutions and has not been quality controlled. Hourly updates.	☐Web ☒API/WMS	HFRADAR Maps

Table B5. Module: Sensors				
Grade	**Tool, Method or Model**	**Description, Uses and Limitations**	**Data Availability**	**Source**
B	NWS AHPS River Gages (Observed and Forecasted)	National Weather Service river stage gages, including observed and predicted values at over 7,000 locations nationally. Forecasts may be useful supplements to NFHL and AHPS inundation estimates.	☐Web ☒API/WMS	Observed River Stage Forecasted River Stage
B	NRCS SNOTEL Snow Water Equivalent	Snow-water equivalent and other snow-related products. This data set can be used to enhance awareness of locations where water stored as snow has the potential to increase flood risk during melt/rainfall events.	☐Web ☒API/WMS	NRCS Air-Water Database Web Service