Rapid Response Flood Modeling Final Report
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Contract # HSFE60-15-D-0003
January 17, 2019

Prepared for:
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FEMA Mitigation Branch | FEMA | DHS
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Revision History

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CLIN = Contract Line Item
PMO = Program Management Office

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COR = Contracting Officer’s Representative
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<td>AHPS</td>
<td>Advanced Hydrologic Prediction Services</td>
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<td>ASTER</td>
<td>Advanced Spaceborne Thermal Emission and Reflection Radiometer</td>
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<td>Gridded Binary or General Regularly distributed Information in Binary form</td>
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<td>QPF</td>
<td>Quantitative Precipitation Forecast</td>
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<td>registered dual in-line memory module</td>
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<td>Serial Attached Small Computer System Interface</td>
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<td>TUFLOW</td>
<td>Two-Dimensional Unsteady Flow</td>
</tr>
<tr>
<td>TUFLOW FV</td>
<td>Two-Dimensional Unsteady Flow Finite Volume</td>
</tr>
<tr>
<td>TUFLOW HPC</td>
<td>Two-Dimensional Unsteady Flow Heavily Parallelized Compute</td>
</tr>
<tr>
<td>WMS</td>
<td>Watershed Modeling System</td>
</tr>
<tr>
<td>XPSWMM</td>
<td>XP Storm Water Management Model</td>
</tr>
<tr>
<td>xp2D</td>
<td>Undefined</td>
</tr>
</tbody>
</table>
Executive Summary

The immediate period after a storm event is a critical period in terms of loss of life and property. Mitigation of these losses could be strengthened by improving the pre-storm forecasting of a storm’s impacts. This requires identifying the best rapid flood risk modeling products that can be used to incorporate hydrologic and hydraulic (H&H) modeling into the disaster preparedness efforts that are undertaken by the Federal Emergency Management Agency (FEMA) and the disaster response community in major flooding events across the Nation. At FEMA’s request, Compass Production and Technical Services Joint Venture (PTS JV) conducted a study, referred to as the Rapid Response Flood Modeling Study, to identify the best rapid modeling process available. The study was funded by FEMA and the Department of Homeland Security (DHS) Flood Apex Program and conducted under Contract HSFE60-15-D-0003, Task Order 70FA6018F00000038.

A total of 26 H&H models and interfaces were scored based on 10 evaluation factors that were developed for the study. The evaluation factors were weighted based on their importance to the objective of the task order and graded on a 5-point scale. The scores were used to support the selection of three models for further review and testing. The study was not intended to be inclusive of all models that could be used in this type of application. A manageable number of available models were selected.

Evaluation of the models and scoring was focused on the application of that model for this specific project. The scoring is not a measure of the model’s overall technical accuracy and validity for other applications. The three models that were selected were FLO-2D, HEC-RAS 2D,1 and TUFLOW.2 Background data such as the methodology, input data, and outputs of the three models were documented. Additional assessments of the three models were completed via two pilot studies of a selected pilot geography.

One pilot study modeled the 1-percent-annual-chance flood event, and the other one was a rapid response use case analysis that modeled a historic flood event. The pilot geography location that was selected for the two case studies is in the East Fork San Jacinto Hydrologic Unit Code 8 (HUC-8) watershed in Montgomery County, TX (Figure ES-1). The pilot geography location was chosen based on the availability of regulatory Flood Insurance Rate Maps (FIRMs), existing Base Level Engineering (BLE), and observed historic flood event data.

---
1 Hydrologic Engineering Center–River Analysis System 2D
2 Two-Dimensional Unsteady Flow
1-Percent-Annual-Chance Flood Event Pilot Study

For the 1-percent-annual-chance flood event pilot study, peak discharges were estimated using regression equations. Inflow hydrographs were then estimated based on average dimensionless hydrographs using U.S. Geological Survey (USGS) gaging stations on Peach Creek at Splendora, TX (08071000), and Caney Creek near Splendora, TX (08070500). The dimensionless inflow hydrographs were scaled based on peak flow frequencies and used as model inputs to produce the 1-percent-annual-chance water surface elevation (WSEL) and depth rasters. The results were then compared to the regulatory FIRM and BLE data.

The comparison showed that of the three models, HEC-RAS 2D had the least bias and highest correlation (Table ES-1). All three models showed reasonable accuracy with median values of significantly less than 1.5 feet when compared to the flood depths estimated by the FIRM and BLE studies. The results also showed that the correlation improved when the results were compared to the BLE as opposed to the FIRM data. This is likely because the FIRM studies included a more rigorous, detailed study process that incorporates structure and survey data.

<table>
<thead>
<tr>
<th>Model</th>
<th>Established Dataset</th>
<th>Median (ft)</th>
<th>Standard Deviation (ft)</th>
<th>Correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>FLO-2D</td>
<td>BLE</td>
<td>0.18</td>
<td>1.78</td>
<td>0.89</td>
</tr>
<tr>
<td></td>
<td>FIRM</td>
<td>1.15</td>
<td>2.71</td>
<td>0.73</td>
</tr>
<tr>
<td>HEC-RAS 2D</td>
<td>BLE</td>
<td>−0.64</td>
<td>1.30</td>
<td>0.94</td>
</tr>
<tr>
<td></td>
<td>FIRM</td>
<td>0.63</td>
<td>2.14</td>
<td>0.84</td>
</tr>
<tr>
<td>TUFLOW</td>
<td>BLE</td>
<td>−0.7</td>
<td>1.53</td>
<td>0.92</td>
</tr>
<tr>
<td></td>
<td>FIRM</td>
<td>0.49</td>
<td>2.23</td>
<td>0.81</td>
</tr>
</tbody>
</table>

Rapid Response Use Case Analysis

The referenced event for the rapid response use case analysis was Hurricane Harvey, a historic flood event that made landfall along the Texas coast in August 2017. The storm slowed down as it moved inland and produced tremendous amounts of rainfall over southeastern Texas. Modeling for this case study used archived forecasted precipitation data to develop the hydrologic inputs for the three models. The analysis served to demonstrate the efficiency and credibility of estimating flood inundation areas in advance of approaching storms. Four model iterations were completed for FLO-2D, HEC-RAS 2D, and TUFLOW. The iterations were based on updated forecast data issued 6 hours after the forecast data used for the previous model iteration. A WSEL and depth raster were produced for each simulation.

It was determined that up to seven iterations could be completed within a 48-hour assessment time frame for all three models because simulation run times were less than 2 hours. The availability of updated forecast data is the driving factor in the number of iterations that can be completed since forecast updates are published every 6 hours.
The model iterations were compared in Figure ES-2, where Delta is the variation between the modeled and observed flood depths. The comparison showed that the variation between the modeled and observed flood depths decreased as forecast data were updated (approximately 3-foot depth increase occurred in 18 hours). This assessment demonstrated that using the best available forecast data at a given moment is paramount to estimating flood inundation and that even in such a short period of time, predictions can be significantly affected.

The results of each model simulation were then validated against the following sources of observed post-Hurricane Harvey data: Individual Assistance (IA) Assessments, National Flood Insurance Program (NFIP) claims, Substantial Damage Estimates (SDE), USGS high water marks (HWMs), and USGS inundation mapping. The project team determined that the IA and NFIP datasets were unfit for reliable validations because both datasets had at least two sources of error and were excluded from further assessment. The available SDE data were confined to a very small geographical area within the pilot geography. Therefore, these data were assessed as part of the validation process, but the project team’s conclusions rely more heavily on the two USGS datasets.

The results of the statistical comparison (Table ES-2) of the Hurricane Harvey models using the USGS HWM and USGS inundation mapping data showed that of the three models, FLO-2D had the worst median (accuracy measurement) and standard deviation (precision measurement).

<table>
<thead>
<tr>
<th>Model</th>
<th>Established Dataset</th>
<th>Median (ft)</th>
<th>Standard Deviation (ft)</th>
<th>Correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>FLO-2D</td>
<td>HWM</td>
<td>2.95</td>
<td>1.51</td>
<td>0.92</td>
</tr>
<tr>
<td></td>
<td>USGS grids</td>
<td>2.71</td>
<td>2.58</td>
<td>0.88</td>
</tr>
<tr>
<td>HEC-RAS 2D</td>
<td>HWM</td>
<td>–1.72</td>
<td>1.12</td>
<td>0.91</td>
</tr>
<tr>
<td></td>
<td>USGS grids</td>
<td>–2.08</td>
<td>1.89</td>
<td>0.92</td>
</tr>
<tr>
<td>TUFLOW</td>
<td>HWM</td>
<td>–0.27</td>
<td>1.29</td>
<td>0.90</td>
</tr>
<tr>
<td></td>
<td>USGS grids</td>
<td>–0.64</td>
<td>2.00</td>
<td>0.91</td>
</tr>
</tbody>
</table>

The results also showed that TUFLOW produced the most accurate results when compared to the observed data, but that HEC-RAS 2D produced the most precise and reliable results. Both models showed strong predictive power with high correlation values.
Recommendations

Incorporation of the rapid response modeling and mapping for disaster response process identified and assessed in this study into FEMA’s standard practices will require proper planning and execution. Appropriate planning and execution involve identification of subject matter experts (SMEs), of tools and technologies needed, and of actions to be taken by FEMA.

Nine SME organizations were identified based on the following criteria:

- Existing contract vehicle with FEMA
- Familiarity with referenced datasets (e.g., BLE data, FIRM data, gage data, post-event data)
- Experience with HEC-RAS 2D, FLO-2D and TUFLOW
- Access to proprietary software (FLO-2D or TUFLOW)
- Experience relevant to rapid response modeling and mapping
- Knowledge of emerging technologies relevant to the identified rapid modeling approach (e.g., cloud or parallel computing)
- Limitations (e.g., manpower confined to working within a specific geographic location)
- Capacity in which the organization could provide support in case of a pending flood event
- Capacity to allocate resources within 48 hours

The tools, technologies, and capabilities identified in this report provide viability and efficiency solutions and potential enhancements to the rapid response modeling and mapping process. The identified tools, technologies, and capabilities focused on Geographic Information System (GIS) tools, cloud computing and storage, probabilistic modeling connections, damage and loss estimation, and utilization and sharing of rapid modeling results with the disaster response community to activate mitigation measures.

Lastly, recommendations based on the findings of this task order are as follows:

- Use Quantitative Precipitation Forecasts for determination of hydrologic inputs.
- Investigate quantification of precipitation forecast uncertainty.
- Use HEC-RAS 2D as the hydraulic model of choice when high-resolution terrain is available and use TUFLOW as the model of choice when only low-resolution terrain is available.
- Assess Recommendation 3 further through additional pilot studies that use disaster events other than Hurricane Harvey as the baseline event.
- Establish on-call provider teams.
- Develop a guidance document.
- Establish training for on-call providers.
- Compile a FEMA GIS library of easily accessible data needed by the on-call providers for this type of work.
- Establish a GIS portal viewer to enable the disaster response community to view and use the results.
- Conduct an outreach campaign for the disaster response community.
# Background and Introduction

The immediate period after a storm event is a critical period in terms of loss of life and property. Mitigation of these losses could be strengthened by improving the pre-storm forecasting of a storm’s impacts. Improving pre-storm forecasting requires identifying the best rapid flood risk modeling products that can be used to incorporate hydrologic and hydraulic (H&H) modeling into the disaster preparedness efforts that are undertaken by the Federal Emergency Management Agency (FEMA) and the disaster response community in major flooding events across the Nation.

The rapid flood risk modeling products must be tested and available and allow rapid data collection and modeling within a disaster response time frame (before the event begins and within 48 hours after initiation of analysis).

At FEMA’s request, Compass Production and Technical Services Joint Venture (PTS JV) conducted a study, referred to as the Rapid Response Flood Modeling Study, to identify the best modeling and mapping process for use in the disaster response time frame. The study was funded by FEMA and the Department of Homeland Security (DHS) Flood Apex Program, which applies new and emerging technologies to improve community resilience from flood disasters and conducted under Contract HSFE60-15-D-0003, Task Order 70FA6018F0000038.

The following factors are considered essential in the models:

- Time parameters
- Credibility of modeling and mapping data produced by the methodology
- Ability to produce data in 48 hours or less
- Replicability of the process for future use by FEMA and the disaster response community

The report is organized as follows:

- Background and introduction (Section 1)
  - Need for the study, objective of the study, essential factors in rapid flood risk models, and report organization
- Methodology (Section 2)
  - Ten evaluation factors (e.g., speed, inputs, reliability) that were used to screen 26 models (Section 2.1) down to three models that were then reviewed in detail (Section 2.2)
  - Description of a case study that was conducted to simulate a 1-percent-annual-chance rainfall event in a pilot geography using the three selected models (Section 2.3)
  - Description of a second case study (a case analysis of rapid response use) that was performed for the three selected models using Hurricane Harvey as the baseline event (Section 2.4)
- Results (Section 3)
  - Validation of the results of the 1-percent-annual-chance flood event pilot study against regulatory Flood Insurance Rate Map (FIRM) and Base Level Engineering (BLE) data (Section 3.3)
- Validation of the results of the rapid response use case analysis using observed data collected from Hurricane Harvey to determine the adequacy of the three selected models in providing reliable and accurate H&H data using forecasted precipitation data (Section 3.4)

- Recommendations (Section 4)
  - Recommendations that support incorporating a rapid response modeling and mapping process into FEMA’s standard practices, including the following: selection criteria for subject matter experts (SMEs) who could support FEMA with incorporating the process (Section 4.1), resources and data related to the selected H&H models that are needed but may not yet be available (Section 4.2), and actions that could best begin the incorporation process (Section 4.3)

- Bibliography
  - Cited references and additional resources

- Appendices
  - Initial Model Reviews (Appendix A)
  - Mean Precipitation Calculation Procedure (Appendix B)
  - Analysis of Hurricane Harvey Observed Datasets (Appendix C)
2 Methodology

Section 2 describes the methodology used to identify the best available process to achieve the project goals. The methodology included a review of available H&H models, selection of three models for additional assessment, and the approach that was used for the three selected models in two pilot case studies (the 1-percent-annual-chance flood event pilot study and the rapid response use case analysis).

2.1 Model Selection

The project team (Compass) was tasked with assessing a multitude of existing H&H models to support the selection of three models for further review. A model review matrix was developed for this project and provides an overview of the models that were assessed. The matrix includes the evaluation factors that were considered and weighted (see Table 2-1) based on their importance to the project objectives. Input regarding the matrix was received from FEMA and incorporated.

<table>
<thead>
<tr>
<th>Evaluation Factors</th>
<th>Weight</th>
<th>Scale (5= best option, 1= least desired option)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation runtime (per 100 miles for 1D model / # cells for 2D model)</td>
<td>0.15</td>
<td>5 (&lt; 30 minutes / &lt;500,000 cells) 4 3 (&lt; 2 hours / &lt;1 million cells) 2 1 (&gt; 2 hours / &gt;1 million cells)</td>
</tr>
<tr>
<td>Hydrologic input parameters</td>
<td>0.1</td>
<td>5 (Peak flow only from regression or NWS forecast/direct rainfall for 2D models) 4 3 (Hydrograph required, some routing) 2 1 (Required structural data)</td>
</tr>
<tr>
<td>Hydraulic input parameters (number/availability)</td>
<td>0.125</td>
<td>5 (Basic: topo, land use) 4 3 (Moderate: topo, land use, n-values, cross-section locations) 2 1 (Required structural data or combined 1D/2D)</td>
</tr>
<tr>
<td>Output manipulation requirements</td>
<td>0.075</td>
<td>5 (Flood inundation mapping and depth grids automated in a GIS-accessible format) 4 3 (Limited user input required to produce inundation and depth grids) 2 1 (Flood inundation mapping and depth grids must be created using separate software)</td>
</tr>
</tbody>
</table>
### Evaluation Factors Weight Scale (5= best option, 1= least desired option)

<table>
<thead>
<tr>
<th>Evaluation Factors</th>
<th>Weight</th>
<th>Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ability to utilize existing 1D and 2D BLE datasets (assuming Data Capture Standards compliance)</strong></td>
<td>0.075</td>
<td>5 (Model can directly import from BLE)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3 (Portions of model input can be imported/extracted from existing BLE)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 (Model must be created from raw data)</td>
</tr>
<tr>
<td><strong>Flexibility of input parameters</strong></td>
<td>0.1</td>
<td>5 (Can accept data such as topo and flows in most common formats)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3 (Limited manipulation of input datasets required)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 (Requires input to meet proprietary format)</td>
</tr>
<tr>
<td><strong>Replicability</strong></td>
<td>0.1</td>
<td>5 (Models are easily rerun by others with open source off-the-shelf software)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3 (Model requires readily available proprietary or open-source software and limited specialized knowledge)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 (Model requires proprietary software that is expensive or difficult to obtain and use)</td>
</tr>
<tr>
<td><strong>Ease of model modifications (e.g., update flows, incorporate new structure geometry)</strong></td>
<td>0.1</td>
<td>5 (Individual inputs such as hydrology and geometry can be readily modified and model rerun)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3 (Modification may require refresh of entire input dataset)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 (Model requires significant rebuild to incorporate modifications)</td>
</tr>
<tr>
<td><strong>Engineering community’s familiarity with model</strong></td>
<td>0.075</td>
<td>5 (Most water resources engineers are proficient with the model)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3 (Many water resources engineers are proficient with the model)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 (Proprietary model that requires specialized training)</td>
</tr>
<tr>
<td><strong>Reliability of model</strong></td>
<td>0.1</td>
<td>5 (Widely accepted globally)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3 (Acceptable documentation of validation done completed by a professional engineer)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 (No documentation found supporting accuracy of model outputs)</td>
</tr>
</tbody>
</table>

1D = one dimensional  
2D = two dimensional  
BLE = Base Level Engineering  
GIS = Geographic Information System  
NWS = National Weather Service

#### 2.1.1 Initial Model Reviews

The project team compiled a list of 64 models and model interfaces to start. The list was narrowed based on research and input from the project team, which was based on model experience. In general, research-only programs were removed from the list. Some of the models were outdated and had been
replaced by newer models. The model list was narrowed to a total of 26 models/model interfaces to be included in the initial model reviews.

An engineer was tasked with researching and evaluating each model. Each completed model matrix was then reviewed by a technical lead. Lastly, a technical advisor reviewed the complete set of matrices for consistent scoring of factors.

A number of data sources were used in the evaluation of the 26 models/model interfaces. Reviewers assessed sources such as the developer’s website and model user manual to determine factors such as data input requirements, compatibility with other models, possible formats of data outputs, and typical uses for the software. Due to limited resources modeling software itself was generally not obtained and run, but resources such as user forums and online tutorials provided insight into how the models work and any common issues that might arise while using the software.

Literature and other model assessment studies were also reviewed. The United Kingdom (UK) Environment Agency developed a nine-part benchmarking test (UK Environment Agency, 2013) of 15 2D hydraulic modeling software packages. This third-party benchmark was useful for comparisons of computational speed and also for general overviews of model capabilities and requirements. Other benchmarks, both internal and external to the Compass team, were used to get apples-to-apples comparisons of model speed and capabilities. Many modern hydraulic modeling software packages use Graphics Processing Unit (GPU) processing to improve computational speed; this capability is generally noted in the benchmark write-ups and was taken into consideration in the review.

To determine the general acceptance of and the engineering community’s familiarity with a model, reviewers analyzed FEMA’s and other regulatory agencies’ acceptance and use of the models as well as a national survey of more than 160 respondents (75% of whom actively use 2D hydraulic models or are generally familiar with them and plan to use them in the future) (Texas Floodplain Management Association, 2016).

The completed initial model review matrices for the 26 models that were reviewed had scores ranging from a low of 1.100 to a high of 4.075 out of 5. The scores can be found in Appendix A. The following sections summarize the results of the model assessments.

2.1.1.1 Delft3D

Matrix Score: 2.000

Delft3D is a multi-dimensional (2D or 3D) hydrodynamic and transport simulation program that calculates non-steady flow and transport phenomena resulting from tidal and meteorological forces on a curvilinear, boundary fitted grid or spherical coordinates. Delft3D performs computations for coastal, river, and estuarine areas; it can carry out simulations of flows, sediment transports, waves, water quality, morphological developments, and ecology. The grid generation module, RGFGRID, is required to create, manipulate, and visualize orthogonal, curvilinear model grids for the Delft3D water motion program. In 2D simulations, the Delft3D computation is depth averaged by solving the unsteady shallow water equations in two dimensions.
Delft3D’s matrix score (2.000) is the result of low scores on the following factors: the U.S. engineering community’s lack of familiarity with the program; downloading and setting up the software are complicated and require extra effort; grid data cannot be modified after loading a grid into the program; existing one-dimensional (1D) and 2D BLE datasets cannot be imported in the program (the model must be created from raw data); although the program download is free, any additional packages and technical services have associated costs; and the model is not included on FEMA’s list of accepted models.

2.1.1.2 DSS-WISE Lite

Matrix Score: 3.175

DSS-WISE Lite is free for use on a web-based platform, but users must register at the website. DSS-WISE is a web-based, automated 2D dam- and levee-break flood modeling and mapping capability platform. It was developed at the University of Mississippi with funding from FEMA. The Graphical User Interface (GUI) with real-time error checking allows the user to set up and run dam and levee breach scenarios resolutions from 20 to 200 feet. Data entry by the user is minimal. The preparation of the input data for the numerical model, based on the user-provided scenario, is fully automated. However, the U.S. Geological Survey (USGS) Digital Elevation Model (DEM) and national land cover data are default data in the program and cannot be edited by users.

The parallelized computational engine of DSS-WISE Lite solves full dynamic shallow water equations efficiently and provides the results quickly. It does not perform hydrological routing; only one inflow hydrograph can be imported per model. BLE models cannot be imported into the program. Once a model is created and run, users cannot modify or change the model setup. Users would have to rebuild the model to incorporate modifications.

2.1.1.3 FESWMS

Matrix Score: 3.000

FESWMS is an assemblage of programs published by the USGS to facilitate the 2D modeling of surface water flows. It is composed of four programs that prepare the data, model the flow, analyze the output, and convert the corresponding output to graphics.

Although FESWMS is on the FEMA list of regionally accepted models, it is in a state of disuse and is mostly unfamiliar to the engineering community. Employees in USGS water science centers across the country have either not utilized the software in years or were not aware of its existence. FESWMS is a good finite element model, but it has been superseded in performance by several other finite volume models. Anything that can be done with FESWMS can be done much more efficiently and effectively with other models. FESWMS has become obsolete in recent years and has been outperformed by other software.

Despite the credibility of FESWMS, the above issues are significant when considering the goals of the project.
2.1.1.4 FINEL

Matrix Score: 1.850

FINEL is a 2D hydraulic model that was designed for free-flow hydraulics and has been used primarily for coastal/estuarine analyses, but it also has riverine capabilities. FINEL is a proprietary model developed and used by Svašek Hydraulics for over 30 years and is currently not available for wide usage. Svašek creates an account for outside users on its computer cluster. FINEL has not been used extensively for riverine flooding and floodplain mapping purposes and is not on FEMA’s lists of approved hydrologic or hydraulic models.

FINEL uses a finite element model that employs a Roe solver on a triangular flexible mesh. Svašek has a mesh generator based on Matlab routines, but FINEL can also use meshes generated using outside software. FINEL can model “rigid lid” flow to assess pressure flow in structures such as bridges and culverts.

Svašek does not share its user manuals with non-registered users, which makes evaluating pre-processing and post-processing routines difficult. Because FINEL uses a flexible mesh, it can use a similar model definition to a HEC-RAS 2D model, but the cell faces are straight lines and do not have the same level of detail. FINEL input files are either in plain American Standard Code for Information Interchange (ASCII) or Matlab-specified format. Based on the visualizations shown on its website, it appears that Svašek uses Matlab for post-processing and visualization. Matlab is flexible but requires knowledge of Matlab programming.

FINEL does not appear to have well-developed rainfall methodology and has no infiltration loss methodology. The developer provided an example of a rain-on-grid model in which the rain was “implemented as a constant water level on all cells.”

2.1.1.5 FLO-2D

Matrix Score: 3.475

FLO-2D is a 2D hydraulic model that was designed for flood-routing simulations over alluvial fans, in channels, and in floodplains. It was developed and has been supported by FLO-2D Software since 1988. Over the past 30 years, commercially available FLO-2D has become widely used and is on FEMA’s list of approved hydraulic models. It has been used extensively by federal agencies such as the U.S. Army Corps of Engineers (USACE), U.S. Bureau of Reclamation (USBR), USGS, Natural Resources Conservation Service (NRCS), U.S. Fish and Wildlife Service, and the National Park Service.

FLO-2D is a finite difference model that uses a square system of grid elements overlain on the downstream topographic mapping. Although FLO-2D does not have the capacity to directly import BLE models, the square system makes it easy for users to create and edit a large-scale flood hydraulic model. In addition, FLO-2D can perform hydrologic routing using rain-on-grid and runoff loss-on-grid with

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3 Lynyrd de Wit, Deputy Director, Svašek, written communication, September 27, 2018.
spatially varied Next-Generation Radar (NEXRAD) rain data and runoff loss coefficients. FLO-2D is a
combined H&H model, so there is no need to separate rainfall/runoff and flood routing.

FLO-2D outputs are initially written to ASCII files. The post-processing MAPPER program can create
shaded contours, line contours, or grid element flow depth plots and hazard maps. Flood damage can be
assessed, and FLO-2D output can be viewed as a flood animation. MAPPER also automatically generates
shapefiles that can be imported directly into ArcGIS. A Digital Flood Insurance Rate Map (DFIRM) tool is
available for FEMA Flood Insurance Studies (FISs).

2.1.1.6 Flood Modeller

Matrix Score: 3.325

Flood Modeller is a proprietary model that was developed and is supported by Jacobs. It is not on
FEMA's list of regionally accepted models.

Flood Modeller is described in the UK benchmarking report (UK Environment Agency, 2013) mentioned
previously as one of the fastest 2D modeling software. The ease of transforming modeling results into
usable outputs competes with HEC-RAS 2D. Standard output includes water surface elevation (WSEL)
and depth rasters along with vector data such as flow and velocity. The GUI allows for animation of 2D
output. The animations can be saved as movie files.

Time-series information can be extracted for a given cell, and inundation boundary polygons can be
calculated for any time step within the simulation. The flood inundation boundaries or corresponding
animations can be exported into the Google Earth format. The GUI has GIS-like capabilities in which
inputs and outputs can be manipulated. In certain cases, BLE datasets can be imported into the model.
Tools are provided to dynamically link and/or import data from commonly used hydraulic models such as
HEC-RAS, SWMM, TUFLOW, and Delft-FEWS. The model can be modified through the development of
automation tools by the Jacobs development team. A representative from Jacobs stated that the “open
file data system enables users to develop custom pre- and post-processing tools and scripts. A
development team works with customers to custom-build automation tools.”4 Additionally, the model is
robust in its ability to produce precise results due to the input of a multitude of parameters including
roughness, topography, cross-section locations, operation rules of structures, and links between varying
models.

Flood Modeller’s lack of familiarity in the U.S. engineering community and its proprietary status are
disadvantages. With the project goals of rapid results using nationally available input data, the degree of
inputs into this model could hinder its ability to be used in a time-sensitive, pre-storm situation.
However, it is possible that some of the inputs could be ignored or accounted for with simplified
assumptions.

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**2.1.1.7 Flow-3D**  
**Matrix Score: 2.400**

Flow-3D is proprietary software with high licensing costs. Flow-3D is not widely used for channel modeling but is generally used for site-specific modeling rather than for large watershed-level analyses. For example, Flow-3D is used to model complex flows around or through hydraulic structures. Flow-3D is not on FEMA's list of accepted models.

Outputs from Flow-3D are typically animations of hydraulic movement through complex structures. The animations are 3D and are used to visualize the movement of water.

Creating a 3D flow model can use a variety of inputs. Terrain data and computer-aided design (CAD) data are needed to develop a 3D flow model. Inflow hydrographs must be developed using outside software and then be imported into the model. N-values need to be added to the model for the hydraulic simulation. BLE models cannot be imported into Flow-3D. The model uses a multitude of gridded meshing capabilities to model complex flows.

Flow-3D does not seem to be easily accessible by GIS technology. However, the model has been tested against scale models and has reliability in modeling complex situations. The project team tested Flow-3D to model dam overflows and siphon flows. While the software worked well, it seemed geared for localized applications.

**2.1.1.8 Flowroute-i**  
**Matrix Score: 3.100**

Flowroute-i is not on FEMA's list of accepted models. Flowroute-i is a proprietary model developed and supported by Ambiental, an environmental assessment firm in the UK.

Flowroute-i has a variety of advantages. A unique capability of the software is that it solves the full Saint-Venant shallow water equations. A variant of the model, Flowroute-Hydro, can use live rainfall information and input spatially variable precipitation. Model inputs and outputs can be in multiple types of raster format (e.g., .tiff, .img). A conversion process is required to develop GIS shapefiles from results or to input data that are in a format other than a raster. The model has been used in the North America, Africa, Europe, Australia, and Southeast Asia; has been licensed to third-party companies; and is well known throughout the UK.

Disadvantages include the inability to use U.S. customary units, necessary adaptation of 1D and 2D BLE datasets to fit input schema, potential need of specialized training, and lack of familiarity with the model from in the U.S. engineering community.

**2.1.1.9 GSSHA**  
**Matrix Score: 3.300**

The GSSHA model is a physics-based, distributed model for hydrologic, sediment, and constituent fate and transport processes. GSSHA was developed by the USACE’s Coastal Hydraulic Laboratory, a division
of the Engineer Research and Development Center, to conduct studies in watershed modeling. GSSHA is on FEMA’s list of approved hydrologic models but is not on FEMA’s list of approved hydraulic models. Its primary purpose is hydrologic assessment. GSSHA has been verified for use in simulating stream discharge in Hortonian, non-Hortonian, and mixed basins; soil moisture in Hortonian basins; and sediment discharge in Hortonian basins.

GSSHA uses a finite difference solver on a square system of grid elements based on a DEM plus gridded information about land use and soil texture/soil type. For larger watersheds, GSSHA allows for use of a 1D channel routing option that assumes uniform flow conditions. 1D elements can include channel segments, reservoir areas, and flow control features.

While GSSHA is open source and can be used without a proprietary GUI, there are no significant open-source tools for creating GSSHA input files or for viewing GSSHA output files. Pre- and post-processing are usually performed using the Watershed Modeling System (WMS), a proprietary tool developed by Aquaveo, that acts as a pre-processor and post-processor for GSSHA and several other H&H models. With the WMS software, GSSHA includes tools for visualizing inputs and outputs, including contouring and animation of all outputs, which include surface and channel depths.

While GSSHA includes both H&H analyses, the hydraulic calculations have not been the focus of development and are not certified by FEMA for delineation of floodplains.

2.1.1.10 HEC-RAS 2D
Matrix Score: 4.075

HEC-RAS 2D is the top-rated model from the initial reviews and is on FEMA’s list of accepted models. It is one of the most widely used 2D models and enjoys great familiarity within the engineering community. Because the software is available for free, it is easy for communities and reviewers to view model results and parameters natively. Outputs from HEC-RAS are easily obtained in convenient formats: model results can be exported to a raster, and model geometry information can be exported as a shapefile for viewing or manipulation within GIS software.

Creating a 2D HEC-RAS model can use a variety of inputs. HEC-RAS can use a variety of hydrologic data (direct rainfall, inflow hydrographs, stage hydrographs), although some manipulation is required (the hydrograph has to be developed rather than simply inputting the peak flow, and HEC-RAS does not yet handle rainfall losses). Terrain data are also able to be imported into HEC-RAS with a variety of formats. The fact that existing BLE studies and many effective detailed studies used HEC-RAS will facilitate importing data from existing models.

While many of the other models allow for use of GPUs during computations to increase computational speed, HEC-RAS does not do this. HEC-RAS’s modeling strategy allows for larger grid cells than most of the other models without the loss of terrain detail, compensating for some of this difference. This results in slightly lower runtime scores than some of the other models, but the computational speed of HEC-RAS is not exceptionally low compared to them.
The project team recently used HEC-RAS 2D to model simulations of Hurricane Florence in a rapid time frame using forecast data. The study assessed six Hydrologic Unit Code (HUC)-8 watersheds in 96 hours.

2.1.1.11 HEC-WAT

Matrix Score: 1.100

HEC-WAT was developed for the USACE, is used to help USACE study teams perform the necessary hydrologic, hydraulic, and consequence planning analyses required for water resource studies. HEC-WAT does not replace any existing software but rather forms a framework that allows existing software to work together. HEC-WAT is an open source tool that interfaces to manage different scenarios and to provide control of inputs and outputs between various H&H modeling software. This interface helps to manage different scenarios and provide control of inputs and outputs between various H&H modeling software. The software does not appear to be widely used.

HEC-WAT operates on a plug-in concept to allow other software to work together in a coordinated fashion so that water resources and economic decisions can be made from the same interface. HEC-WAT is not on FEMA's list of accepted models by itself, but many of the plug-in packages are.

2.1.1.12 HYDRO_AS-2D

Matrix Score: 3.150

HYDRO_AS-2D was developed by a German-based company, Hydrtotec/Nujic. This model is not on FEMA's list of accepted models. It is a 2D flow model that is linked to a Surface-water Modeling System (SMS) interface. Models generated with SMS are imported into HYDRO_AS-2D. HYDRO_AS-2D uses the finite volume method for solving flow equations and works with linear meshes only. It was mainly developed for the calculation of dam break and flood wave propagation, but can be used for 2D flow simulations. The 2D numerical calculation of flow is based on the 2D depth averaged flow equations. Disadvantages of the software are that the license carries an expensive annual cost that additionally requires the purchase of SMS Riverine Pro. HYDRO_AS-2D is popular modeling software in Europe but is not yet prevalent in the United States.

2.1.1.13 ICPR Expert

Matrix Score: 3.100

The ICPR model was developed in Florida to model ponds in areas with flat terrain. It is typically used in other flat topographic areas such as Lubbock, TX. ICPR Expert couples 1D and 2D to perform calculations. The model is proprietary software developed by Streamline Technologies. The cost of the software is expensive compared to other options.

While the 1D version of the ICPR model is on FEMA's list of accepted models, the 2D version is not at this time.

The model is capable of performing H&H computations. It is also capable of performing rainfall-on-mesh calculations. Inflow hydrographs can be imported into the software as well.
Some disadvantages of ICPR Expert are that bridges can only be modeled in 1D and that BLE models cannot be imported. Project team members that have used ICPR Expert rainfall computations have found the model to be generally slower than other software packages such as HEC-RAS 2D.

### 2.1.1.14 InfoWorks ICM

**Matrix Score: 3.725**

InfoWorks ICM is not on FEMA's list of accepted models, but it is widely used in the Austin, TX, area and in different parts of the country and world. It can directly import 1D BLE data without any user input but requires some manipulation for import of 2D BLE datasets. Simulation runtime tests indicated that the low-end GPU cards had a significant effect on reducing the overall run times.

The ability to simulate both hydrology and hydraulics in a single environment, including directly applying rainfall on mesh provides an efficient workflow. The function to convert the GIS shapefiles to depth grids in GIS provides useful graphic output.

Innovyze recently released new software named ICM Live that combines “the comprehensive integrated catchment modeling capabilities of InfoWorks ICM with sophisticated real-time operational forecasting, early warning, and emergency management” (Innovyze, n.d.).

A disadvantage of the software is that it is still relatively expensive and does require some user experience to operate and run. In addition, making revisions to a topographic surface requires going back through the “meshing” process, which can take significant time or even fail, depending on the size and complexity of the mesh surface. There is a log file available when a simulation fails; however, tracking down the issue can be difficult if the model ends as “incomplete,” resulting in significant delays in obtaining results.

### 2.1.1.15 JFlow

**Matrix Score: 3.350**

JFlow is not on the FEMA-approved model list but received the highest individual rating on several criteria of the initial model review scoring matrix, including its enhanced simulation run time, its flexibility, and its easy modification of its H&H input parameters.

JFlow is a proprietary hydraulic model that solves the 2D shallow water equations. JFlow has been in development since 2001, when JBA Consulting created it as a reduced-complexity modeling package for broad-scale studies. By 2007, the software had evolved to solve the diffusion wave equations and make use of the greater parallel processing power offered by GPUs.

JFlow is designed for efficient modeling of shallow flows over large areas. This includes simulating the routing of water from surface water floods, rising groundwater levels, reservoir failure, coastal defense overtopping, and out-of-bank flows from fluvial floods. JFlow allows flexibility in the development and manipulation of H&H input parameters. The model allows direct rainfall as input to the 2D grid and/or inflow hydrograph at a point. Each parameter set within the model is independent and able to be edited/updated/added as required.
The software has limitations. It cannot utilize existing 1D and 2D BLE datasets. Data must be converted to the appropriate formats. Model inputs and outputs must be processed in PostgreSQL or SQLite databases. The user manual claims that Arc 10.x is unable to edit spatial data in these databases and recommends QGIS.

### 2.1.1.16 MIKE FLOOD

**Matrix Score: 3.425**

MIKE FLOOD is a proprietary model developed by the Danish Hydraulic Institute and is included on FEMA’s list of accepted models. It integrates MIKE 11 (1D), MIKE21 (2D), and MIKE URBAN (storm drainage) with a wide selection of specialized 1D and 2D engines, enabling it to simulate any flood problems, including riverine, urban, coastal, dam and levee breaches, or any combination of these. MIKE FLOOD uses unstructured computational meshes that offer the flexibility to capture structural and topographical details.

Considering the simulation run time criteria, MIKE FLOOD has a very fast engine when used with GPU computations and offers parallel simulation capabilities. MIKE FLOOD can also analyze rain-on-grid using either a single rainfall pattern or a gridded rainfall time series. It is capable of integrating flood modeling consisting of dynamic coastal, urban, river, and floodplain interactions. MIKE FLOOD 2D outputs are in a proprietary format and flood inundation mapping and depth grids are prepared inside the model. Conversion utilities are available to export these files to GIS-accessible formats.

A disadvantage of MIKE FLOOD is its inability to directly import 1D BLE geometry files into its 1D component. Some consultants have attempted to improve the data importing limitation by developing a tool to convert RAS 1D files to MIKE 11 format. Additionally, MIKE 21 uses a proprietary grid/mesh format requiring all model inputs, such as terrain and land use data, to be converted to this format. GIS to MIKE tools are available to facilitate this process.

### 2.1.1.17 NWM

**Matrix Score: 1.700**

The NWM is not on FEMA’s list of accepted models. It was developed by David Maidment of the University of Austin with support from the National Oceanic and Atmospheric Administration (NOAA). NWM is an open-source hydrologic model that simulates observed and forecast streamflow over the entire continental United States. All program setups are default and operated by NOAA. The model runs are executed hourly, while medium-range forecasts out to 10 days are produced four times per day. All model configurations provide streamflow for 2.7 million river reaches and other hydrologic information on 1-kilometer and 250-meter grids. The NWM is a large-scale hydrologic routing model with an average basin size greater than 420 square miles and does not provide the level of flood H&H detail expected in rapid flood prediction. All NWM outputs are stored in NetCDF format, which can be read using the NWM image viewer. NWM is a predictive tool that requires gage data. Although it may be useful for predicting precipitation, the results are insufficient for the supporting 1D/2D modeling.
2.1.1.18 PCSWMM

Matrix Score: 3.325

PCSWMM, developed by Computational Hydraulics International, is a GUI for the U.S. Environmental Protection Agency’s (EPA’s) SWMM model and has a 25+ year history. The computational engine uses the unchanged EPA SWMM code to perform the 1D hydraulic calculations. PCSWMM applies these calculation methods to a distributed mesh of links and nodes to simulate overland flow in a manner described as “2D,” where the 2D links are all rectangular open channels with no side walls. The model is not suitable for large-scale 2D applications because the 2D application uses 1D links and nodes and the model run time would be excessive. PCSWMM does not include a full range of industry-standard hydrologic methods and may need to be paired with a hydrologic model to generate flows. PCSWMM can perform associated hydrologic analyses, but these hydrologic analyses are not among FEMA’s list of approved hydrologic models.

SWMM is on FEMA’s list of approved hydraulic models for 1D unsteady flow applications. Because PCSWMM’s 2D functionality utilizes the 1D flow equations, the model’s 2D applications fall under FEMA’s 1D hydraulics approval. PCSWMM has the full functionality of SWMM and can seamlessly analyze the full range of urban hydraulic scenarios, including subsurface flow in pipe networks, open channel flow through irregular shaped channels, and culvert flow, and interconnect the 1D elements with the 2D elements. Bridge hydraulics cannot be directly modeled in PCSWMM, which must approximate bridge openings as a collection of custom-shaped culverts plus an irregular conduit for the roadway deck.

PCSWMM’s post-processing for floodplain mapping can create floodplain inundation polygons for a 1D open channel model but does not automatically create depth grids for its 2D model areas. Although PCSWMM is used widely throughout the United States for urban drainage analysis and low impact development (LID) design, it clearly has disadvantages with respect to 2D analysis.

2.1.1.19 RIFT

Matrix Score: 3.525

RIFT is a 2D hydrodynamic computer model developed by researchers at the Pacific Northwest National Laboratory (PNNL) under a contract with DHS to better understand infrastructure risk surrounding events ranging from cybersecurity to inland flooding from hurricanes. The model is not on FEMA’s list of accepted models, but was evaluated based on FEMA recommendations, recent publications, and the practical use of RIFT in the recent extreme events of Hurricanes Florence and Michael.

The objective of the RIFT model is to increase situational awareness of flooding events for federal, state, and local officials. Typically, DHS requests the monitoring and modeling of a particular location during an extreme event. When there is mutual interest between DHS and other agencies, model results may be distributed to entities such as FEMA or local governments. The RIFT model is program/script-based and can produce gridded .asc files for depth, velocity, peak inundation timing, etc. RIFT allows for a scalable resolution of input/output grids, depending on area of interest, urgency of results, and level of detail required in simulations. It also facilitates rapid GPU-based computation times across large areas, utilizing scripts that include automated linkages to data from the National Weather Service (NWS) radar and the
USGS 3DEP topography dataset. According to the lead developer and on-call modeler, David Judi, a working model can be assembled and running within 30 minutes to 1 hour of a request. During Hurricane Florence, 7- to 10-day runs with more than 100 million grid cells were processed in 4 hours.\(^5\) In this simulation, grid cells were based on nationally available 10-meter, DEM-resolution, USGS topography. The model was set up remotely (only an internet connection is required for PNNL employees to edit and run a simulation) and run on efficient graphics processors and computing machines at PNNL.\(^6\)

The model results are meant to promote situational awareness and not necessarily to provide WSEls to the level of accuracy associated with most FEMA floodplain models. Model results can be calibrated, but the focus is on quickly understanding which structures, roads, and electrical utilities are at risk. Additionally, the model is heavily script-focused, because DHS needs to assess a diverse set of infrastructure risks, with various formats of inputs and outputs required. Although this software requires specialized knowledge, the program-based nature allows the software to quickly adapt to innovations in technology and data as they are released. Researchers have not developed a downloadable and user-friendly version of the software.

This script-focused software efficiently serves a very specific purpose and could potentially be tailored to accommodate specific FEMA criteria, parameters, and time frames. User friendliness, GUI capabilities, and user familiarity with a model are beneficial, but may not be necessary if the software has proper validation, adequate computing power, and a sufficient number of trained users that can set up and run a model anywhere throughout the country on short notice. RIFT is a great example of software that does not have widespread usage or GUI capabilities, but still accomplishes rapid flood risk assessment goals. For example, there are a handful of trained individuals at PNNL who are responsible for DHS modeling across the country. Models can be created and running within 1 hour by one person, and computation times are fast relative to the other 2D hydraulic models.

Although RIFT does not meet this specific project’s requirement of being a readily available model, it efficiently serves a very specific purpose and could potentially be tailored to accommodate specific FEMA criteria, parameters, and time frames.

**2.1.1.20 RiverFlow2D**

**Matrix Score: 3.700**

RiverFlow2D is H&H modeling software developed by Hydronia. The software is proprietary and requires an initial license cost and annual subscription fee. The model is not included in FEMA’s list of accepted models but is used globally. The software has been extensively validated in a range of different projects.

The software can be operated with other interfaces, such as SMS, which allows the use of GIS datasets. GIS data can be imported to establish 2D boundaries, infiltration areas, and rainfall areas. It allows for a wide variety of input data formats, including ASCII files and Autodesk Drawing Exchange Format (DXF)

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\(^6\) David Judi, Lead Developer, Pacific Northwest National Lab, oral communication, September 26, 2018.
files to generate hydrographs. The model is also useful for visualizing and exporting the results. Output options include inundation shapefiles and animations of flood extents, but the outputs may require some manipulation to work with other software.

RiverFlow2D uses an unstructured mesh for 2D calculations. The use of a triangular mesh allows flow to be modeled around complex structures. The model uses a robust wet-dry bed algorithm that allows the efficient calculation of overflow into channels. It performs calculations using the finite-volume numerical engine, which ensures stability in different flow regimes. It can also model culverts and bridges in the 2D mesh.

The model has a hydrologic component built into it that relies on the 2D surface to simulate runoff. Runoff is generated using a distributed model that accounts for the variation of the different parameters in space applicable to rainfall and infiltration.

A benefit of RiverFlow2D is having combined H&H modeling. Rainfall can be varied spatially over the 2D surface so that historical, real-time, and synthetic rainfall events can be simulated. Simulation times can be increased over 100 times when using a GPU option. RiverFlow2D does not have a 1D component; therefore, models will need to be built for BLE incorporation.

### 2.1.1.21 RMA2

**Matrix Score: 3.400**

RMA2 was developed by the USACE in 1973 and is included on FEMA’s list of accepted models. RMA2 requires SMS as pre- and post-processor. The model is a 2D, depth-averaged, finite-element, hydrodynamic numerical model. It computes WSEIs and horizontal velocity components for subcritical, free-surface-dimensional flow fields. RMA2 cannot evaluate more complex flows such as pressurized flow or super critical flow conditions. The software computes a finite element solution of the Reynolds form of the Navier-Stokes equations for turbulent flows. Friction is calculated with the Manning’s or Chezy equation, and eddy viscosity coefficients are used to define turbulence characteristics. Both steady and unsteady (dynamic) conditions can be analyzed. RMA2 can model up to five types of 1D flow control structures. Rainfall and evaporation can be used as types of boundary conditions. Existing BLE 1D and 2D models would have to be rebuilt in RMA2 models for computation.

### 2.1.1.22 SOBEK

**Matrix Score: 3.125**

SOBEK is proprietary software developed by Deltares that is not on FEMA’s list of accepted models. The cost of the software ranges from $4,000 per year to $16,000 per year. SOBEK consists of various interlinked modules. The modules include 1D flow, 2D flow, rainfall/runoff, water quality, and real-time control. Harris County, TX, used SOBEK to model overflows from Cypress Creek; however, the model is used primarily in Europe.

SOBEK can compute hydrographs using various methodologies. However, rainfall on the mesh is not an option. Run times can be longer than other reviewed models. The model has the flexibility to receive
input data in multiple formats, such as ASCII, that can be easily manipulated to be used in the software. The mapping output can be displayed in GIS formats. Results can also be measured from the 2D surface.

The preferred hardware specifications require a 3 gigahertz (GHz) Intel Core processor, 6 gigabytes (GB) of random access memory (RAM) on a 64-bit Windows Operating System, 20 GB of free hard disk space, and a graphics adapter with 256 megabytes of video memory.

2.1.1.23 SRH-2D

Matrix Score: 2.900

SRH-2D River Flow Modeling is on FEMA’s list of accepted models. It is a 2D hydraulic, sediment, temperature, and vegetation model under development at the USBR for river systems. SRH-2D adopts a zonal approach for coupled modeling of main and side channels and floodplains. SRH-2D solves the 2D depth-averaged form of the diffusive wave or the dynamic wave equations. The dynamic wave equations are the standard Saint-Venant depth-averaged shallow water equations. Both the diffusive wave and dynamic wave solvers use the implicit scheme to achieve solution robustness and efficiency. SRH-2D can model 1D hydraulic structures, including bridges, culverts, gates, and weirs.

SRH-2D is the typical 2D model used by federal agencies and is popular in the western United States. Technical support response is handled by one individual and the available users’ manual has not been updated since 2008. Simulation run time of a small 2D area is short compared to other model program capabilities. SRH-2D requires SMS as pre- and post-processor, and current BLE 1D and 2D models would have to be rebuilt in SRH-2D models.

2.1.1.24 TUFLOW

Matrix Score: 3.550

TUFLOW is on the FEMA list of regionally accepted models. TUFLOW received a high rating on several criteria of the scoring matrix, including its enhanced simulation run time and its flexibility in its H&H input parameters. In addition, the TUFLOW engine is utilized by the less accessible, but highly rated xp2D.

TUFLOW is a proprietary model developed by British Maritime Technology (BMT) Group. It solves the full shallow water equation using the finite volume approximation numerical scheme. While the TUFLOW Classic version uses regular square grid elements as computational mesh, the enhanced TUFLOW FV uses unstructured computational meshes that offer more flexibility to capture structural and topographical details. TUFLOW is optimized to use GPUs to rapidly process data and can use direct rainfall and/or hydrographs as its hydrologic input parameter. TUFLOW is dynamically linked (fully integrated) with external 1D solvers, such as Flood Modeller and XPSWMM 1D engines.

Based on the previously mentioned UK benchmarking test for 2D models (UK Environment Agency, 2013), TUFLOW schemes are suitable for predictions of maximum flooding extent, depth, and velocity, as well as prediction of temporal variations in flooding extent, depth, and velocity. TUFLOW is also ideally suited for large-scale regional rapid hydraulic solutions, real-time flood inundation forecasting, and high-
resolution 2D solutions. The power of modern GPUs combined with TUFLOW's super-fast solver allows very large models with more than 10 million cells with fine resolution to be simulated within a practical time frame. TUFLOW also allows for splicing terrain alterations into the model for a high level of flexibility.

2.1.1.25 Vflo

Matrix Score: 2.400

Vflo is a physics-based hydrologic model that provides real-time and post-analysis prediction of rainfall-runoff. It is developed and operated by Vieux & Associates and is not on FEMA's list of accepted models.

Vflo uses geographic information and multi-sensor precipitation input to simulate rainfall and snowmelt runoff from major river basins to small catchments. It uses kinematic wave analogy (KWA) to solve flood hydraulics for overland and channel cells. The numerical solution of the KWA is determined using a finite element solution in space and finite difference approximation in time. For flood inundation extents delineation, the Vflo extension, Inundation Analyst, is required to simulate flood inundation. The Inundation Analyst extension is available for an additional fee. The hydrological input can come from radar rainfall or rain gauge data. Vflo is used for flood prediction, recharge estimation, water quality management, and water resources management. The software is available for free when used for educational or evaluation purposes. Access to the software requires an online account holder login. Current BLE 1D and 2D models would have to be rebuilt in Vflo. The reference documentation is limited, and the software has a reputation of not being very well known.

2.1.1.26 xp2D

Matrix Score: 3.900

Despite being a proprietary model developed by Innovyze, xp2D is widely used and well known within the engineering community because of its presence on FEMA's list of approved models. xp2D utilizes GPU processing to minimize computation time.

xp2D can take in a variety of hydrologic data (direct rainfall or inflow hydrographs). One advantage of xp2D is that it can account for soil losses due to infiltration. It can import terrain data in a variety of formats and allows for terrain modifications to account for various scenarios (e.g., addition of a roadway) within the model. This program imports 1D data from BLE models, but cannot import 2D BLE model data yet.

Outputs from xp2D can be difficult to use. The model can be “encrypted” for sharing with a client or a reviewer, but outputs are otherwise exported as a .mid or a .mif file. TUFLOW_to_GIS, a standalone tool, can be used to export the raw grids at a specific time step or at the maximum value.

2.1.2 Model Selections for Pilot Study

A lower matrix score does not mean the model has less credibility. Because the matrix was designed for this project, it considers factors such as the ability to incorporate BLE data and the possibility of
replicability of the process. These factors are important to the project but can lower the score of a model that is useful under other circumstances.

Table 2-2 displays the 10 highest scoring models from the initial reviews. A panel composed of technical leaders on the project team discussed the top-scoring models to select the three models that are best suited to meet the project objectives. One important decision factor was the replicability of the process. The process had to be one that FEMA and its partners can replicate. Any models on the list that were not readily available to Compass or FEMA were removed.

The three models that were selected for further research and for use in the pilot study portion of the project are FLO-2D, HEC-RAS 2D, and TUFLOW. The models were selected based on their use in the engineering community, being readily available to and accepted by FEMA, and computational speeds.

FLO-2D is a 2D hydraulic model that is designed for flood routing simulations over alluvial fans, in channels and floodplains. It has become a widely used, commercially available flood model and has been used extensively by numerous U.S. federal agencies. FLO-2D is a combined H&H model so it does not require the user to separate rainfall/runoff and flood routing.

HEC-RAS 2D is the top-rated model from the initial reviews and is one of the most widely used 2D models, having great familiarity within the engineering community. Because the software is available at no cost, it is very easy for communities to view the model results and parameters natively. Outputs from HEC-RAS 2D are easily obtained in convenient formats: model results can be exported straight to a raster and model geometry information can be exported as a shapefile for viewing or manipulation within GIS software.

TUFLOW is a proprietary model ideally suited for large-scale regional rapid hydraulic solutions, real-time flood inundation forecasting, and high-resolution 2D solutions. The power of modern GPUs combined with TUFLOW’s super-fast solver allows it to execute very large models with more than 10 million cells with fine resolution to be simulated within a practical time frame. Additionally, its ability to efficiently utilize different third-party tools such as GIS and SMS as pre- and post-processing tools makes TUFLOW suitable for this effort.

### 2.2 Model Reviews

In-depth research was conducted for each of the three selected models prior to commencement of the pilot study analyses. The subsequent sections provide general information collected about each model, including the methodologies used by the model, model inputs, and available model outputs.
2.2.1 FLO-2D

The following sections provide general information regarding the methodology, capabilities, input parameters, and outputs of the FLO-2D model.

2.2.1.1 Background

FLO-2D is a 2D hydraulic model that is designed for flood routing simulations over alluvial fans and in channels and floodplains. It was developed in 1988 and is supported by FLO-2D Software.

The model routes overland flow in eight directions as either sheet flow or flow in multiple channels. Overland flow computations utilize either the kinematic or diffusive wave equation. For flood routing, parameters having the greatest effect on the area of inundation or outflow hydrographs are as follows (FLO-2D Software, 2017b):

- Topography
- Inflow hydrograph discharge and volume
- Manning’s n values

FLO-2D is a combined H&H finite difference model that uses a square system of grid elements overlain on topographic mapping. The square system makes it easy for users to create and edit large-scale hydraulic models. It can perform hydrologic routing using rain-on-grid and runoff loss-on-grid with spatially varied NEXRAD rain data and runoff loss coefficients.

Very detailed flow hydraulics, such as hydraulic jumps and flow in river bends, around bridge piers, or around other complicated hydraulic structures, cannot be simulated with the FLO-2D model. FLO-2D does not distinguish between subcritical or supercritical flow and has no restrictions when computing the transition between the flow regimes. For minor flows, such as the beginning of the inflow hydrograph or the split of flow on a floodplain, the flow discharge is simulated as shallow sheet flow in the computation grids. Manning’s n roughness coefficients are adjusted based on sheet flow depth. Thinner sheet flow is computed with higher flow roughness and less flow velocity. These computations make these sheet flow grids become sticking grids and produce very long flow travel times for these sheet flow grids. The following sections briefly introduce the general model inputs and outputs.

2.2.1.2 Input Parameters

Data needs include topography, watershed and channel geometry, hydrologic data, hydraulic data, and boundary conditions. Table 2-3 lists the required datasets and their associated model files.

A FLO-2D model consists of a series of ASCII files that are organized according to model components: FPLAIN.DAT, CADPTS.DAT, CONT.DAT, TOLER.DAT, RAIN.DAT, and OUTFLOW.DAT. Additional components can be added by turning on or off switches in the CONT.DAT file, including channel flow, rainfall, infiltration, and hydraulic structures. Topographic data are contained in the FPLAIN.DAT and CADPTS.DAT files. The CONT.DAT and TOLER.DAT files control numerical stability. The RAIN.DAT file contains the precipitation histogram and the OUTFLOW.DAT file contains outflow nodes and optional outflow water surface control. To make data processing efficient, the model uses a coordinate and elevation file called
Table 2-3: FLO-2D Data Files for Model Development

<table>
<thead>
<tr>
<th>Data</th>
<th>Model File</th>
<th>Common Source/Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project file</td>
<td>fplain.dat</td>
<td>NA</td>
</tr>
<tr>
<td>Terrain data</td>
<td>topo.dat</td>
<td>DEM or LiDAR</td>
</tr>
<tr>
<td>Surface roughness</td>
<td>mannings_n.dat</td>
<td>• NLCD</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Chow (1959) and Calenda et al. (2005)</td>
</tr>
<tr>
<td>Precipitation</td>
<td>rain.dat</td>
<td>• NOAA 24-hr 100-year frequency precipitation depths</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Regional design rainfall distributions</td>
</tr>
<tr>
<td>Monitoring cross sections</td>
<td>fpxsec.dat</td>
<td>NA</td>
</tr>
<tr>
<td>Downstream boundary</td>
<td>outflow.dat</td>
<td>• Free flow</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Rating table</td>
</tr>
<tr>
<td>Numerical computation setup</td>
<td>cont.dat</td>
<td>• Courant numbers</td>
</tr>
<tr>
<td></td>
<td>toler.dat</td>
<td>• Numerical tolerances</td>
</tr>
<tr>
<td>DEM = Digital Elevation Model</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LiDAR = Light Detection and Ranging</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NA = Not Applicable</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NLCD = National Land Cover Database</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NOAA = National Oceanic and Atmospheric Administration</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

TOPO.DAT and a Manning’s roughness value file called MANNINGS_N.DAT. The Grid Developer System (GDS) and PROFILES programs help facilitate the manipulation and development of the input files.

2.2.1.3 Outputs

The FLO-2D outputs are initially written to ASCII files. The post-processor MAPPER program can create shaded contours, line contours, or grid element flow depth plots and hazard maps. FLO-2D output can be viewed as a flood animation. MAPPER will also automatically generate shape files that can be imported directly to ArcGIS. A FIRM tool is available for FEMA FISs.

After a FLO-2D flood simulation is complete, the computed hydraulic results are presented in output files that contain hydrographs, maximum flow depths, and velocities. A summary of the inflow volume, final volumes left on the floodplain (storage), and outflow from the grid system is presented in the SUMMARY.OUT file. If the inflow does not equal the outflow plus final storage within a fraction of 1%, there is problem with the simulation.

In the FLO-2D GDS setup window, options are available to create output files with either a spatial or temporal format. Output files that have substantial detail involving all the time steps (temporal output) or all the grid elements (spatial output) can be generated. Some output files are designed for a simple review of specific flow hydraulics. Output data include WSEL, flow depth, velocity, discharge, impact pressure, specific energy, sediment concentration, and other variables. Overland flow hydraulics may be viewed as individual grid elements or the grid elements can be grouped together to produce floodplain cross sections. Summary tables listing maximum velocity and flow depths and their times of occurrence appear near the end of the BASE.OUT file. Users can specify the desired type of output using the CONT.DAT file.
FLO-2D MAPPER is a post-processor program that creates maps and other plots of the FLO-2D model results, including hydraulic variables, WSELs, duration of inundation, impact force, static pressure, specific energy, sediment scour or deposition, and others. Three types of map plots can be generated:

- Grid element plots where each element is assigned a color depending on the value of the selected plot variable
- Line and shaded contour maps based on the grid element values
- Digital terrain model (DTM) points to generate detailed flow depth contour plots based on grid element WSELs and DTM point ground elevations

MAPPER can also generate depth and velocity versus time graphs at user selected locations, flow depth profiles along user defined sections, flood damage plots, and hazard maps.

2.2.2 HEC-RAS 2D

The following sections provide general information regarding the methodology, capabilities, input parameters, and outputs of the HEC-RAS 2D model.

2.2.2.1 Background

HEC-RAS 2D is a component of the HEC-RAS model for unsteady flow hydraulic simulation in a 2D flow area and has been available since the release of version 5.0 in February 2016. HEC-RAS is so widely used in part because it is open and free for universal download and use. It was originally developed by the USACE in 1995 as a strictly 1D model, but has gained broader usage as a 2D model in the past 2 years. In June 2018, its 2D capability broadened further with the inclusion of the internal boundary conditions option. HEC-RAS 2D solves either the Saint-Venant equation or the Diffusion Wave equation. In general, the Diffusion Wave equation allows the software to run faster and have greater model stability properties. Moreover, the 2D flow area has the capability to run its computational solution using multiple processors (parallelization) on a computer, which allows it to run faster than on a single processor. The current version of HEC-RAS comes with both 64-bit and 32-bit computational engines. The program uses the 64-bit computational engine automatically when installed on a 64-bit operating system. The 64-bit engine runs faster and has more storage space to handle large datasets.

HEC-RAS 2D modeling is performed in the form of 2D flow areas within HEC-RAS geometry files. These 2D flow areas can stand alone or be linked dynamically with a 1D feature. A 2D flow area is a computational mesh that uses an implicit finite volume solution scheme, developed for either a structured or unstructured mesh. The mesh can be composed of three to eight polygon sides. This is a particularly powerful feature as it allows for break lines to be added that capture details of linear features, such as roads, embankments, and levees.

HEC-RAS 2D requires the use of unsteady flow modeling to create WSEL, depth grids, velocity grids, and inundation polygons. However, steady flow conditions can be approximated by inputting uniform boundary conditions, and restart files can be created from the results that can be used as initial conditions. Boundary conditions can take several forms, including inflow stage or flow hydrographs, excess precipitation, and normal depth. Starting with HEC-RAS 5.0.5, boundary conditions can be
included within the middle of the mesh as well as the exterior boundary, and single boundary conditions can be spread across multiple grid cells.

2.2.2.2 Input Parameters

Table 2-4 provides a list of files required for set up of a HEC-RAS 2D model.

<table>
<thead>
<tr>
<th>File</th>
<th>Extension</th>
<th>Description</th>
<th>Format</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project file</td>
<td>.prj</td>
<td>Set of data associated with a particular model system. The data files for a</td>
<td>ASCII</td>
</tr>
<tr>
<td></td>
<td></td>
<td>project are categorized into plan data, geometric data, steady or unsteady</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>flow data, quasi-steady flow data, sediment data, water quality data, and</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>hydraulic design data.</td>
<td></td>
</tr>
<tr>
<td>Plan files</td>
<td>.p01 to .p99</td>
<td>“P” indicates the plan file, while the numbers represent the plan number.</td>
<td>ASCII</td>
</tr>
<tr>
<td></td>
<td></td>
<td>The plan file is associated with geometric file and unsteady flow file.</td>
<td></td>
</tr>
<tr>
<td>Run files</td>
<td>.R01 to .R99</td>
<td>“R” indicates a run file, while the number is associated with a particular</td>
<td>ASCII</td>
</tr>
<tr>
<td></td>
<td></td>
<td>plan file. The run file contains all of the necessary data to perform the</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>computations that are requested by the associated plan file. The run file</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>contains the input to any computational engines available in the HEC-RAS</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>system.</td>
<td></td>
</tr>
<tr>
<td>Output files</td>
<td>.O01 to .O99</td>
<td>“O” indicates output file, while the number is associated with a particular</td>
<td>Binary</td>
</tr>
<tr>
<td></td>
<td></td>
<td>plan file.</td>
<td></td>
</tr>
<tr>
<td>Unsteady flow data</td>
<td>.U01 to .U99</td>
<td>“U” indicates an unsteady flow data file, while the number corresponds to</td>
<td>ASCII</td>
</tr>
<tr>
<td></td>
<td></td>
<td>the order in which the files were saved for a particular project. It contains</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>flow hydrographs, starting flow conditions, and downstream boundary</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>conditions.</td>
<td></td>
</tr>
<tr>
<td>Geometric data</td>
<td>.G01 to .G99</td>
<td>“G” indicates a geometric file, while the number corresponds to the order</td>
<td>ASCII</td>
</tr>
<tr>
<td></td>
<td></td>
<td>in which the files were saved for a particular project. A geometric file</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>contains all geometric data for the river system to be analyzed. This</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>includes cross section, hydraulic structures, coefficients, and modeling</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>approach information.</td>
<td></td>
</tr>
</tbody>
</table>

The schematic diagram shown in Figure 2-1 depicts how the data files fit together in the model. In this example, there are three plans and geometries in the project file. Each plan represents a specific set of unsteady flow data and geometry data. Each geometry data contains different computational cell sizes.

2.2.2.3 Outputs

HEC-RAS 2D results are processed into grids using the RAS Mapper option within HEC-RAS. These grids can be generated at any user-specified time step, or at maximum or minimum values for a variety of variables, including WSEL, depth, velocity, duration, Froude number, arrival time, and inundation maps. These grids are stored as georeferenced Tagged Image File Format files (TIFFs), which can be easily loaded into mapping software such as AutoCAD and ArcGIS.
2.2.3 TUFLOW

The following sections provide general information regarding the methodology, capabilities, input parameters, and outputs of the TUFLOW model.

2.2.3.1 Background

TUFLOW software products are proprietary advanced numerical engines developed by BMT WBM. These products simulate free-surface water flow for a range of environments, including urban waterways, rivers, floodplains, estuaries, and coastlines. TUFLOW solves the full shallow water equation using the finite volume approximation numerical scheme. Products include:

- TUFLOW Classic, which leverages a fixed grid computational mesh
- TUFLOW HPC, which leverages a fixed grid computational mesh similar to TUFLOW Classic, but can harness GPU capabilities to reduce run times by up to 100 times when compared with a purely Central Processing Unit (CPU)-driven simulation
- TUFLOW FV, which leverages unstructured computational meshes that offer more flexibility when representing complex topographical features, including 3D modeling
- TUFLOW offers 1D/2D dynamic linking capabilities and can be linked to a number of 1D solvers, including ESTRY, XPSWMM, and Flood Modeller.

TUFLOW requires several software programs to build and view models. Many modelers use third-party Graphic User Interfaces (GUIs) when working with TUFLOW. The following software programs are commonly used:

- Text Editor – UltraEdit, Notepad++, Textpad, etc.
- Spreadsheet software – Microsoft Excel, Libre Office
- GIS Platforms – ArcGIS, MapInfo Professional, QGIS
- (Optional) 1D third-party solvers – ESTRY, XPSWMM, Flow Modeller

The text editor is used to create and modify TUFOLOW simulation control files. The control files list all of the simulation commands and file path references to GIS and tabular datasets. The table of control files used in TUFOLOW is shown in Table 2-5.

<table>
<thead>
<tr>
<th>File</th>
<th>Extension</th>
<th>Description</th>
<th>Format</th>
</tr>
</thead>
<tbody>
<tr>
<td>TUFOLOW Simulation Control File</td>
<td>.tcf</td>
<td>Controls the data input and output for 2D or 1D/2D simulations. The filename (without extension) is used for naming all 2D domain files. Mandatory for all simulations.</td>
<td>Text</td>
</tr>
<tr>
<td>TUFOLOW Boundary Conditions Control File</td>
<td>.tbc</td>
<td>Controls the 2D boundary condition data input. Mandatory for a 2D or 1D/2D simulation.</td>
<td>Text</td>
</tr>
<tr>
<td>TUFOLOW Event File</td>
<td>.tef</td>
<td>Database of .tcf and .ecf file commands for different events.</td>
<td>Text</td>
</tr>
<tr>
<td>TUFOLOW Geometry Control File</td>
<td>.tgc</td>
<td>Controls the 2D geometric or topographic data. Mandatory for a 2D or 1D/2D simulation.</td>
<td>Text</td>
</tr>
<tr>
<td>ESTRY Simulation Control File</td>
<td>.ecf</td>
<td>Controls the data input and output for the 1D domain. The filename (without extension) is used for naming all 1D output files. Mandatory for a 1D or 1D/2D simulation modelled as a 1D element.</td>
<td>Text</td>
</tr>
<tr>
<td>TUFOLOW Operating Controls File</td>
<td>.toc</td>
<td>Contains operating rules that can be applied to hydraulic structures, pumps, and other controllable devices contained within a control definition. More than one structure/device can use the same control definition.</td>
<td>Text</td>
</tr>
<tr>
<td>Read Files</td>
<td>.trd .erd .rdf</td>
<td>A file that is included inside another file and accessing the Read File command in .tcf, .tgc, and .ecf files. Minimizes repetitive specification of commands common to a group of files. The file extension can be anything; .trd, .erd, and .rdf are most commonly used.</td>
<td>Text</td>
</tr>
</tbody>
</table>

Time-series and non-geographical data are tabulated in the spreadsheet software. GIS software is used to establish, edit, and visually map and manage all geographic data. These software programs process the necessary data to run a TUFOLOW model.

**TUFOLOW Versions**

TUFOLOW is offered in three versions: TUFOLOW Classic, GPU/HPC (also known as Heavily Parallelized Compute), and TUFOLOW FV. TUFOLOW Classic and GPU/HPC use the implicit and explicit solvers, respectively. Computational speed depends on the number of core/graphical processing units and types of hardware the computer has. Simulations run much faster on computers equipped with GPUs and a TUFOLOW GPU/HPC license. Models run using both TUFOLOW Classic and TUFOLOW GPU/HPC produced contrasting run times as shown in Table 2-6.
Table 2-6: TUFLOW Model Version Run Times

<table>
<thead>
<tr>
<th>Model Size (Wet Cell Count)</th>
<th>TUFLOW Classic Simulation Time (hr)</th>
<th>TUFLOW HPC (GPU) Simulation Time (hr)</th>
<th>GPU Speed-up Ratio (Times Faster than Classic – CPU)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7,500</td>
<td>0.20</td>
<td>0.05</td>
<td>4</td>
</tr>
<tr>
<td>31,000</td>
<td>0.25</td>
<td>0.05</td>
<td>5</td>
</tr>
<tr>
<td>125,000</td>
<td>1.53</td>
<td>0.08</td>
<td>21</td>
</tr>
<tr>
<td>7,500,000</td>
<td>15.22</td>
<td>0.33</td>
<td>47</td>
</tr>
<tr>
<td>3,100,000</td>
<td>146.00</td>
<td>1.92</td>
<td>76</td>
</tr>
<tr>
<td>12,500,000</td>
<td>1,152.00</td>
<td>18.50</td>
<td>78</td>
</tr>
</tbody>
</table>

TUFLOW FV consists of a 1D/2D/3D flexible mesh finite volume numerical solution that simulates hydrodynamic sediment transport and water quality processes in oceans, coastal waters, estuaries, and rivers. The 3D module assumes a hydrostatic pressure on the water column and includes baroclinic terms. TUFLOW FV can also model temperature, salinity, and density stratification within the module. FV can also model tidal activity and wind driven currents, which include tsunamis. TUFLOW FV can be useful in creating more complex and detailed models of river systems and becomes imperative to model coastal waters.

**GUI Interface**

TUFLOW does not offer a self-contained GUI, but models can be built and reviewed, and results evaluated using third-party products, including QGIS, SMS, WaterRIDE, xp2D, 12D, and Flood Modeller Pro (previously known as ISIS).

**Setting up a 2D Grid**

To establish a 2D grid, the 2D domain must be defined using a list of commands in the TUFLOW Geometry Control files. These files either contain or access data on the orientation and size of the 2D grid, active or inactive grid cells, bed and ground elevations, material type or flow resistance, and soil types. The grid comprises square cells and characteristics in relation to the topography, resistance value, and the initial water levels. The TUFLOW Geometry Control file contains a series of commands that help build the model and are to be applied in sequential order. This order facilitates the override of older information with newer data to modify the model. The override is useful where areas need to be updated or options tested.

**2.2.3.2 Input Parameters**

TUFLOW does not calculate runoff using unit hydrograph methods. Instead, it can calculate runoff by applying rainfall to a 2D surface. Hydrological model parameters primarily consist of topography, land use, soil type, and rainfall.
Topography

To assign elevations to the 2D grid, an elevation model can be directly input into TUFLOW (Classic or HPC) as either a triangulated irregular network (TIN) or gridded DEM dataset. The formats supported for the DEM datasets are Esri ASCII grids (.asc) and binary grids (.flt). Elevations are assigned from the elevation dataset within the DEM/TIN. Elevations can also be defined at cells in the 2D grid.

Assigned elevations can also be altered by enforcing break lines within the 2D domain. Break lines are usually used to define crests such as levees or embankments or the thalweg of a creek or river. Break lines assign the elevation height of that crest or thalweg to either the cell centers or entire grid squares. Using an elevation dataset offers the benefits of speed and flexibility in that elevations are assigned directly to the cells and can be updated automatically if needed.

Land Use

For land use, roughness values used for the 2D domains are created using polygon GIS layers or raster grids. The bed resistance is established either using Manning’s n, Manning’s M (1/n), or Chezy values as defined in the TUFLOW Control File. Manning’s n is chosen as the default and is the recommended roughness variable to use. The layer can be used to set land use hazard categories and set rainfall losses when using direct rainfall. It is common to digitize one or multiple 2D material layers and assign Manning’s n values to materials that are useful during sensitivity analyses or model calibration.

Rainfall

TUFLOW does not compute hydrologic calculations. Any hydrographs that need to be generated to simulate design storms would need to be derived using a third-party package such as the Hydrologic Engineering Center – Hydrologic Modeling System (HEC-HMS). Inflow hydrographs can then be applied in either 1D or 2D domains.

Rainfall is applied directly to the 2D grid using a hyetograph. Three methods can be utilized to apply direct rainfall on the 2D grid:

- Polygon to assign a rainfall gauge with spatial and temporal adjustments if needed.
- Gridded rainfall in which distribution over time as a series of .asc/.flt Esri grids or NetCDF file.
- A rainfall control (.TRFC) file to allow the user to specify rainfall gauges or points over the model and a series of commands to control the interpolation of the rainfall.

Choosing a method depends on available data. The first method would be useful in applying a design storm rainfall where a uniform depth is applied on the grid, while the second and third method would be useful for calibration storms by adding spatial distribution of rainfall depths. Rainfall losses can also be applied to the 2D grid through the Material Definition File (.TMF or .csv file) and removes the loss depth from the rainfall before it is applied to the 2D domain.

Infiltration methods include Green-Ampt, Horton, and the Initial Loss/Continuing Loss approach. Infiltration rate depends on which method and loss parameters are chosen, depth to groundwater or impervious layer, soil porosity and initial moisture, and the impervious value of the overlying material
layer. Only wet cells can infiltrate into the soil layer and the default groundwater depth is treated as infinite.

**Hydraulics Model Parameters**

TUFLOW (Classic and HPC) simulates depth-averaged, 1D and 2D free-surface flows. The implicit 2D solver in TUFLOW is based on Stelling (1984) and solves 2D, depth-averaged, momentum and continuity equations for free-surface flow using a second order semi-implicit matrix solver. The solver includes viscosity and turbulence terms that are not calculated in other models. The 1D engine, ESTRY, uses full 1D free-surface Saint-Venant flow equations using the Runge-Kutta explicit solver.

Several components are needed to build a 1D model that can be linked to a TUFLOW model. In 1D/2D combined models, the 2D portion of the model generally represents the overbanks, while the 1D portion represents the channel from bank to bank. Therefore, if any 1D model representing the entire floodplain is converted to a 1D/2D combined model, the overbanks are removed from the 1D model and the 2D surface is used to model the overflow. The components are discussed in detail below.

**Ability to Import BLE Models**

BLE models are usually created using HEC-RAS software developed by the USACE. These models can be merged with TUFLOW using third-party software by converting the HEC-RAS files into a compatible format. Cross section information can be incorporated as 1D ESTRY sections or stamped into the 2D domain. Structures and inflow boundaries cannot be imported. A utility available on the TUFLOW website is used to convert the HEC-RAS geometry into a TUFLOW-compatible GIS and .csv format. The process to import HEC-RAS geometry into TUFLOW consists of the following steps:

1. **Export RAS Geometry to .sdf Format** – Export the geometry in HEC-RAS to GIS data and include items such as centerlines, cross sections, and cross-section properties. The export will create an .sdf file to be used for utility.
2. **Assign a GIS Projection File** – A projection file is needed to translate the spatial dataset from .sdf format to a .mif or .shp format. Include a projection or header file in the same folder directory as the .sdf file to correctly convert the file.
3. **Create a Batch File to Run the Utility** – Create a new text file in the same location as the .sdf file; the file must have the extension “.bat.” Enter the relevant command syntax to the batch file and double click to execute the model conversion.

The imported model will need to be trimmed so that the overbanks are modeled in 2D using TUFLOW and the channel remains in 1D and represented by ESTRY. The two components must then be linked together using Head External (HX) or Source External (SX) connections.

**Boundary Conditions**

GIS layers are used to define inputs for 1D boundary conditions. A range of boundary conditions can be applied, including inflow hydrographs and head-time boundaries. The 1D boundary condition layer can be applied directly to a cross section or structure by snapping to it. Regions can also be used to apply flow versus time boundaries and will equally distribute flow to all cells within the region.
Regions are established as polygons to specify the area of cells where the boundary is applied. It is not possible to assign both a flow type and water level type boundary to the same nodes.

Table 2-7 shows the specific 1D boundary conditions used in TUFLOW. Flow versus water level boundary conditions should be considered for model development.

<table>
<thead>
<tr>
<th>Boundary Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water level</td>
<td>Sinusoidal (tidal) water level</td>
</tr>
<tr>
<td>HQ</td>
<td>Water level (head) versus flow</td>
</tr>
<tr>
<td>HT</td>
<td>Water level (head) versus time</td>
</tr>
<tr>
<td>Flow</td>
<td>QC Constant flow</td>
</tr>
<tr>
<td>QH</td>
<td>Flow versus water level (head)</td>
</tr>
<tr>
<td>QT</td>
<td>Flow versus time</td>
</tr>
</tbody>
</table>

The 2D boundary conditions as well as the links between the 1D and 2D domains use a combination of one or multiple GIS layers, which may consist of polylines, lines, points, and regions. The boundary must intersect the cross-hairs of the cell, which extend from the mid sides of the cell, to be selected. The cross-hair selection approach only applies to polylines and lines and not points or polygons (regions). Only one boundary can be assigned to a cell from a single GIS layer. If other boundaries need to be assigned to a cell, these boundaries must be in separate GIS layers. Table 2-8 lists the 2D boundaries that can be assigned to cells in a TUFLOW model.

<table>
<thead>
<tr>
<th>Boundary Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water level</td>
<td>Link Two 2D Domains</td>
</tr>
<tr>
<td>HQ</td>
<td>Sinusoidal (Tidal) Water Level</td>
</tr>
<tr>
<td>HT</td>
<td>Water Level (Head) versus Flow</td>
</tr>
<tr>
<td>HX</td>
<td>Water Level (Head) versus Time</td>
</tr>
<tr>
<td>Flow</td>
<td>QC Constant Flow</td>
</tr>
<tr>
<td>QT</td>
<td>Flow versus Time</td>
</tr>
<tr>
<td>VT</td>
<td>Velocity versus Time</td>
</tr>
</tbody>
</table>

**1D/2D Linkages**

There are two types of 1D/2D link options available in TUFLOW. These options include HX and SX. Both options are discussed in detail below.

- **HX Boundary** – This boundary allows flow to enter or leave the 1D and 2D domains by calculating the head difference between them. The volume entering or leaving the 2D boundary is added or subtracted from the 1D domain. When the water level in the 1D node exceeds the 2D water level calculated in the cell center, flow enters the 2D domain and vice versa.
SX Boundary – The water level in the 1D node is determined based on the average water level along the 2D SX cells. Conversely, the water level in the 2D SX cell is determined based on the flow from the 1D node. Flow is proportioned via depth if multiple SX cells are connected to a single node. When using an SX boundary to connect a structure, the connected SX cell width must match the size of the structure.

2.2.3.3 Outputs

Several methods can be used to produce results from TUFLOW. The user must access the TUFLOW Control File and enter the command “Map Output Format ==.” The following options are used for this command:

- GIS Grid Format (.asc or .flt) – An ASCII file is recommended for MapInfo/Vertical Mapper users and a float file is recommended for ArcMap and QGIS users.
- SMS .dat Format – Used by SMS and the Crayfish QGIS plugin.
- SMS .xmdf Format – More advanced version of the .dat file. Contains all of the results in a single file output.
- WaterRIDE .wrb Format – Used by WaterRIDE.
- BlueKenue .t3 format – Used by BlueKenue.

The mapping results consist of time-varying depth, velocity, and WSEL grids. Users can toggle velocity arrows on these grids to identify flow patterns within the model. These can be viewed in QGIS using the Crayfish plugin.

2.3 1-Percent-Annual-Chance Flood Event Pilot Study

This 1-percent-annual-chance flood event pilot study simulated the theoretical 1-percent-annual-chance flood event and estimated the inundation WSELs and depths of this event.

The pilot study geography has two sets of available, existing 1-percent-annual-chance data: regulatory DFIRM data and recent BLE data. A 1-percent-annual-chance rainfall event simulation was performed for the pilot study using the three selected models. The simulation was done to compare the results to the two already established sets of 1 percent flood data.

The regulatory DFIRM study consists primarily of detailed modeling done in the 1980s and includes floodway analyses. The mapping has since been re-delineated using Light Detection and Ranging (LiDAR) data collected in 2008.

BLE studies are scalable (to a more detailed analysis), large-scale (typically HUC-8 watershed-based), highly automated studies that do not include modeling of structures. The purpose of a BLE study is to establish flood risk data in unmapped areas and identify and prioritize scoping and mitigation needs.

Being able to compare the results of the pilot study against established data was useful in assigning a level of credibility to the results of a particular model.
2.3.1 Pilot Geography

The requirements for the selection of a pilot geography included:

- Available BLE data
- Available effective or preliminary DFIRM data
- High flood risk/exposure area
- Occurrence of a landmark event

A portion of Montgomery County, TX, was selected as the pilot study location because it met the above requirements along with other factors. One of the other factors was that the area was impacted significantly by a recent, high-profile event—Hurricane Harvey in 2017 (DR-4332). This event has a significant amount and variety of validation data that will allow for thorough validation of the disaster response analysis results. The various sources of validation data available for the Hurricane Harvey event within the pilot geography footprint are gage records, inundation mapping data, high water marks (HWMs), Substantial Damage Estimates (SDEs), and National Flood Insurance Program (NFIP) claims records.

Several hydrologic data sources are also available within the pilot geography: flood frequency analysis, precipitation frequency estimates, Qualitative Precipitation Forecast (QPF) data, and real time gage data.

The pilot geography was used for both the 1-percent-annual-chance flood event pilot study and the rapid response use case analysis (see Section 2.4).

Figure 2-2 through Figure 2-4 display the extents of some of the data sources that are discussed.

2.3.2 Data Acquisition

The data acquired for the pilot study are described in the following subsections.

2.3.2.1 BLE Data

A 1D BLE study was completed for the East Fork San Jacinto HUC-8 watershed in 2017. The BLE database contains various data. The BLE hydrologic sub-basins file was used as the starting point for delineation of the hydrologic sub-basins for H&H modeling. The Compass team completed this BLE study and had this data readily available, but it can also be located on the FEMA Mapping Information platform (MIP) under Case Number 17-06-1112S.

2.3.2.2 Terrain

The terrain developed for the East Fork San Jacinto BLE study was used for modeling and mapping purposes in this task order. Five topographic datasets were used to develop a composite DTM for this terrain source. Only four of the datasets touched the pilot geography: 2008 Houston-Galveston Area Council (H-GAC) LiDAR, 2011 Texas Natural Resources Information System (TNRIS) LiDAR (for Austin, Grimes, and Walker Counties), 2011 Liberty County TNRIS LiDAR, and 2017 StratMap LiDAR. The H-GAC and StratMap LiDAR datasets cover the majority of the pilot geography footprint. The terrain can be located on the FEMA MIP under Case Number 17-06-1112S.
Figure 2-3: FIRM Coverage within Pilot Geography
Figure 2-4: Validation Data within Pilot Geography
2.3.2.3 Land Use Data
The National Land Cover Database (NLCD) is a seamless national dataset of land cover, percentage of developed imperviousness, and percentage of tree canopy. These data were used to develop a runoff Curve Number (CN) and roughness coefficients for modeling purposes. The current 2011 dataset can be downloaded from the Multi-Resolution Land Characteristics consortium website (https://www.mrlc.gov/data).

2.3.2.4 Soils Data
The U.S. Department of Agriculture (USDA) NRCS has published soil surveys since 1899. Soil surveys were used to help develop CN data for modeling purposes. The data can be downloaded from the USDA NRCS Soil Survey website (https://www.nrcs.usda.gov/wps/portal/nrcs/soilsurvey/soils/survey/state/).

2.3.2.5 Stream Gage Data
Stream gage data were used as part of the hydrologic analysis. Information was collected for gages 08071000 and 08070500 to develop inflow hydrographs within the pilot geography. The data can be collected from the USGS National Water Information System.

Regression parameter data are also needed for the hydrologic analysis. The USGS National Streamflow Statistics Program (https://water.usgs.gov/osw/programs/nss/pubs.html) can be used to develop the information without having to acquire the various parameter datasets. Therefore, these data were used but did not need to actually be collected.

2.3.3 Model Assumptions
The following assumptions were used to ensure a consistent modeling approach across the three models that were assessed:

- Because the existing BLE study is a 1D study, no data from the BLE models were directly incorporated into the pilot study models. However, the 1% peak flows from the BLE model were used to scale up the unit hydrographs developed at the two USGS streamflow gages.
- No structures were modeled unless a dam existed in the National Inventory of Dams within the pilot geography that was classified as a flood control structure. There are currently no such dams within the pilot geography.
- Catchment inflows were applied at the upstream extent of the contributing catchment area.
- Land cover input parameters were informed by data in the 2011 NLCD. For modeling purposes, there was no consideration of development post-2011.
- A 200-square-foot computational mesh size was assumed.
- Sediment transport and debris flow were not considered.

2.3.4 Hydrologic Approach
The existing BLE and regulatory DFIRM mapping was developed using steady-state, 1D H&H modeling. The hydrology inputs for the existing BLE mapping consisted of 1-percent-annual-chance peak discharges estimated using regional regression equations from Scientific Investigation Report (SIR)
2009-5087 (USGS, 2009). The models selected for the pilot assessments are dynamic, 2D models that require hydrologic inputs in the form of either inflow hydrographs at selected locations within the pilot geography or excess precipitation over the pilot geography. The regression equations mentioned provided only estimates of peak discharge. As a result, the existing BLE hydrology was not used as inputs.

The hydrology inputs used for the pilot flood simulation models consisted of estimated 1-percent-annual-chance inflow hydrographs based on the 1-percent-annual-chance peak discharges at selected external and internal boundary condition locations. Development of the inflow hydrographs required the following processes:

- Delineation of the pilot study area drainage sub-basins
- Estimation of the 1-percent-annual-chance peak discharges
- Development of inflow hydrographs for the 1-percent-annual-chance peak discharges

These processes are described in further detail in the following subsections.

2.3.4.1 Delineation of Study Area Drainage Sub-basins

The study area selected for evaluation was the Peach Creek – Caney Creek watershed (HUC 1204010301), which is in Region 12 Texas Gulf, Sub-region 1204 Galveston Bay-San Jacinto, Accounting Unit 120401 San Jacinto, and Cataloging Unit 12040103 East Fork San Jacinto, as defined in Federal Standards and Procedures for the National Watershed Boundary Dataset (WBD) (USGS and NRCS, 2013). The study area watershed encompasses 372 square miles and comprises 10 sub-basins that range in the drainage area from 23.1 to 49.7 square miles.

The 10 sub-basins were established by condensing the BLE sub-basins into larger contributing drainage areas for significant reaches (Figure 2-5). The final sub-basin resolution falls between the resolution scales of the HUC-12 and HUC-14 basins.

2.3.4.2 Estimation of the 1-Percent-Annual-Chance Peak Discharges

The 1-percent-annual-chance peak discharges for the sub-watersheds in the Peach Creek – Caney Creek watershed were estimated using the regional regression equations presented in USGS SIR 2009–5087 (USGS, 2009). The regression equations that include the OmegaEM adjustment factor as an explanatory variable were used to estimate the 1-percent-annual-chance peak discharges. In addition to OmegaEM, the explanatory variables used in the regression equation for the 1-percent-annual-chance peak discharge were mean annual precipitation in inches, drainage area in square miles, and dimensionless main channel slope. Table 2-9 shows the estimated peak discharges for each sub-watershed.
**Figure 2-5: Hydrologic Sub-basins Used for Pilot Study**

**Table 2-9: Estimated 1-Percent-Annual-Chance Peak Discharges for Pilot Study**

<table>
<thead>
<tr>
<th>Sub-Basin</th>
<th>1-Percent-Annual-Chance Peak Flow (cfs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1_Caney_Creek_1</td>
<td>2,912</td>
</tr>
<tr>
<td>1_Caney_Creek_2</td>
<td>1,922</td>
</tr>
<tr>
<td>1_Caney_Creek_3</td>
<td>7,984</td>
</tr>
<tr>
<td>1_Caney_Creek_4</td>
<td>5,365</td>
</tr>
<tr>
<td>1_Caney_Creek_5</td>
<td>3,149</td>
</tr>
<tr>
<td>1_Dry_Creek</td>
<td>12,844</td>
</tr>
<tr>
<td>1_Little_Caney_Creek_No2</td>
<td>14,064</td>
</tr>
<tr>
<td>1_McRae_Creek</td>
<td>10,409</td>
</tr>
<tr>
<td>1_Spring_Branch</td>
<td>17,992</td>
</tr>
<tr>
<td>2_Jayhawker_Creek</td>
<td>14,121</td>
</tr>
</tbody>
</table>

cfs = cubic feet per second
2.3.4.3 Development of 1-Percent-Annual-Chance Inflow Hydrographs

The models selected for this analysis require inflow hydrographs as the hydrologic inputs. The inflow hydrographs were estimated by developing average dimensionless hydrographs based on large discharge events observed at two USGS stream gages within the Peach Creek – Caney Creek watershed: Peach Creek at Splendora, TX (08071000), and Caney Creek near Splendora, TX (08070500). The Peach Creek gage drains a total watershed area of 117 square miles, and the Caney Creek gage drains 105 square miles.

Observed peak discharge events that occurred in July 2001, May 2016, and August–September 2017 (Hurricane Harvey) were selected because these events were single peak events with large peak discharges. The discharges from the selected events were normalized by dividing the discharge at each time step (Q) by the peak discharge (Qp). The normalized discharge in terms of Q/Qp was then applied to the computed 1-percent-annual-chance discharge determined for each desired discharge input location.

2.3.5 Hydraulic Modeling Approach

The hydraulic modeling approach for the 1-percent-annual-chance flood event pilot study consisted of the use of an established terrain dataset, land use data, and hydrologic inputs. The hydrologic inputs were in the form of inflow hydrographs or rainfall excess that was spatially distributed over the Caney-Peach Creek watershed within the pilot geography footprint.

The approach used to develop the 1-percent-annual-chance flood event models consisted of the following steps:

1. 2D domain was prepared: Terrain and elevation data in raster format with appropriate vertical and horizontal datum (North American Vertical Datum of 1988 [NAVD88] and North American Datum [NAD] 1983 State Plane Texas Central) were developed from the 10-foot LiDAR dataset established as part of the BLE study using Esri ArcGIS tools. A fixed grid computational mesh was developed with a 200-foot cell resolution, unless otherwise noted.

2. Manning’s n-values were assigned: Land use for the pilot study area was informed by the 2011 NLCD dataset. Manning’s n roughness values for the given land classifications were assigned over the 2D pilot study area domain. Tables of values for the Manning’s coefficients are provided in the respective subsections for each model.

3. Hydrologic inputs were incorporated: The rain-on-grid (pluvial) analysis methodology was used. HEC-HMS was used to develop rainfall excess at a temporal distribution of 15 minutes for the Peach Creek – Caney Creek watershed. The 24-hour and 1-percent-annual-chance recurrence interval precipitation grid was obtained from NOAA Atlas 14 (U.S. Department of Commerce, 2018) partial duration series. The rainfall excess was assumed as uniform rainfall depth that occurred spatially over the entire watershed. Figure 2-6 shows the excess rainfall depth temporal distribution used for the analysis.
4. Boundary conditions were set up: The downstream study limit is along the boundary line between Montgomery County and Harris County. Reasonable model adjustments were made to tie in to the regulatory FIRM WSEL of 65.2 feet obtained at the White Oak Creek outfall. This elevation is the governing elevation at the confluence of Caney Creek and White Oak Creek and, therefore, was the WSEL that was tied in to.

5. Model simulations were run.

6. Model outputs were developed: A 1-percent-annual-chance WSEL and depth raster were produced for each model.

Additional details regarding the methodology unique to each model are provided in their respective sub-sections below.

2.3.5.1 FLO-2D

In the selection of the grid element size, the model resolution had to be balanced with the total number of grid cells. Increasing the resolution increases the total number of grid cells, thereby significantly increasing model computation time. Considering the computer configuration used for FLO-2D in this study, a grid element size of 300 feet was used, which is different from what was used in the other two modeling software programs. This was done to create reasonable simulation run times that allowed for multiple iterations within 48 hours. The given elevation points were imported to the FLO-2D GDS, and grid element elevations were interpolated and assigned.

Manning’s n roughness coverage was developed using the values recommended in *Open-Channel Hydraulics* (Chow, 1959) for given land use classifications. Table 2-10 shows the recommended roughness matrix that was used for the study area.
### Table 2-10: Land Use/Manning’s N-Value Matrix Used in the FLO-2D Model

<table>
<thead>
<tr>
<th>Land Cover Layer Geometry Overrides</th>
<th>Land Cover Layer</th>
<th>Default Manning’s n</th>
<th>Base Manning’s n</th>
<th>Main Channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 no data</td>
<td></td>
<td>0.06</td>
<td>0.04</td>
<td></td>
</tr>
<tr>
<td>2 barren land rock/sand/clay</td>
<td></td>
<td>0.04</td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>3 cultivated crops</td>
<td></td>
<td>0.06</td>
<td>0.06</td>
<td>0.04</td>
</tr>
<tr>
<td>4 deciduous forest</td>
<td></td>
<td>0.1</td>
<td>0.1</td>
<td>0.04</td>
</tr>
<tr>
<td>5 developed, high intensity</td>
<td></td>
<td>0.15</td>
<td>0.15</td>
<td>0.04</td>
</tr>
<tr>
<td>6 developed, low intensity</td>
<td></td>
<td>0.1</td>
<td>0.1</td>
<td>0.04</td>
</tr>
<tr>
<td>7 developed, medium intensity</td>
<td></td>
<td>0.08</td>
<td>0.08</td>
<td>0.04</td>
</tr>
<tr>
<td>8 developed, open space</td>
<td></td>
<td>0.04</td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>9 emergent herbaceous wetlands</td>
<td></td>
<td>0.08</td>
<td>0.08</td>
<td>0.04</td>
</tr>
<tr>
<td>10 evergreen forest</td>
<td></td>
<td>0.12</td>
<td>0.12</td>
<td>0.04</td>
</tr>
<tr>
<td>11 grassland/herbaceous</td>
<td></td>
<td>0.045</td>
<td>0.045</td>
<td>0.04</td>
</tr>
<tr>
<td>12 mixed forest</td>
<td></td>
<td>0.08</td>
<td>0.08</td>
<td>0.04</td>
</tr>
<tr>
<td>13 open water</td>
<td></td>
<td>0.035</td>
<td>0.035</td>
<td>0.04</td>
</tr>
<tr>
<td>14 pasture/hay</td>
<td></td>
<td>0.06</td>
<td>0.06</td>
<td>0.04</td>
</tr>
<tr>
<td>15 shrub/scrub</td>
<td></td>
<td>0.08</td>
<td>0.08</td>
<td>0.04</td>
</tr>
<tr>
<td>16 woody wetlands</td>
<td></td>
<td>0.12</td>
<td>0.12</td>
<td>0.04</td>
</tr>
</tbody>
</table>

A rainfall distribution must be converted to an ASCII format file (rain.dat) and shown as a cumulative percentage of the total storm that initiates at the time interval. Therefore, the developed excess rainfall depth distributions were converted from an MS Excel table to an ASCII format and then imported into the FLO-2D model.

To achieve an acceptable tie-in to the regulatory effective WSEL, two cross sections were created near the downstream study limit to obtain simulated flood hydrographs at these locations. The simulation times were 48 hours. The simulation times are longer than the time to peak discharge at the downstream study limit and allow the simulated flood peaks to pass through the entire study reach. This approach varies from the normal depth conditions used in the other two models.

The FLO-2D model was built with the default tolerance values.

#### 2.3.5.2 HEC-RAS 2D

The current version of HEC-RAS 5.0.5 was used for this analysis.

The 2D flow area was created with a maximum cell center spacing of 200 feet. Cell faces generally followed break lines, connection lines, and external boundary lines where applicable. All other cells were 200-foot squares.

Manning’s roughness values based on land use for the HEC-RAS 2D model were from Chow (1959), as they were for the FLO-2D analysis.
An additional process included in the HEC-RAS 2D modeling was the delineation of break lines along the crown of prominent linear features.

In addition to the rain-on-grid approach, inflow hydrographs were also used based on dimensionless hydrographs developed at the two USGS gaging stations within the pilot footprint. The dimensionless hydrographs were scaled-up based on the peak flow values obtained from the existing BLE study at several tributaries. The inflow hydrographs have been applied at the upstream extent of the contributing catchment area. Section 2.3.4 details the development of the inflow hydrographs for the respective catchment area. Figure 2-7 shows the inflow hydrographs loading locations within the pilot study area.
In addition to the normal depth boundary condition setup, rating curve approaches were considered an alternative for determining the downstream boundary condition for the pluvial analysis of the pilot study with the goal of tying-in to the regulatory effective WSEL at the downstream limit of the study area.

Several model iterations were required to achieve an appropriate tie-in. Similar elevations were achieved approximately 20 hours from the start of the simulation as shown in Figure 2-8.

A computational time step of 30 seconds was used. The HEC-RAS default unsteady computation options and tolerances were used, including the diffusion wave equation for this analysis. The model simulation outputs were extracted at the maximum flow values using RAS Mapper.

2.3.5.3 TUFlow

TUFlow Version 2018-03-AC was used for the analysis. To establish the 2D grid, the 2D domain was defined through a list of commands in the .tgc files. The extent of the active 2D domain was defined using the “Read GIS Code ==” command, elevation data were defined using the “Read Grid Zpts ==”
command, and spatial variations in roughness were defined using the “Read Grid Mat ==” command. The grid size of 200 feet was specified using the “Cell Size == 200” command.

Manning’s n roughness coefficients were informed by land uses defining the percentage runoff where direct rainfall was applied. The roughness coefficients used in the TUFLOW model come from the same data source used for the HEC-RAS 2D study (Table 2-11).

### Table 2-11: Land Use/Manning’s N-Value Matrix Used in HEC-RAS 2D Model

<table>
<thead>
<tr>
<th>NLCD Value(1)</th>
<th>Normal Manning’s n Value</th>
<th>Allowable Range of n Values</th>
<th>Land Cover Definition</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>0.040</td>
<td>0.025–0.05</td>
<td>Open Water. All areas of open water, generally with less than 25% cover or vegetation or soil.</td>
<td>Table 5-6 D-1.a.3(2)</td>
</tr>
<tr>
<td>21</td>
<td>0.040</td>
<td>0.03–0.05</td>
<td>Developed, Open Space. Includes areas with a mixture of some constructed materials, but mostly vegetation in the form of lawn grasses. Impervious surfaces account for less than 20% of the total cover. These areas most commonly include large-lot, single-family housing units, parks, golf courses, and vegetation planted in developed settings for recreation, erosion control, or aesthetic purposes.</td>
<td>Figure 3-19[3]</td>
</tr>
<tr>
<td>22</td>
<td>0.100</td>
<td>0.08–0.12</td>
<td>Developed, Low Intensity. Includes areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 20–49% of the total cover. These areas most commonly include single-family housing units.</td>
<td>Figure 3-19[3]</td>
</tr>
<tr>
<td>23</td>
<td>0.080</td>
<td>0.06–0.14</td>
<td>Developed, Medium Intensity. Includes areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 50–79% of the total cover. These areas most commonly include single-family housing units.</td>
<td>Figure 3-19[3]</td>
</tr>
<tr>
<td>24</td>
<td>0.150</td>
<td>0.12–0.20</td>
<td>Developed, High Intensity. Includes highly developed areas where people reside or work in high numbers. Examples include apartment complexes, row houses, and commercial/industrial. Impervious surfaces account for 80–100% of the total cover.</td>
<td>Figure 3-19[3]</td>
</tr>
<tr>
<td>31</td>
<td>0.025</td>
<td>0.023–0.030</td>
<td>Barren Land (Rock/Sand/Clay). Barren areas of bedrock, desert pavement, scarps, talus, slides, volcanic material, glacial debris, sand dunes, strip mines, gravel pits, and other accumulations of earthen material. Generally, vegetation accounts for less than 15% of the total cover.</td>
<td>Table 5-6 C.b.1(2)</td>
</tr>
<tr>
<td>41</td>
<td>0.160</td>
<td>0.10–0.16</td>
<td>Deciduous Forest. Areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. More than 75% of the tree species shed foliage simultaneously in response to seasonal change.</td>
<td>Table 5-6 D-2.d.5 Max. Debris(2)</td>
</tr>
<tr>
<td>42</td>
<td>0.160</td>
<td>0.10–0.16</td>
<td>Evergreen Forest. Areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. More than 75% of the tree species maintain their leaves all year. Canopy is never without green foliage.</td>
<td>Table 5-6 D-2.d.5 Max. Debris(2)</td>
</tr>
<tr>
<td>43</td>
<td>0.160</td>
<td>0.10–0.16</td>
<td>Mixed Forest. Areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. Neither deciduous nor evergreen species are greater than 75% of total tree cover.</td>
<td>Table 5-6 D-2.d.5 Max. Debris(2)</td>
</tr>
</tbody>
</table>
**Table 5-6 D-2.c.5**

<table>
<thead>
<tr>
<th>NLCD Value</th>
<th>Normal Manning's n Value</th>
<th>Allowable Range of n Values</th>
<th>Land Cover Definition</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>52</td>
<td>0.100</td>
<td>0.07—0.16</td>
<td>Shrub/Scrub. Areas dominated by shrubs; less than 5 meters tall with shrub canopy typically greater than 20% of total vegetation. This class includes true shrubs, young trees in an early successional stage, or trees stunted from environmental conditions.</td>
<td>Table 5-6 D-2.c.5(2)</td>
</tr>
<tr>
<td>71</td>
<td>0.035</td>
<td>0.025–0.050</td>
<td>Grassland/Herbaceous. Areas dominated by grammanoid or herbaceous vegetation, generally greater than 80% of total vegetation. These areas are not subject to intensive management such as tilling, but can be utilized for grazing.</td>
<td>Table 5-6 D-2.a.2(2)</td>
</tr>
<tr>
<td>81</td>
<td>0.030</td>
<td>0.025–0.050</td>
<td>Pasture/Hay. Areas of grasses, legumes, or grass-legume mixtures planted for livestock grazing or the production of seed or hay crops, typically on a perennial cycle. Pasture/hay vegetation accounts for greater than 20% of total vegetation.</td>
<td>Table 5-6 D-2.a.1(2)</td>
</tr>
<tr>
<td>82</td>
<td>0.035</td>
<td>0.025–0.050</td>
<td>Cultivated Crops. Areas used for the production of annual crops, such as corn, soybeans, vegetables, tobacco, and cotton, and also perennial woody crops such as orchards and vineyards. Crop vegetation accounts for greater than 20% of total vegetation. This class also includes all land being actively tilled.</td>
<td>Table 5-6 D-2.b.2(2)</td>
</tr>
<tr>
<td>90</td>
<td>0.120</td>
<td>0.045–0.15</td>
<td>Woody Wetlands. Areas where forest or shrub land vegetation accounts for greater than 20% of substrate or substrate is periodically saturated with or covered with water.</td>
<td>Table 5-6 D-1.a.8(2)</td>
</tr>
<tr>
<td>95</td>
<td>0.070</td>
<td>0.05–0.085</td>
<td>Emergent Herbaceous Wetlands. Areas where perennial herbaceous vegetation accounts for greater than 80% of vegetative cover and the soil or substrate is periodically saturated with or covered with water.</td>
<td>Table 5-6 D-1.a.7(2)</td>
</tr>
</tbody>
</table>

1. National Land Cover Database (USGS, 2011)
2. Open-Channel Hydraulics (Chow, 1959)

Direct rainfall and normal depth boundary conditions were used for the analysis. Both were specified in the TUFLOW Boundary Control file. Direct rainfall was applied using the “Read GIS RF ==” command across the entire active 2D domain by reading in a shapefile polygon linked to a boundary condition database containing the rainfall hyetograph.

Normal depth boundary conditions were applied using the “Read GIS BC ==” command. The friction slope was fixed through several iterations of model runs so that the resulting WSEL tied in to the regulatory effective WSEL at the downstream study limit properly. Figure 2-9 shows the extent of the 2D domain and location of the downstream boundaries.

An adaptive time-step approach was used to maintain unconditional stability and a Courant number of less than 1.0. The initial simulation used a time step of 1 second. All subsequent time steps were automatically calculated using the adaptive time-step approach governed by a range of control number criteria (including Courant, Shallow Wave Celerity, and Diffusion numbers). The simulation was run for 100 hours.
2.4 Rapid Response Use Case Analysis

The main objective of the rapid response use case analysis was to simulate real-time conditions of an impending event and to test the efficiency and credibility of the rapid modeling and mapping approach on the three selected flood simulation models. To accomplish this, a well-documented historic event, Hurricane Harvey (DR-4332), served as the baseline. This event was modeled as if it had not yet occurred so that the results could be compared against known Hurricane Harvey data collected and developed post-disaster. This comparison allowed Compass to assess the validity of the results of each model tested.
2.4.1 Data Acquisition

The same terrain, land use, soils, and stream gage data sources described in Section 2.3.2 were used for this pilot study. Additional data collected for the purpose of this task are described in the following subsections.

2.4.1.1 Forecast Data

The NWS Weather Prediction Center (WPC) produces QPF data nationwide. QPF data are available for a 7-day forecast period. Real-time stream gage data are another potential data option to model a forecasted event. Real-time gage data may also be available for an area, but will not be as widely available as QPF data, which is why QPF data are recommended. QPF data can be obtained from the NWS WPC website (https://www.wpc.ncep.noaa.gov/qpf/qpf2.shtml). For the purposes of this project, archived forecast data were needed because the simulation was being run for an event that had passed using forecasted precipitation. Compass submitted a request to the West Gulf River Forecast Center to obtain access to an unadvertised online archive of QPF data.

2.4.1.2 Hydrologic Sub-basins

The BLE sub-basins were merged to define larger hydrologic sub-basins for this pilot study. If such a dataset is not readily available, then another readily-available set of basins like the USGS HUC Watersheds could be used (HUC-12 or HUC-14 size recommended). These data can be collected from the USGS Water Resources website (https://water.usgs.gov/GIS/huc.html).

2.4.2 Approach

The model assumptions for this pilot study are outlined in Section 2.3.3. An additional assumption was applied: All disaster response models assumed normal depth as the boundary conditions.

Four model runs were completed for each of the three models. For the purposes of this analysis, it was assumed that Compass was tasked with this effort on August 23, 2017, at 12:00 am (referred to as “Time 0:00” in report). Each model run used forecast data published 6 hours in advance of the last dataset used. So, the first model run used forecast data available at Time 0:00, the next model run used forecast data that was issued at Time 6:00, and so on. This approach was used to determine how significantly the results changed based on updated forecasts within a short time frame.

A WSEL and depth raster were produced for each model run (four per model). Areas of 0.5-foot flooding depth or less were removed from all final mapping rasters. Flooding of this depth can generally be considered minor and removal of such areas simplifies interpretation of the mapping results by FEMA and the disaster response community, especially in a high-stress situation such as an impending flood disaster.
2.4.3 Hydrology

The rapid response use case analysis tests the efficiency and credibility of forecasting potential inundation areas in advance of major storms using forecasted precipitation data. For the purposes of this analysis, it was assumed that Compass was tasked with this effort on August 23, 2017, at 12:00 am.

2.4.3.1 Methodology

The hydrology inputs required for the rapid response use case analysis consist of a time-series of excess precipitation over the pilot geography. The excess precipitation was determined based on forecasted precipitation depths, derived from the QPF data, for the Hurricane Harvey event.

Forecasted precipitation was used for this process because the QPF data are available nationwide for a 7-day forecast period. Stream gage data may be available for some potential study areas; however, forecasted discharge and elevation data are not as widely available as the QPF data and where available, the forecasted discharge and elevation data will be based on the QPF data or, in some cases, on regionally or locally derived precipitation forecasts.

The hydrology inputs were determined by leveraging the delineation of the study area sub-basins that were produced for the 1-percent-annual-chance flood event pilot study models (see Section 2.3.4). Determination of the hydrology inputs for this modeling also included the following processes:

- Development of forecast storm precipitation inputs
- Development of a hydrologic model for the study area
- Determination of the excess precipitation

Development of Forecast Precipitation Inputs

Estimation of the potential volume and distribution of precipitation associated with an approaching storm event uses the QPF data.

The QPF presents the amount of liquid precipitation that is forecasted to fall in a defined period of time—7 days from the issue time. The forecasted precipitation is provided in 6-hour increments for the initial 3 days from the forecast issue date and time, and subsequently the data are provided in 48-hour increments for days 4 to 7 from the forecast issue date and time. The 6-hour increment forecasts are updated every 6 hours (at 0000, 0600, 1200, and 1800 Greenwich Mean Time [GMT]) and the 48-hour increment forecasts are updated every 12 hours (at 0000 and 1200 GMT).

Downloaded QPF data were provided as a GRIB (Gridded Binary or General Regularly distributed Information in Binary form) file and used the following naming convention: p##m_yyyyymmddhhf###.grb. The “p##m” prefix is the duration of the forecast period. So, p06m represents a product in a 6-hour block of time and p48m represents a product in a 48-hour block. “Yyyyymmddhh” is the year (yyyy), month (mm), day (dd), and hour (hh) the product was created (product issuance date/time). Hour is referenced to GMT or Zulu time. Products were created on a 00, 06, 12, and 18 Zulu cycle daily. The “###” is the forecast period in hours from the issuance date/time. This is a relative (not absolute) reference representing the period end time in the future from the issuance date/time.
Table 2-12 illustrates the file structure for the forecasted Hurricane Harvey data and indicates that the archived QPF files provided forecast precipitation depths for the period from the forecast issue date to 7 days in the future.

Table 2-12: Archived QPF Files Used to Develop Excess Precipitation for Hurricane Harvey

<table>
<thead>
<tr>
<th>Filename</th>
<th>Issue Time</th>
<th>Ending Offset (hr)</th>
<th>Duration (hr)</th>
<th>Start Date and Time</th>
<th>End Date and Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>p06m_2017082300f006.grb</td>
<td>8/23/17 0:00</td>
<td>006</td>
<td>6</td>
<td>8/23/17 0:00</td>
<td>8/23/17 6:00</td>
</tr>
<tr>
<td>p06m_2017082300f012.grb</td>
<td>8/23/17 0:00</td>
<td>012</td>
<td>6</td>
<td>8/23/17 6:00</td>
<td>8/23/17 12:00</td>
</tr>
<tr>
<td>p06m_2017082300f018.grb</td>
<td>8/23/17 0:00</td>
<td>018</td>
<td>6</td>
<td>8/23/17 12:00</td>
<td>8/23/17 18:00</td>
</tr>
<tr>
<td>p06m_2017082300f024.grb</td>
<td>8/23/17 0:00</td>
<td>024</td>
<td>6</td>
<td>8/23/17 18:00</td>
<td>8/23/17 0:00</td>
</tr>
<tr>
<td>p06m_2017082300f030.grb</td>
<td>8/23/17 0:00</td>
<td>030</td>
<td>6</td>
<td>8/24/17 0:00</td>
<td>8/24/17 6:00</td>
</tr>
<tr>
<td>p06m_2017082300f036.grb</td>
<td>8/23/17 0:00</td>
<td>036</td>
<td>6</td>
<td>8/24/17 6:00</td>
<td>8/24/17 12:00</td>
</tr>
<tr>
<td>p06m_2017082300f042.grb</td>
<td>8/23/17 0:00</td>
<td>042</td>
<td>6</td>
<td>8/24/17 12:00</td>
<td>8/24/17 18:00</td>
</tr>
<tr>
<td>p06m_2017082300f048.grb</td>
<td>8/23/17 0:00</td>
<td>048</td>
<td>6</td>
<td>8/24/17 18:00</td>
<td>8/25/17 0:00</td>
</tr>
<tr>
<td>p06m_2017082300f054.grb</td>
<td>8/23/17 0:00</td>
<td>054</td>
<td>6</td>
<td>8/25/17 0:00</td>
<td>8/25/17 6:00</td>
</tr>
<tr>
<td>p06m_2017082300f060.grb</td>
<td>8/23/17 0:00</td>
<td>060</td>
<td>6</td>
<td>8/25/17 6:00</td>
<td>8/25/17 12:00</td>
</tr>
<tr>
<td>p06m_2017082300f066.grb</td>
<td>8/23/17 0:00</td>
<td>066</td>
<td>6</td>
<td>8/25/17 12:00</td>
<td>8/25/17 18:00</td>
</tr>
<tr>
<td>p06m_2017082300f072.grb</td>
<td>8/23/17 0:00</td>
<td>072</td>
<td>6</td>
<td>8/25/17 18:00</td>
<td>8/26/17 0:00</td>
</tr>
<tr>
<td>p06m_2017082300f078.grb</td>
<td>8/23/17 0:00</td>
<td>078</td>
<td>6</td>
<td>8/26/17 0:00</td>
<td>8/26/17 6:00</td>
</tr>
<tr>
<td>p06m_2017082300f084.grb</td>
<td>8/23/17 0:00</td>
<td>084</td>
<td>6</td>
<td>8/26/17 6:00</td>
<td>8/26/17 12:00</td>
</tr>
<tr>
<td>p48m_2017082300f120.grb</td>
<td>8/23/17 0:00</td>
<td>120</td>
<td>48</td>
<td>8/27/17 0:00</td>
<td>8/28/17 0:00</td>
</tr>
<tr>
<td>p48m_2017082300f168.grb</td>
<td>8/23/17 0:00</td>
<td>168</td>
<td>48</td>
<td>8/29/17 0:00</td>
<td>8/30/17 0:00</td>
</tr>
<tr>
<td>p48m_2017082312f120.grb</td>
<td>8/23/17 12:00</td>
<td>120</td>
<td>48</td>
<td>8/27/17 12:00</td>
<td>8/28/17 12:00</td>
</tr>
<tr>
<td>p48m_2017082312f168.grb</td>
<td>8/23/17 12:00</td>
<td>168</td>
<td>48</td>
<td>8/28/17 12:00</td>
<td>8/30/17 12:00</td>
</tr>
</tbody>
</table>
The spatial data associated with each GRIB file contain a grid size of 2,539.7 x 2,539.7 meters. Each cell contains a forecast precipitation value in tenths of an inch. For this effort, the mean precipitation value for the entire HUC-8 watershed was needed.

To calculate the mean precipitation for the study area using the GRIB files, a raster analysis procedure was developed using zonal statistical tools. A detailed description of the procedure is provided in Appendix B.

The zonal statistical process described in Appendix B results in individual output files similar to Figure 2-10. As shown, the process provides minimum, maximum, and mean precipitation values and some standard statistical results. For the file shown in Figure 2-10, the mean precipitation value is 46.74 (tenths of an inch), or 4.67 inches of precipitation for the period of 8/29/2017 00:00 to 8/31/2017 00:00.

Because the QPFs are updated every 6 hours, they extend the projected data 6 hours further into the future with each update. Figure 2-11 illustrates the QPF precipitation values for the entire set of QPF files generated on August 23, 2017. As shown, the QPF projects associated with the 12- and 18-hour datasets estimated greater incremental precipitation values than the 00- and 06-hour files.
Development of Study Area Hydrologic Model

To conduct the rapid response modeling exercise, an analysis using the QPF precipitation data must be performed. This process starts with the identification of the study area. For this project the study area was designated as the Peach Creek – Caney Creek watershed.

The hydrologic modeling program, HEC-HMS, version 4.2, was used to estimate the excess precipitation. Within the HEC-HMS environment, the Soil Conservation Service (SCS) CN method was used to calculate losses and define excess precipitation for the model study area. A single basin model was used to simulate the entire Peach Creek – Caney Creek watershed. To efficiently develop the HEC-HMS model to meet the time constraint required, the modeling effort used datasets readily available for the entire continental United States, the NLCD and the NRCS soils data.

The land cover usage from the NLCD was overlaid with the Hydrologic Soil Group data from the NRCS to create a spatial distribution of the CN. The assignment of the CN was based on the Land Use-Soils-CN Matrix shown in Table 2-13. For the hydrologic model, a single CN was used to represent the entire watershed, so a weighted average CN was estimated.

<table>
<thead>
<tr>
<th>NLCD LU_GridCode</th>
<th>NLCD Land Use Description</th>
<th>CN by Hydrologic Soil Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>Open Water</td>
<td>99 99 99 99</td>
</tr>
<tr>
<td>21</td>
<td>Developed Open Space</td>
<td>49 69 79 84</td>
</tr>
<tr>
<td>22</td>
<td>Developed Low Intensity</td>
<td>61 75 83 87</td>
</tr>
<tr>
<td>23</td>
<td>Developed Medium Intensity</td>
<td>81 88 91 93</td>
</tr>
<tr>
<td>24</td>
<td>Developed High Intensity</td>
<td>89 92 94 95</td>
</tr>
<tr>
<td>31</td>
<td>Barren Land</td>
<td>39 61 74 80</td>
</tr>
<tr>
<td>41</td>
<td>Deciduous Forest</td>
<td>30 55 70 77</td>
</tr>
<tr>
<td>42</td>
<td>Evergreen Forest</td>
<td>30 55 70 77</td>
</tr>
<tr>
<td>43</td>
<td>Mixed Forest</td>
<td>30 55 70 77</td>
</tr>
<tr>
<td>52</td>
<td>Shrub Scrub</td>
<td>30 48 65 73</td>
</tr>
<tr>
<td>71</td>
<td>Herbaceous</td>
<td>49 62 74 85</td>
</tr>
<tr>
<td>81</td>
<td>Hay Pasture</td>
<td>39 61 74 84</td>
</tr>
<tr>
<td>82</td>
<td>Cultivated Crops</td>
<td>51 67 76 80</td>
</tr>
<tr>
<td>90</td>
<td>Woody Wetlands</td>
<td>72 80 87 93</td>
</tr>
<tr>
<td>95</td>
<td>Emergent Herbaceous Wetlands</td>
<td>72 80 87 93</td>
</tr>
</tbody>
</table>

CN = Curve Number  
LU = land use  
NLCD = National Land Cover Database
**Estimation of Excess Precipitation**

The final step results in an excess precipitation time series to be used in the selected hydraulic flood simulation models. Temporal distribution of rainfall totals used to estimate the excess precipitation was based on the data present in the QPF files.

The precipitation data provided from the QPF files was used to create a cumulative precipitation time series for use in the HEC-HMS model. Using the totals for each time given in the QPF data, hourly increments were interpolated to create continuous precipitation distribution. Figure 2-12 illustrates the cumulative precipitation time series established using the 00-hour QPF data. This procedure was duplicated for each of the four QPF datasets developed on August 23, 2017.

![Figure 2-12: Cumulative Precipitation for Hurricane Harvey from QPF Files](image)

The HEC-HMS hydrologic model was run using the cumulative precipitation data, resulting in an excess precipitation time series. Figure 2-13 illustrates the hydrologic model results for the study area. As shown in the top portion of the figure, the dark blue area is the precipitation being applied to the study area. The red areas represent the precipitation that is infiltrated into the soil. The difference between the two datasets is the excess precipitation.

Figure 2-14 contains the Excess Precipitation time series for the four August 23, 2017, QPFs developed for this assessment. Each time series is shifted 6 hours, reflecting the time the dataset was created.

Once the HEC-HMS is created, updating the model to reflect new information related to an approaching storm event only requires the development of the QPF precipitation data. The other parameters in the HEC-HMS model can remain constant.
2.4.3.2 Process Overview

The steps required to complete the hydrologic portion of this process are as follows:

1. Acquire data (hydro sub-basins, land use data, soils data, QPF data)
2. Process data (QPF data to excess precipitation time-series, land use and soils data to calculate CN)
3. Set up HEC-HMS model
4. Run HEC-HMS model
5. Process HEC-HMS outputs to excess precipitation for use in hydraulic model
6. Acquire data (updated QPF data)
7. Process data (QPF data to excess precipitation time-series)
8. Run HEC-HMS
9. Process HEC-HMS outputs to excess precipitation for use in hydraulic model
10. Repeat steps 6 through 9 as time allows

2.4.3.3 Time-Series Matrix
Some of the tasks included in the hydrologic portion of this process can occur in parallel affecting the overall time-series of the task. Updated QPF data are available every 6 hours starting at 0:00 GMT. Figure 2-15 displays the time-series process for the hydrologic steps taking both of these factors into consideration. Because the pilot geography is approximately half of Montgomery County, TX, conservative estimates of time were applied to sub-tasks to account for at least a countywide assessment.

2.4.4 Model Application
The following sections provide details on the computing configurations used for these model runs, an overview of the process for each model, and a time-series matrix that provides an outline of when model outputs are available within the disaster response time frame of 48 hours.

As previously mentioned, the BLE study available in the pilot geography was a 1D study. This prevented any direct use of geometry and model inputs from the BLE model. In locations where 2D BLE models are available, there is a potential 1- to 2-hour time savings to be gained within the data acquisition and model setup for each model. Overall though, this time savings does not allow for additional model iterations as it depends on the availability of updated forecast data.

2.4.4.1 FLO-2D
The following sections discuss the specific computing configuration, provide an outline of the modeling process, and present a time-series flow chart outlining what outputs are available and at what time when using the FLO-2D model.

Computing Configuration
The simulations for this analysis were performed using the following computer configurations:

- Dell Precision 7920 XL Tower
- Intel Xeon Gold 6134 3.2G, 8C/16T, 10.4GT/s 2UPI, 24.75M Cache, Turbo, HT (130W) DDR4-2666
- NVIDIA Quadro P600 2GB, 4 mDP, (7X20T)
Figure 2-15: Time-Series Chart of Hydrologic Process

*This process can be repeated at Hours 12, 16, 18, 24, 30, and 36. This would produce updated hydrologic inputs to begin an updated hydraulic simulation at Hours 15.5, 19.5, 21.5, 27.5, 33.5, and 39.5.
- 64 GB (4x16GB) 2666 MHz DDR4 RDIMM ECC
- MegaRAID SAS 9440-8i 12 Gb/s PCIe SATA/SAS controller -SW RAID 0, 1, 5, 10
- 3.5" 2TB 7200rpm SATA Hard Drive

A 300-foot computational grid size was selected for this model to produce results in an adequate time frame for use in rapid response modeling using the high-resolution terrain source.

Process Overview

Any data acquired for the hydrologic process that are also needed for the hydraulic process have been excluded from this general overview. The steps required to complete the hydraulic portion of this process using FLO-2D are as follows:

1. Acquire data (terrain data)
2. Set up FLO-2D model (model simulation period must be adjusted to be at least 2 hours after the time to peak discharge at the downstream limit)
3. Process data (terrain and land use to determine roughness coefficients data, excess precipitation hyetograph converted to an ASCII format with units of time and precipitation depth in hours and inches, respectively)
4. Run FLO-2D model
5. Resolve instability issues within the model
6. Re-run FLO-2D model (if Step 5 is required)
7. Process results using post-processor program, MAPPER
8. Convert MAPPER-produced outputs to rasters
9. Perform raster cleanup
10. Repeat steps 3 through 9 as time allows

Time-Series Matrix

Some of the tasks included in the hydraulic portion of this process can occur in parallel affecting the overall time-series of the task. The overall time-series for this model incorporates the hydrologic process time-series (as shown in Section 2.4.3.3), which drives the timing of updated iterations due to the availability of updated forecast data. Because the pilot geography is approximately half of Montgomery County, TX, conservative estimates of time were applied to sub-tasks to account for at least a countywide assessment. Model instability is assumed in this time-series (Figure 2-16) to be conservative as well. One round of model debugging was assumed.
Figure 2-16: Time-Series Chart of FLO-2D Model Process

- Hydrologic outputs ready
- Data acquisition (1 hr)
- Process terrain and land use data (1 hr)
- Set up FLO-2D model (0.5 hr)
- Process hydrologic inputs (0.5 hr)
- Run FLO-2D model (2 hrs)
- Are there model instability issues?
  - Yes; debug. (1 hr)
  - Run FLO-2D model (2 hrs)
  - Create raster outputs (2 hrs)
  - Clean raster outputs (1 hr)
- No
  - Run FLO-2D model (2 hrs)

Updated hydraulic simulations can begin at Hours 15.5, 19.5, 21.5, 27.5, 33.5, and 39.5 (8.5 hrs apiece)

Producing updated raster outputs at Hours 24, 28, 30, 36, 42, and 48
2.4.2 HEC-RAS 2D

The following sections discuss the computing configuration, provide an outline of the modeling process, and present a time-series flow chart outlining what outputs are available and at what time when using the HEC-RAS 2D model.

**Computing Configuration**

An 8-core processor setup was used with a 200-foot computational mesh. The model simulation times were approximately 12.5 hours making them significantly longer than of the FLO-2D and TUFLOW model runs, both of which benefitted from the use of GPUs. HEC-RAS 2D does not benefit from GPUs, so two other tests were done to determine whether it could run within a reasonable time for use in this approach.

The first additional test run modeled conditions identical to the original run, but utilized cloud computing techniques. This decreased the simulation time by nearly half to 7.5 hours. This is a significant improvement, but comes with additional costs.

The second additional test run modeled conditions identical to the original run that used forecast data published at Hour 18 of the assessment process, except that it used a 500-foot computational mesh. This option was tested because the mapping output from HEC-RAS 2D is based on the underlying terrain cell size. Therefore, using a coarser mesh cell size does not significantly impact the overall accuracy. Other studies have also shown that simulation run times increase exponentially as the number of cells increases (Compass, 2017a). This test run resulted in a simulation time of less than 1 hour, further supporting the previous findings. This test run produced results very comparable to the 200-foot computational mesh as shown in Figure 2-17.

Model outputs typically changed by less than 6 inches as compared to the results produced using a 200-foot computational cell size. The 2nd test run that used the increased computational mesh size improved the simulation time the most, did not require any additional costs, and produced similar results to those produced by the model using the 500-foot computational cell size. Therefore, that option is the obvious choice for use in this process.

**Process Overview**

Any data acquired for the hydrologic process that are also needed for the hydraulic process have been excluded from this overview. The steps required to complete the hydraulic portion of this process using HEC-RAS 2D are as follows:

1. Acquire data (terrain data)
2. Process data (terrain and land use to determine roughness coefficients data, setting spatial reference projection, creating .hdf files from terrain and land use grids)
3. Set up HEC-RAS 2D model
4. Input hydrologic data
5. Run HEC-RAS 2D model
6. Resolve instability issues within the model
7. Re-run HEC-RAS 2D model (if Step 6 is required)
8. Export results using RAS Mapper
9. Perform raster cleanup
10. Repeat steps 4 through 9 based on updated hydrologic data as time allows

**Time-Series Matrix**

Some of the tasks included in the hydraulic portion of this process can occur in parallel affecting the overall time-series of the task. The overall time-series for this model incorporates the hydrologic process time-series (as shown in Section 2.4.3.3), which drives the timing of updated iterations due to the availability of updated forecast data. Because the pilot geography is approximately half of Montgomery County, TX, conservative estimates of time were applied to sub-tasks to account for at least a countywide assessment. Model instability is assumed in this time-series to be conservative as well. One round of model debugging was assumed.
The time-series matrix for this model (Figure 2-18) displays the most efficient model and computing configuration, in which a 500-foot computational mesh was used, but provides visualization for all three scenarios in this model.

2.4.4.3 TUFLOW
The following sections discuss the specific computing configuration, provide an outline of the modeling process, and present a time-series flow chart outlining what outputs are available and at what time when using the TUFLOW model.

Computing Configuration
The simulations for this analysis were performed using a 200-foot computation mesh with the following computer configurations:

- 3DBOXX W8920
- Intel Xeon CPU E5-2643 Dual 3.5 GHz Core Processor

Process Overview
Any data acquired for the hydrologic process that are also needed for the hydraulic process have been excluded from this general overview. The steps required to perform hydraulic simulation with the TUFLOW model are as follows:

1. Acquire data (terrain data)
2. Set up TUFLOW model
3. Process data (terrain and land use to determine roughness coefficients data, excess precipitation hyetograph converted to proper format)
4. Run TUFLOW model
5. Resolve instability issues within the model
6. Re-Run TUFLOW model (if Step 5 is required)
7. Generate GIS outputs
8. Perform raster cleanup
9. Repeat steps 3 through 8 based on updated hydrologic data as time allows

Time-Series Matrix
Some of the tasks included in the hydraulic portion of this process can occur in parallel, affecting the overall time-series of the task. The overall time-series for this model incorporates the hydrologic process time-series (as shown in Section 2.4.3.3), which drives the timing of updated iterations due to the availability of updated forecast data. Because the pilot geography is approximately half of Montgomery County, TX, conservative estimates of time were applied to sub-tasks to account for at least a countywide assessment. Model instability is assumed in this time-series matrix (Figure 2-19) to be conservative as well. One round of model debugging was assumed.
Figure 2-18: Time-Series Chart of HEC-RAS 2D Model Process

*T-hours depending on model and machine configuration

<table>
<thead>
<tr>
<th>No.</th>
<th>Processor</th>
<th>T-hours</th>
<th>Cell Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Intel®Xeon®Platinum 8124M CPY @ 3.00 GHz 3.00GHz (8 core processors) – Cloud Computing</td>
<td>7.5</td>
<td>200 feet</td>
</tr>
<tr>
<td>2</td>
<td>Intel®Xeon® CPY @ 3.20 GHz 3.20GHz (8 core processors)</td>
<td>12.5</td>
<td>200 feet</td>
</tr>
<tr>
<td>3</td>
<td>Same as 2 above but 500-foot cell size</td>
<td>1.0</td>
<td>500 feet</td>
</tr>
</tbody>
</table>
Figure 2-19: Time-Series Chart of TUFLOW Model Process
3 Results

This section of the report examines the results of the two case studies that were completed as part of the task order. The 1-percent-annual-chance flood event model results were validated against two sets of established data for the same theoretical event. The rapid use case analysis results were validated against Hurricane Harvey flood observation data. Section 3 describes the data, assumptions, calculations, and analysis involved with the validation assessments, along with the results and interpretation of said results.

3.1 Validation Data

Datasets from several data sources were collected to complete the model validation assessments. A summary of the datasets are described below.

3.1.1 Established 1 Percent Annual Chance Flood Data

The two available datasets for validation of the 1-percent-annual-chance flood event modeling results were regulatory FIRM data and BLE data. The datasets are described below.

3.1.1.1 Base Level Engineering Data

The BLE data are described in Section 2.3.2.1. BLE cross sections, 1-percent-annual-chance WSEL raster, and 1-percent-annual-chance depth raster were compared to the 1-percent-annual-chance flood event pilot study model results.

3.1.1.2 Flood Insurance Rate Map Data

FIRM data consist of maps, an FIS, and a National Flood Hazard Layer (NFHL) database. Only two files from the NFHL were needed to compare the pilot study results to the effective regulatory data: the Special Flood Hazard Area (SFHA) file and the cross section file. All NFHL data can be downloaded from the FEMA Map Service Center on a state- or countywide basis. The last update to the FIRM dataset for Montgomery County, TX, became effective on August 18, 2014.

3.1.2 Observed Hurricane Harvey Data

Several datasets were observed and measured post-Hurricane Harvey that served as validation data for the rapid response use case study modeling results. The datasets are described below.

3.1.2.1 Individual Assistance Assessments

Following a flood disaster, FEMA offers aid through its Individual Assistance (IA) program, which provides funds to survivors who sustained flood damage. The IA data collection process identifies the location of the structure being assessed as well as an HWM. The project team collected 252 IA assessments within the pilot geography footprint for Hurricane Harvey. These data are not publicly available but are maintained by FEMA’s IA program.
3.1.2.2 National Flood Insurance Program Claims Data
FEMA’s NFIP collects claims data during insurance claims processing. Like IA, NFIP data include the location of the structure and a HWM. The validation team collected 195 NFIP claims with relevant, adequate data for Hurricane Harvey within the pilot geography footprint. These data are not publicly available but are maintained by the NFIP.

3.1.2.3 Substantial Damage Estimates
In conjunction with the NFIP process, FEMA communities are required to track structures within the SFHA that are more than 50% damaged by a flood event. The SDE process is maintained at the community level, making data quality uncertain from flood to flood. For Hurricane Harvey, FEMA Region VI provided the project team with 101 SDE records that fell within the pilot geography. The records included exterior depth and interior HWM height. These data are not publicly available.

The multiple depth metrics made the SDE data more reliable than the IA and NFIP datasets described in Sections 3.1.2.1 and 3.1.2.1 (in the vertical axis).

3.1.2.4 High Watermark Data
The USGS collected thousands of HWMs post-Hurricane Harvey in affected areas. These data can be found in USGS’s Flood Event Viewer at https://stn.wim.usgs.gov/fev/#HarveyAug2017. A total of 22 HWMs were available within the pilot geography.

The data reported WSEL along with an estimated error that ranged from ± 0.1 foot to ± 0.4 foot. The lowest quality data are indicated as ± >0.4 foot. The lowest quality data are assumed to be within ± 1 foot based on the consistency of the observations and the emphasis on precision by the USGS. The lowest level of quality appears to be comparable to the best quality estimates from the other Hurricane Harvey validation datasets.

3.1.2.5 USGS Inundation Mapping Data
The USGS used the HWM data described above and peak-stage data from USGS streamflow-gaging stations to create inundation mapping data for the Hurricane Harvey event consisting of flood inundation extents boundaries and depth rasters. These data were used in the validation process for this project and can be found in USGS’s Science Base-Catalog at https://www.sciencebase.gov/catalog/item/5aa023ebe4b0b1c392e6881b. Unlike the other observed datasets, the USGS inundation mapping data include depth information in raster format instead of simple point estimates. The rasters are ideal for extracting a validation sample data.

3.2 Approach
The assessed models’ results were compared to external baseline data (FIRM and BLE data) and to observed Hurricane Harvey data, based on the case study being validated. The data and calculations that were used are provided in this section, and the results of the comparisons are provided in report sections 3.3 through 3.5.
The comparisons evaluated a simple difference: modeled WSEL minus the established WSEL (both measured in feet). This difference is the error or “delta” of the model result. Deltas were calculated at many sample points, and the distribution of deltas was compared across models. To perform the comparison, the statistics listed in Table 3-1 were calculated.

**Table 3-1: Calculated Validation Statistics**

<table>
<thead>
<tr>
<th>Statistic</th>
<th>Definition</th>
<th>Key Questions Answered by Statistic</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>“Average” delta</td>
<td>How far are model results offset from actual observations, on average?</td>
<td>Accuracy</td>
</tr>
<tr>
<td>Median</td>
<td>“Middle” delta</td>
<td>How well are model results centered on actual observations, disregarding outliers?</td>
<td>Accuracy</td>
</tr>
<tr>
<td>25th percentile</td>
<td>Lower bound of the “middle” 50% of deltas</td>
<td>How spread out are deltas at the middle of the distribution?</td>
<td>Precision</td>
</tr>
<tr>
<td>75th percentile</td>
<td>Upper bound of the “middle” 50% of deltas</td>
<td></td>
<td>Precision</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>“Average” delta’s variation from the mean</td>
<td>How much variation do the deltas have?</td>
<td>Precision</td>
</tr>
<tr>
<td>Correlation</td>
<td>Predictive relationship between model depth and validation depth</td>
<td>How do variations in the model output correspond to variations in the actual data?</td>
<td>Predictive value</td>
</tr>
<tr>
<td>Percent in ±1 ft</td>
<td>Percentage of deltas between −1 ft and 1 ft (inclusive)</td>
<td>How many of the predicted results are accurate?</td>
<td>Accuracy</td>
</tr>
<tr>
<td>Percent in ±2 ft</td>
<td>Percentage of deltas between −2 ft and 2 ft (inclusive)</td>
<td></td>
<td>Accuracy</td>
</tr>
</tbody>
</table>

The accuracy of modeled flood depths depends greatly on the resolution of the model grid size while modeled flood WSELS do not because water surfaces tend to be smoother than ground surfaces. In this analysis, Compass opted to calculate the flood depth indirectly as the difference between the modeled WSELS and the high-resolution DEM, rather than use the lower resolution depth grids generally generated by the models. This is the recommended approach in cases when depth information is required for specific point locations, such as the corner of a structure. In cases where only general inundation information is being gathered, the model’s default, grid-level resolution may be sufficient.

The variety of validation data made it essential to develop consistent, repeatable validation calculations. Sometimes there were multiple validation measurements to choose from, including multiple HWMs and WSELS. Table 3-2 summarizes the calculations that were used. Each calculation assumed that the listed fields were available. The calculation tiers indicate the order of preference for one calculation over another, depending on the availability of relevant fields in the source data.

When it was difficult to determine whether a depth measurement in a validation dataset was an interior or exterior depth, it was assumed to be an exterior depth (measured from ground level). This assumption is equivalent to assuming a foundation height of zero.
Table 3-2: Validation Calculations

<table>
<thead>
<tr>
<th>Validation / Model</th>
<th>Tier</th>
<th>Condition</th>
<th>Calculation</th>
<th>Relevant Datasets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Validation WSEL</td>
<td>1</td>
<td>WSEL ≥ DEM</td>
<td>WSEL</td>
<td>BLE, FIRM, HWM</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>WSEL &lt; DEM</td>
<td>null</td>
<td>BFE, HWM</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>WSEL is not measured</td>
<td>Depth + DEM</td>
<td>IA, NFIP, SDE, Inundation Grids</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>WSEL and depth do not exist</td>
<td>(Interior HWM) + Foundation Height + DEM</td>
<td></td>
</tr>
<tr>
<td>Model WSEL</td>
<td>1</td>
<td>WSEL ≥ DEM</td>
<td>WSEL</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>WSEL &lt; DEM</td>
<td>null</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>WSEL is null</td>
<td>null</td>
<td></td>
</tr>
<tr>
<td>Validation depth</td>
<td>1</td>
<td>Validation WSEL is not null</td>
<td>(Validation WSEL) − DEM</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Validation WSEL is null</td>
<td>null</td>
<td></td>
</tr>
<tr>
<td>Model depth</td>
<td>1</td>
<td>Model WSEL is not null</td>
<td>(Model WSEL) − DEM</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Model WSEL is null</td>
<td>null</td>
<td></td>
</tr>
</tbody>
</table>

The calculations occasionally returned a “null” value when the data were not consistent with the baseline DEM. When either the model output or the validation point was calculated as null, no validation could be accurately performed. By enforcing this rule, the project team focused the comparison on the best available data.

3.3 1-Percent-Annual-Chance Flood Event Simulation Validation

This section discusses the validation of the 1-percent-annual-chance flood event model results. These results were validated against two sets of established data – the regulatory FIRM data and BLE data.

3.3.1 FIRM

The FIRM is a regulatory map developed by FEMA that delineates SFHAs and risk premium zones for establishing insurance rates. Detailed FIRM studies are significantly more granular than BLE studies because they include cross-section and structure survey data. FIRMs indicate the expected extent of flooding during 1-percent-annual-chance flood events. They also demarcate the boundary between the SFHA and the floodway components of the floodplain for detailed studies. The Compass team used the FIRM floodplain extents to qualitatively assess the accuracy of the models’ estimation of the flood inundation extents of the 1-percent-annual-chance flood event.

The base flood elevation (BFE) is a component of the FIRM that provides the WSEL of the 1-percent-annual-chance flood event at a specified location. BFEs are isopleth lines that show whole foot WSELS in increments along regulatory floodplains. To compare model results to regulatory BFE data, the project team selected BFE sample points. The sample points are located at the intersection of the BFE isopleth lines and the SFHA and floodway boundaries. This method provided 3,090 sample points within the pilot geography footprint.
The comparison began with a map of the model deltas. In Figure 3-1, each point represents a sample comparison between the modeled WSEL and the BFE.

![Figure 3-1: Simulated 1-Percent-Annual-Chance Flood Event Pilot Results versus FIRM BFE – Model Deltas](image)

The results across all three models correlated closely but had clear variations. The following conclusions can be drawn from the comparison:

- All three models predicted deeper flooding than the FIRM data in the northern headwaters.
- All three models estimated shallower flooding in the lower tributaries of the watershed.
- FLO-2D is biased higher than the other two models.
- TUFLOW had a slightly more extreme range of deltas than HEC-RAS 2D.

The models generally deviated in similar ways. To explain this pattern, Figure 3-2 plots the average delta across the three models versus the FIRM WSEL and floodway width (in nominal units).

![Figure 3-2: Simulated 1-Percent-Annual-Chance Flood Event Pilot Study Results versus FIRM BFE – Average Model Bias](image)

Although Figure 3-3 does not quantify the comparative quality of the model predictions, it helps explain how they are biased:
- The models overestimated flooding in the narrower, deeper channels at higher elevations.
- The models underestimated flooding in the broader, shallower floodplains at lower elevations.

To confirm this qualitatively, Figure 3-3 compares the raw model output depth raster to the SFHA extents in the narrow, steep, northern headwaters and in the low, flat, southern plains. In this visual, only the HEC-RAS 2D depth grid is shown since it was the only model that produced a high-resolution depth raster that was automatically compatible with the high-resolution DEM. However, it is clear in Figure 3-2 that the terrain-correlated model errors illustrated in Figure 3-1 are common across all three models.

![Northern Headwaters](image1.png) ![Southern Plains](image2.png)

---

**Figure 3-3: Simulated 1-Percent-Annual-Chance Flood Event Pilot Study Results versus FIRM SFHA Extent (HEC-RAS 2D)**

The modeled flood depths are overestimated in the narrower channels of the headwaters, but this does not greatly affect the extent of the flooding due to the steep terrain. In flatter areas, the models generally underestimated flooding extents. The main stem, Caney Creek, has a significantly higher flow than its tributaries, and the models therefore still overestimated flooding extents in the southern plains of the pilot geography.

In addition to showing variations in flooding extents at the SFHA boundary, Figure 3-4 highlights the extensive, shallow pluvial flooding that is not captured by the FIRM studies.

Figure 3-4 focuses on the statistical aspect of each model’s performance and highlights the range of deltas produced by the models at the SFHA and floodway boundaries.

Comparisons at the SFHA boundary are susceptible to invalid comparisons (in which either the validation calculation or the model result calculation produced a null value) because, by definition, flood depth
tends to be shallow at the SFHA boundary. The project team determined that including the SFHA data in the final analysis was still beneficial for gaging the relative accuracy of the models.

In the case of TUFLOW, it appears that the model is relatively unbiased but has less precision (higher standard deviation and lower correlation) than HEC-RAS 2D. As such, some of the results deviated slightly lower than HEC-RAS 2D while others deviated slightly higher. The lower results generated zero-depth estimates at the SFHA boundary. These estimates were necessarily removed, leaving only the higher estimates. Predictions at the SFHA boundary should be clustered around zero. The presence of zero-depth estimates does not indicate that TUFLOW has far lower quality, only that its flooding extents were estimated as slightly less than HEC-RAS 2D in many areas.

Based on Figure 3-4, the following results can be stated:

- HEC-RAS 2D has the narrowest distribution of deltas across the models and is the best centered on zero across the three models.
- All three models overestimated flooding at the SFHA boundary more than at the floodway boundary.
- TUFLOW produced the largest number of zero-depth (WSEL = null or < DEM) predictions at the SFHA boundary.

Statistical analysis of the model deltas confirmed HEC-RAS 2D as the best performing model relative to the regulatory BFE. Table 3-3 provides the key evaluation statistics. This table presents only the results at the floodway boundary to ensure that the table presents comparable results that were unaffected by the issues described above.
In summary, the comparison of the model results to the regulatory FIRM data provided the following insights:

- All three models overestimated flood depths (relative to FIRM BFES) in the narrower, steeper floodplains in the headwaters.
- Due to steeper terrain in the headwaters, overestimation of flood depths does not significantly affect the estimation of flood extents.
- All three models underestimated flood depths (relative to FIRM BFES) in the wider, shallower floodplains in the downstream area of the pilot geography.
- All three models underestimated flooding extents (relative to FIRM SFHA extents) in the lower floodplains except for the main stem (Caney Creek) due to higher flows.
- Regulatory FIRM data did not account for pluvial flooding.
- All three models had a standard deviation of between 2 and 3 feet from the regulatory BFE.
- HEC-RAS 2D and TUFLOW performed nearly equally across all metrics and outperformed FLO-2D.
- FLO-2D had the lowest precisions and greatest bias (>1 foot).

### 3.3.2 BLE

As discussed in Section 3.1.1, the available BLE data provide a WSEL and depth raster for the 1-percent-annual-chance flood event. Although the BLE data may lack the rigor of regulatory FIRM maps, they can establish an estimate of the 1-percent-annual-chance flood inundation extent WSELS and flood depths for a large geographical area relatively quickly compared to detailed studies.

Compass began its analysis by mapping the deltas of the models compared to the BLE data. In Figure 3-5, each point represents a sample comparison between the modeled WSEL compared to the BLE WSEL. This assessment uses the same sample points used for validation against FIRM data: the intersection of the FIRM BFE isopleth lines and the SFHA and floodway boundaries.

Comparison to BLE results provided one additional insight beyond those identified in the comparison to FIRM results:

- The deltas tend to be smaller, with fewer deltas in the more extreme categories, than when compared to FIRM data.
Figure 3-5: Simulated 1-Percent-Annual-Chance Flood Event Pilot Study Results versus BLE – Model Deltas

Figure 3-6 focuses on a summary of the statistical distribution of deltas for each model. HEC-RAS 2D has the narrowest distribution of deltas, suggesting that it is the most precise model when compared to the BLE data.

Figure 3-6: Simulated 1-Percent-Annual-Chance Flood Event Pilot Study Results versus BLE – Model Delta Ranges
Statistical analysis of the model deltas confirms HEC-RAS 2D as the best performing model relative to BLE data. Table 3-4 provides the key evaluation statistics.

<table>
<thead>
<tr>
<th>Model</th>
<th>Mean</th>
<th>Median</th>
<th>Percentile</th>
<th>Std. Dev.</th>
<th>Corr.</th>
<th>±1 ft</th>
<th>±2 ft</th>
</tr>
</thead>
<tbody>
<tr>
<td>HEC-RAS 2D</td>
<td>–0.511</td>
<td>–0.638</td>
<td>–1.358</td>
<td>0.138</td>
<td>1.295</td>
<td>0.941</td>
<td>51%</td>
</tr>
<tr>
<td>TUFLOW</td>
<td>–0.547</td>
<td>–0.702</td>
<td>–1.612</td>
<td>0.252</td>
<td>1.527</td>
<td>0.918</td>
<td>46%</td>
</tr>
<tr>
<td>FLO-2D</td>
<td>0.245</td>
<td>0.183</td>
<td>–0.852</td>
<td>1.176</td>
<td>1.776</td>
<td>0.894</td>
<td>49%</td>
</tr>
</tbody>
</table>

In summary, the comparison of the model results to the BLE data provided the following information:

- All three models exhibited similar terrain-related biases like those observed in the FIRM validation.
- All three models produced results with more precision and predictive value relative to their FIRM validation results.
- BLE data, like FIRM data, did not account for pluvial flooding.
- HEC-RAS 2D produced the best standard deviation and correlation results.
- TUFLOW performed worse than HEC-RAS 2D in statistical precision but outperformed FLO-2D in precision and predictive value.
- FLO-2D produced the most accurate results but with the worst precision and predictive value among the three models.

The BLE validation revealed similar trends to the FIRM validation but did not provide conclusive evidence of a clear best model among the three rapid modeling tools. However, as noted previously, the FIRM and BLE validations both compare rapid modeling results to engineering-based datasets, not to actual, field-observed data. This means that the improved model performance against BLE (as opposed to the FIRM) data may arise because the rapid modeling results and the BLE data are both high-level, coarse predictions that do not incorporate structure and survey data that are included in the FIRM detailed studies.

### 3.4 Rapid Response Use Case Analysis Simulation Validation

Section 3.4 evaluates the performance of the model that was used in a real-world flood scenario.

As stated in Section 2.4.2, multiple model iterations were completed to determine whether the multiple iterations would produce significantly different results using updated forecasts over a short period (24 hours). As a representative example, Figure 3-7 shows the improvement of the HEC-RAS 2D model's validation results as new model iterations were completed based on updated forecast data. In this case, median predicted flood levels increased by approximately 3 feet over 18 hours in the rapid assessment process. The other models showed similar trends. For proactive flood prediction, this summary suggests that it is important to use the most up-to-date data available at a given moment because storms can escalate quickly and produce unexpected consequences during that time.
In the cases of HEC-RAS 2D and TUFLOW, the increase in predicted flood levels moved results closer to the observed data measurements. In the case of FLO-2D, the increase in predicted flood levels moved results further from the observed data measurements.

For the purposes of model validation, Compass used the model outputs produced by using the best-available (most current at the time) forecast data. These are the final model iterations that used forecast data available at Hour 18 of the rapid modeling process.

Hurricane Harvey provided a variety of validation data including IA, NFIP, SDE, and multiple USGS datasets.

Early in the analysis, Compass found that IA and NFIP data were unfit for reliable validation. Both data sources included at least two sources of error. First, the data did not establish the horizontal accuracy of the latitude and longitude of the structure versus the location of the depth measurement point. This made it difficult to select an accurate DEM point for calculating the WSEL. Second, the data did not indicate whether the measured depth was an interior (measured from the floor) or exterior (measured from the ground) HWM. The NFIP data also failed to indicate the units used for measuring water depth and included many null or zero flood depth values. For these reasons, IA and NFIP data were excluded from validation assessments.

The validation process began with a map of deltas for the SDE validation points and the USGS HWM validation points. The maps are not presented due to the sensitive nature of the SDE location information and the low number of USGS HWM data points to display. Figure 3-8 shows the boxplot distribution of errors for the SDE and HWM data.
The models produced a wide variety of results when using real-world flood forecast information compared to those produced by the theoretical 1-percent-annual-chance flood event pilot study. HEC-RAS 2D is biased relatively low while FLO-2D is biased relatively high. In addition, all of the models are more negatively biased in the SDE comparison than in the USGS HWM data. This bias most likely arose because of concentrated geographic sampling of the SDE data. All of the SDE data appear to come from a single neighborhood that may be in a region where this rapid modeling approach tends to underestimate flood inundation. The USGS HWMs were distributed throughout the watershed.

Table 3-5 provides the statistical metrics that capture these issues. The following trends appear stable across the following statistics:

- All models exhibit similar, high correlation HWM validation results.
- HEC-RAS 2D is biased toward underestimating flood depth.
- FLO-2D is biased toward overestimating flood depth.
- All three models have 1- to 1.5-foot standard deviations relative to the HWM data.
- HEC-RAS 2D has the lowest standard deviation (best precision) compared to observed data.
- TUFLOW produced the lowest medians (most accurate) compared to observed data, and 94% of the predicted flood levels at the USGS HWMs were within ± 2 feet of the observed values.
Table 3-5: Simulated Hurricane Harvey Flooding – Statistical Results Summary

<table>
<thead>
<tr>
<th>Model</th>
<th>Validation Source</th>
<th>Mean</th>
<th>Median</th>
<th>Percentile</th>
<th>Std. Dev.</th>
<th>Corr.</th>
<th>±1 ft</th>
<th>±2 ft</th>
</tr>
</thead>
<tbody>
<tr>
<td>HEC-RAS 2D</td>
<td>SDE</td>
<td>−3.49</td>
<td>−3.64</td>
<td>−4.11</td>
<td>−3.00</td>
<td>1.30</td>
<td>0.62</td>
<td>4%</td>
</tr>
<tr>
<td></td>
<td>HWM</td>
<td>−1.84</td>
<td>−1.72</td>
<td>−2.57</td>
<td>−1.06</td>
<td>1.12</td>
<td>0.91</td>
<td>27%</td>
</tr>
<tr>
<td>TUFlow</td>
<td>SDE</td>
<td>−1.73</td>
<td>−1.93</td>
<td>−2.40</td>
<td>−1.40</td>
<td>1.15</td>
<td>0.71</td>
<td>13%</td>
</tr>
<tr>
<td></td>
<td>HWM</td>
<td>−0.06</td>
<td>−0.27</td>
<td>−0.74</td>
<td>0.41</td>
<td>1.29</td>
<td>0.90</td>
<td>65%</td>
</tr>
<tr>
<td>FLO-2D</td>
<td>SDE</td>
<td>1.24</td>
<td>1.30</td>
<td>0.48</td>
<td>2.03</td>
<td>1.29</td>
<td>0.77</td>
<td>38%</td>
</tr>
<tr>
<td></td>
<td>HWM</td>
<td>3.39</td>
<td>2.95</td>
<td>2.43</td>
<td>3.81</td>
<td>1.51</td>
<td>0.92</td>
<td>0%</td>
</tr>
</tbody>
</table>

Although FLO-2D produced somewhat accurate results when compared to the SDE data, this appears to reflect the strong positive bias of the SDE results. FLO-2D performed far worse against the USGS HWM data, which are well distributed geographically and are assumed to be accurate.

A comparison of the model outputs to the USGS Hurricane Harvey inundation depth grids was completed as well. The validation sample points for this assessment were taken from the sample points used in the 1-percent-annual-chance flood event comparison analysis outlined in Section 3.3.1. Deltas were calculated at each of the sample point locations that overlapped the USGS inundation grids. The inundation grids were produced using the USGS Hurricane Harvey HWMS (included in the discussion earlier in this section) and USGS gaging stations. The process used to create the USGS inundation grids is outlined in USGS SIR 2018-5070 (USGS, 2018). The deltas for each model when compared to the inundation grids are mapped in Figure 3-9.

![Figure 3-9: Simulated Hurricane Harvey Flooding versus Inundation Grids – Model Deltas](image-url)
This comparison provides the following information:

- HEC-RAS 2D tends to underestimate inundation.
- TUFLOW seems to be the least biased.
- FLO-2D exhibits a strong positive bias.
- As in previous validation steps, the models tend to overestimate Caney Creek flooding.

Although USGS inundation data do not cover many of the smaller, low-order streams in the flatter areas in the southern part of the region, the overarching terrain-related biases identified in 1-percent-annual-chance flood event validation seem to hold true in this analysis as well.

In Figure 3-10, the floodway and SFHA points correspond to the sample points used in the 1-percent-annual-chance flood comparisons. This summary confirms the bias of the individual models. Table 3-6 presents the validation performance for the USGS inundation grids, produced based on the high-quality USGS HWM data and USGS stream gage data.

![Figure 3-10: Simulated Hurricane Harvey Flooding versus Inundation Grids – Range of Model Deltas](image)
Table 3-6: Simulated Hurricane Harvey Flooding versus Inundation Grids – Statistical Results Summary

<table>
<thead>
<tr>
<th>Model</th>
<th>Mean</th>
<th>Median</th>
<th>Percentile</th>
<th>Std. Dev</th>
<th>Corr.</th>
<th>±1 ft</th>
<th>±2 ft</th>
</tr>
</thead>
<tbody>
<tr>
<td>HEC-RAS 2D</td>
<td>−1.671</td>
<td>−2.075</td>
<td>−2.892</td>
<td>−0.714</td>
<td>1.886</td>
<td>0.919</td>
<td>20% 43%</td>
</tr>
<tr>
<td>TUFLOW</td>
<td>−0.238</td>
<td>−0.638</td>
<td>−1.580</td>
<td>0.710</td>
<td>2.002</td>
<td>0.911</td>
<td>36% 70%</td>
</tr>
<tr>
<td>FLO-2D</td>
<td>2.876</td>
<td>2.710</td>
<td>1.710</td>
<td>4.283</td>
<td>2.576</td>
<td>0.876</td>
<td>11% 31%</td>
</tr>
</tbody>
</table>

This analysis included a large number of potential validation data sources. However, IA and NFIP datasets included too much noise and data uncertainty to produce a meaningful validation and were excluded from analysis. The SDE data covered only a small geographic area. Ultimately, the USGS provided the most robust, statistically significant validation data source for Hurricane Harvey. The following statements summarize the findings of the Hurricane Harvey modeling validation results:

- HEC-RAS 2D showed the best correlation and standard deviation among the three models.
- HEC-RAS 2D generated negatively biased results for the Hurricane Harvey estimates.
- TUFLOW produced the most accurate results among the three models, predicting water depths within 2 feet at 70% of the sample locations.
- FLO-2D produced the lowest quality results, including substantial positive bias (overestimates of flooding) and high standard deviation.

This narrative does not include a discussion of a variety of minor analyses done to attempt troubleshooting the poor quality of some of the validation datasets. These results are located in Appendix C.

3.5 Results Summary

Throughout Section 3, data have been presented along with interpretations. Section 3.5 provides an overview across the validation data sources. Table 3-7 provides a statistical overview of all validation assessments.

Interpretations comparing across models are as follows:

- HEC-RAS 2D produced results with the highest precision (standard deviation) and predictive value (correlation).
- TUFLOW results overall showed the least bias (mean and median closest to zero).
- FLO-2D had substantial positive bias, low precision, and low correlation.

Despite this relative ranking, none of the models performed well against the effective FIRM data. This could be a major concern since the FIRM data are considered to be the best available flood risk standard. Interestingly, the rapid modeling approach performed better against the BLE data. Since BLE uses a simpler modeling approach than the detailed modeling used to produce FIRM data, the BLE modeling methodology may be more closely correlated with the rapid modeling approach being assessed. These less detailed and rapid modeling approaches will not consider some details that are captured in the FIRM data.
The models performed with lower accuracy against the Harvey results than against the regulatory FIRM and BLE data. Several plausible factors may be involved:

- Broader variation of flood dynamics associated with real-world precipitation patterns as opposed to the hypothetical 1-percent-annual-chance flood event
- Pluvial flooding being absent from the FIRM and BLE data
- Uncertainty of forecast input data for modeling of the Hurricane Harvey scenario

The observable terrain-specific bias throughout the analyses may reflect the importance of these kinds of dynamics driving variation between the models in the real-world Hurricane Harvey scenario. These items together suggest that the success of the rapid modeling approach may depend heavily on the specific terrain as well as weather patterns. The role of pluvial flooding in the modeling process should be considered as a potential source of variance. The only factor driving the higher bias across models in the Hurricane Harvey scenario was event-specific weather inputs.
4 Recommendations for Incorporation into FEMA Standard Practice

Section 4 provides a list of SMEs who could support rapid response modeling and mapping tasks (Section 4.1), a gap analysis of the resources and data related to the proposed process that do not exist or that could improve the proposed process (Section 4.2), and recommended actions for FEMA to incorporate the proposed process into their standard practices (Section 4.3).

4.1 Subject Matter Experts

Incorporating rapid flood risk modeling into disaster response mechanisms requires rapid H&H modeling and SMEs with expertise in mapping and Information Technology (IT) SMEs with expertise in adapting models to mass computing environments.

Criteria were developed to identify organizations with SMEs who could assist with rapid response modeling and mapping assessments. Potential SME organizations were identified from the professional, academic, public, and federal partner sectors. The criteria are as follows:

- Existing contract or agreement with FEMA
- Familiarity with referenced datasets (e.g., BLE data, FIRM data, gage data, post-event data)
- Experience with HEC-RAS 2D, FLO-2D and TUFLOW
- Access to proprietary software (FLO-2D or TUFLOW)
- Experience relevant to rapid response modeling and mapping
- Knowledge of emerging technologies relevant to the identified rapid modeling approach (e.g., cloud or parallel computing)
- Limitations (e.g., manpower confined to working within a specific geographic location)
- Capacity in which the organization could provide support in case of a pending flood event
- Capacity to allocate resources within 48 hours

Research included industry events, software user groups, literature, professional and academic organizations, and personal networks to identify potential SME organizations. This approach was taken to identify current top rapid-modeling experts, while up-and-coming practitioners, perhaps using new data or advanced computing methods, were not overlooked. Flood disasters can sometimes involve region-specific phenomena, so the approach was to assess a wide geographic distribution of experts.

Twelve organizations were contacted. Out of the 12 organizations, four were private companies, four were Flood Control Districts (FCDs), three were federal agencies, and one was an academic organization. Out of the 12 organizations, 9 replied to the inquiry. Initial contact with the remaining organizations was followed up by phone calls, but no response was received in time for inclusion in this report.

Based on the feedback that was received, most of the organizations are proficient with HEC-RAS 2D and TUFLOW, whereas FLO-2D is not broadly used. The organizations that were contacted ranged from organizations with three engineers to hundreds of engineers and are located mainly on the East and West Coasts. Most of the organizations are prepared to work within 48 hours and are not limited to any
particular region of the country except Harris County FCD, which stated that most of its work is limited to Harris County (this limitation may affect Harris County FCD's availability to assist in other regions of the country).

The USACE noted that it performs a similar response to the one being developed in this task order for USACE-operated infrastructure (e.g., dams, locks, levees), and this capability may be able to be expanded to other areas with an appropriate mission and funding. The USACE suggested that the agency could review the proposed FEMA rapid response protocol to compare how it aligns with its protocol.

Three private organizations, NTM Engineering, WEST Consultants, and Wood Rodgers, do not have a current contract with FEMA. In comparison, several other organizations have existing Cooperating Technical Partner (CTP) contracts with FEMA and work with FEMA under various contracts. All of the organizations have worked with the referenced datasets that are required for rapid H&H modeling, but the majority of the organizations are unfamiliar with emerging technologies such as cloud computing and do not use it in their operations.

Based on the initial assessment of SME availability, it appears that there are sufficient SME staff and organizations that could support FEMA with HEC-RAS 2D or TUFLOW as the models for rapid H&H modeling. The resources in the United States to support the use of FLO-2D as a base model appear to be more limited, so if FEMA selected FLO-2D as the base model, it could increase the risk of not achieving FEMA's goals because of potentially limited SME resources with expertise with this model.

The potential SME organizations and some of their capabilities are listed in Table 4-1. The list focuses on organizations that have existing relationships with FEMA and firms that have been identified as having a particular specialty with one of the three selected models. Numerous private companies could provide assistance with rapid response modeling and mapping. The list is intended to be a representative sample and is not intended to include all SME organizations that could support FEMA.

### 4.2 Gap Analysis

A gap analysis was conducted between use of the currently available data, tools, and common procedures and potential enhancements to the currently available rapid response modeling and mapping process. Suggestions and/or solutions to the gaps are described in this section and are focused primarily on four areas:

- GIS tools
- Cloud computing/storage
- Probabilistic modeling
- Damage/loss estimation

The capability of each potential enhancement to contribute to improving credibility or efficiency of a rapid modeling and mapping process was considered. Consideration was also given to how the mapping results of a rapid response modeling study could be used by decision-makers and stakeholders, including FEMA, disaster responders, and the public.
4.2.1 GIS

The focus in this section is on the evaluation of any missing GIS analysis tools or alternate ways of working with H&H modeling and its components that may differ from, or be a supplement to, the modeling applications assessed as part of the task order.

It should be noted that using “out of the box” GIS analysis tools supplementary to data (such as pre-processed raster and base map vector data) will not give results that are as accurate and comprehensive as the results when using more sophisticated H&H modeling applications. Most data that are output from basic GIS tools, such as the tools that are described in the following subsections, are more economical and generally easier to use but require more processing time, data manipulation, and research than using a full-fledged H&H modeling application such as HEC-RAS 2D, TUFLOW, and FLO-2D, which are designed to give immediate, usable, and applicable measurements and calculations.

Five relevant supplementary, missing or alternate applications, processes, tools, or models have been identified. All five tools could potentially be used in the data acquisition process and/or development of H&H models and model parameters in a rapid response modeling approach.

4.2.1.1 Esri’s Living Atlas of the World

Esri’s ArcGIS software package includes ArcGIS Living Atlas of the World, which has useful and authoritative maps on many topics. ArcGIS Living Atlas of the World is a collection of thousands of maps, intelligent map layers, imagery, tools, and applications built by ArcGIS users worldwide and by Esri and
its partners. This rich catalog of geographic information is available through ArcGIS online and reflects the collective power and reach of the entire ArcGIS community (Esri, 2018).

ArcGIS Living Atlas of the World can assist H&H modeling in several ways. Seamless national datasets are available online and can be extracted locally and used for spatial analysis without extensive pre-processing (Esri, 2018).

Available layers that are relevant to H&H modeling include but are not limited to:

- Topography (3-, 10-, 30-meter DEMs and LiDAR)
- Land use
- Percent impervious
- Soil Survey Geographic Database (SSURGO) Hydrologic Soils Group
- NHDPlus and NHDPlusV2.1 Hydrology

4.2.1.2 USACE HEC-GeoRAS

Hydrologic Engineering Center Geospatial River Analysis System (HEC-GeoRAS) is a set of tools for processing geospatial data in ArcGIS via a GUI. The interface allows for seamless integration of geometric data to be imported into HEC-RAS. HEC-RAS model results can be exported into HEC-GeoRAS for post-processing of results (http://www.hec.usace.army.mil/software/hec-georas/).

4.2.1.3 USACE HEC-GeoHMS

The Hydrologic Engineering Center Geospatial Hydrologic Modeling Extension (HEC-GeoHMS) is a geospatial hydrology toolkit for users with limited GIS experience. HEC-GeoHMS uses the ArcGIS Spatial Analyst extension to develop a number of hydrologic modeling inputs for HEC-HMS (http://www.hec.usace.army.mil/software/hec-geohms/).

4.2.1.4 Esri ArcGIS Analysis Tools

Available through ArcGIS GIS software is a set of specified analysis tools called Arc Hydro. Arc Hydro is available as an extension of the geodatabase model for support of water resources applications. Arc Hydro has tools that support common water resource analyses such as terrain analysis and watershed delineation. It can also link hydrologic features to a time series. Numerous useful GIS analysis tools can calculate contributing drainage area, create a flow direction raster, refine a surface raster for imperfections like sinks, and convert rasters to polygons or polylines (and vice versa) for stream networks, to name a few (Djokic, n.d.).

4.2.1.5 Virtual GIS Data Library

It is recommended that the Living Atlas of the World be used as a primary, initial source since there are many post-processed and ready-to-use GIS data sources available there. Other sources are available online, but many require post-processing in order to use in GIS and modeling projects.

The ease of access to already-processed data for H&H modeling in one location is crucial to the viability of a rapid response modeling and mapping approach for disaster response becoming a standard process.
The creation of a library of data such as CN input data and processed terrain, particularly for the regions of the Nation that are most prone to flooding disasters, that can be easily accessed by FEMA's on-call modeling and mapping partners could increase the likelihood of this process becoming feasible across many geographies.

In regard to processed terrain data, a topographic source such as raw LiDAR is time-consuming to process and could not take place within a rapid response time frame. An inventory of existing topographic datasets would need to be established to see where the gaps are within high flood risk areas. Some processed LiDAR datasets can be located on the FEMA MIP.

Other sources of unprocessed topographic data (DEM's and LiDAR) are:

- U.S. Interagency Elevation Inventory
- Space Shuttle Radar Topography Mission (SRTM)
- Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model
- Japan Aerospace Exploration Agency (JAXA's) Global Advanced Land Observing Satellite (ALOS) 3D World
- Mars Orbiter Laser Altimeter (MOLA)
- Open Topography
- USGS Earth Explorer
- USGS The National Map

### 4.2.2 Cloud Computing / Storage

Flood models are typically run on desktop computers, but there are now options for running flood models on more powerful cloud computers (or functionally equivalent virtual machines) that have been set up for remote access. Datasets also could be set up for cloud storage and remote access. The datasets could be useful for quick model runs or for quick access to large amounts of model results in the period leading up to an impending flood event.

Some models can benefit from various forms of parallel computing for faster computation. One common form of parallel computing is multiple CPU cores. CPU cores are often used in desktop computers and are also offered in cloud computing environments. An even more powerful form of parallel computing is GPUs, which can be installed in a local desktop computer, and are also commonly available in cloud computing environments. Cloud computing typically offers CPUs and GPUs with a range of processing power as well as the ability to use multiple CPUs or GPUs simultaneously (Lardinois, 2018; Pollio, 2018). Of the three flood models selected for this assessment, FLO-2D and TUFLOW benefit from GPUs. HEC-RAS 2D does not benefit from GPUs but can benefit from multiple-core CPUs (USACE, 2018).

Current flood models cannot be run in real time efficiently on a reliable basis. Cloud computing can help in at least two general ways: storing pre-run simulation results and completing model simulations in the cloud.
One-way cloud storage and/or simple cloud computing could be used to pre-run a set of simulations to generate a library of results. In this way, instead of running flood models in real time, users could use search algorithms to find the closest matched pre-run simulation. Development of such a library could represent a substantial cost except when existing modeling is readily available, such as BLE models. Prioritization of establishing libraries in areas that are prone to flooding disasters should be considered in this process.

Cloud computing could also provide the benefit of making flood model runs faster and more reliable. Some types of flood models are notoriously hard to run reliably in real time without the simulation crashing. Although cloud computing alone could not solve all causes for such problems (e.g., missing data), it could make it easier to solve some of the problems by storing or sharing needed data more efficiently. Increased simulation run times consequently increase the number of simulations based on forecast updates in a short time frame.

Cloud computing also provides other reliability benefits from the redundancy it creates. There are risks from reliance on a single computing center, especially if it is located in the area affected by a flooding event in that the loss of power to that center while processing could completely shut down the rapid response effort. Cloud computing provides replicated access to data and applications in multiple geographic locations.

The three primary options for cloud computing/storage are:

- **Cloud storage**: This option is still reliant on local machines to run but can provide access to a large amount of data to many people regardless of physical location.

- **Virtual machine replicas of local computers**: This has the same advantages as cloud storage except that it can also speed up runs by using more powerful hardware and has faster access to cloud storage. It may also be more cost-effective than cloud computing in that costs are not incurred for a virtual machine until it is needed.

- **Whole process running on a cloud-native basis**: This has the same advantages as virtual machine replicas of local computers but can speed up simulation runs further by adding more machines or GPUs.

### 4.2.2.1 Setup and Coordination Needs

For organizations used to local computing, it would be easier to have a physical machine set up and ready to run than set up a virtual machine as a storm is coming in. It is possible to have one or more cloud-based virtual machines continually set up and ready to go, though at higher expense.

Cloud computing/storage could have substantial cost and require substantial time for setup and administration, depending on the option. Key points of considerations for setup and coordination of the three primary options are as follows:

- **Cloud storage**: The simplest option to set up and requires little technical sophistication for users already used to local computing.
Virtual machine replicas of local computers: Often requires more setup than cloud storage, especially for models that are not geared toward cloud computing. For example, some modelers have set up virtual machines running Hazus and a Virtual Private Network (VPN) workaround for an ArcMap license server.

Whole process running on a cloud-native basis: Requires the most technical sophistication and may also require new versions of some models.

Perhaps the most important need in effective cloud computing and storage is developing solutions to challenges of coordination, access and security, version control, metadata, assumptions documentation, system maintenance, and user technical support. Systems need to be robust and usable by a wide range of users. Users of cloud computing/storage systems could include FEMA staff, contractors, and CTPs such as State and local officials and academic researchers. Significant issues are location, access, and ownership of data and how often to update and share.

4.2.3 Probabilistic Modeling

Flood models in this project were run in a deterministic manner or using simple types of probability information such as forecast rainfall. Models typically use single or “point” values for many model parameters without explicitly accounting for uncertainties about the parameters. Probabilistic models frequently incorporate deterministic models with the main difference being that they use a range or probability distribution of values to represent parameter value uncertainty. Probabilistic modeling presents a number of challenges in data, computing, and communication, which do not fit into the 48-hour time frame. Therefore, current probabilistic modeling methods do not lend themselves to rapid response. An exception may be a limited area with an exceptionally high risk, such as a nuclear power plant or sensitive military installation.

The flood model parameter that typically has the greatest uncertainty is rainfall. In the rapid response approach used in this project, the rainfall forecast is updated every 6 hours. The QPF forecast entails the review of multiple meteorological models and expert evaluation, incorporating much of the critical probabilistic approach into the most uncertain parameter.

Due to these factors, probabilistic modeling was not incorporated into this project.

4.2.4 Damage/Loss Estimation

There is a significant gap in the ability to quickly access and integrate location-specific data for critical structures and facilities, which are needed for flood damage/loss estimation in the time leading up to a flood event.

The quantity and quality of hydrological data appear to far exceed the real-time data available for critical facilities (e.g., hospitals, schools, nursing homes). Some of the data may be available from different agencies/sources, but it is currently unclear as to how accessible the data are to FEMA. Other data, such as detailed information on the construction of the facilities, tend to be classified and not readily available.
4.2.4.1 Open Data Sources

Several open data sources are available, but information is limited. Three options were identified:

- **HIFLD Open Data**: The Homeland Infrastructure Foundation-Level Data (HIFLD) website (https://hifld-geoplatform.opendata.arcgis.com/) has metadata where the data exist. Data are actively being updated, though the update frequency is not clear. The data are available for download as Comma Separated Values (CSV), Keyhole Markup Language (KML), and shapefiles and are accessible via web services to support application development and data visualization. HIFLD typically provide the facility name, address, latitude, and longitude. Information such as first floor elevations (FFEes) and detailed construction information is not available.

- **Census data**: Census data are available via the downloadable American Fact Finder census site (https://factfinder.census.gov/faces/nav/jsf/pages/guided_search.xhtml). However, the data are extremely wide ranging and do not provide many of the needed specifics.

- **NOAA**: Data that indicate how many schools or hospitals are present can be collected for any county from the NOAA Digital Coast website (https://coast.noaa.gov/digitalcoast/data/criticalfacilities.html) but do not provide information on construction or facility site information.

4.2.4.2 Hazus Building Inventory Data

The key General Building Stock databases in Hazus include square footage, building count, and valuation by occupancy, building type, and general occupancy mapping. For these databases, residential structures are derived from Census 2010 data and non-residential structures are derived from Dun & Bradstreet. Three reports from the Department of Energy were used to define regional variations in characteristics such as the number and size of garages, type of foundation, and number of stories. Additional information on residential structures in a region of concern can be gathered from the local (often county level) or State accessors’ databases. This information could be combined with different mapping and/or directory databases to allow for individual evacuation notifications to specific at-risk residences ahead of an event.

Hazus default databases also contain information for critical facilities including essential facilities and utility systems. Most of these default databases are out of date and should only be used when no local or State data are available.

4.2.4.3 Needs Going Forward

There is a need for new or enhanced datasets for critical structures and facilities to allow for a more detailed estimation of the potential damage/loss in the time leading up the actual event.

Ideally, the primary data gathered would include:

- Basic location data
- Facility type
- Facility function
- Year built
- Code year (design)
- Construction type/materials
- FFE

Secondary data could include the following:
- Major renovations (including year)
- Emergency power (including capacity/duration of fuel supply)
- Flood remediation measures (including type and extent)
- Access to facility (including key roads and/or bridges)
- Infrastructure at facility required for operations (e.g., electricity/gas/water)

For medical/healthcare facilities, it is envisioned that a joint project (in conjunction with other agencies) could be undertaken to obtain the above data. This type of study could be facilitated through the State agencies that monitor and regulate these types of facilities on an annual basis.

For information related to public schools, most States have accreditation agencies that monitor and work with the public school districts in their States. These State agencies could gather the information needed as part of the annual review process. In a similar manner, the State emergency management agencies could assist with gathering information for police and fire station facilities.

In addition to the logistical challenge of gathering and formatting all of the data, the type of data being collected would require a level of expertise that may not be available within the agency tasked with assisting in gathering the data.

As detailed in the user manual for the recently issued Levee Visualization Dashboard, the incorporation of multiple databases, similar to those discussed above, into a risk framework can be accomplished in a relatively straightforward manner. The real challenge is accessing and supplementing existing databases, or creating new databases, with data of sufficient detail as to provide a tool that can be of significant value prior to an event.

### 4.2.5 Other

Two additional pieces of information worth highlighting could impact the process under consideration. One is a potential modeling enhancement to HEC-RAS 2D that could improve efficiency, and the other is how the results of the analysis can be shared with the disaster response community and public.

#### 4.2.5.1 Potential HEC-RAS 2D Enhancement

HEC-RAS 2D currently does not take losses from rainfall into account, which is why HEC-HMS must be included in the process to complete hydrologic calculations. The USACE HEC is currently working to incorporate infiltration methods into a future version of the model. This enhancement could potentially eliminate steps in the developed approach, improving efficiency. HEC is considering including the new feature in the next release (Version 5.1), but an expected release date has not been shared (Goodell, 2018).
4.2.5.2 Visualization and Sharing of Results

The goal of this project is to recommend a process for use by FEMA, the disaster response community, and potentially the public for rapidly modeling events to inform response and recovery priorities and decisions. Suitable and timely sharing of model results are essential to the benefit they could provide in terms of disaster preparation, mitigation, and response. The data need to be shared in a manner easily interpreted by disaster responders and citizens quickly. FEMA should consider development of a map viewer that can be easily accessed by its modeling and mapping partners to add results as they become available. Story Maps are an open source tool that is a part of Esri’s ArcGIS software (https://storymaps.arcgis.com/en/). Story Maps allow maps to be combined with narration, images, and multimedia content to tell a story. A Story Map could allow for pertinent information such as locations that are expected to be inundated the worst in population centers, critical facilities such as hospitals expected to be inundated, and open evacuation routes to be highlighted. A team outside the modeling team would need to be initiated during impending disasters to focus on continual incorporation of updated information.

The disaster response community should be educated on the map viewer prior to the occurrence of an event. This would likely require working with organizations such as CTPs to support the advertisement and education of this tool.

4.3 Recommended Actions

Compass has developed the ten recommended actions described below on the next steps for FEMA to initiate the incorporation of rapid response modeling and mapping procedures into its standard practices.

1. Use QPFs for determination of hydrologic inputs.

   Quantitative hydrologic forecasting usually requires knowledge of the spatial and temporal distribution of precipitation. First, it is important to accurately measure the precipitation falling over a particular watershed of interest. Second, especially for small watersheds and/or for longer forecast lead times, forecasts of precipitation are critical to the achievement of the greatest possible hydrologic forecast accuracy and longest possible lead time. QPFs are the most complete data source available nationwide to support the development of forecasted hydrologic inputs. In order to perform QPF analysis, teams of hydrologists who are experienced in processing QPF data should be ready to start the process as soon as a flood threat is identified.

2. Investigate quantification of precipitation forecast uncertainty.

   QPF data have inherent uncertainty that varies for different events. Uncertainty in QPFs decreases as the time of forecast to the actual event decreases. It is recommended that a factor of safety be applied to the precipitation forecast to account for the uncertainty. Additional investigation is warranted to determine the safety factor applied to account for uncertainty in precipitation forecasts.
3. Use HEC-RAS 2D as the hydraulic model of choice when high-resolution terrain is available and use TUFLOW as the model of choice when low-resolution terrain is available.

The results of this study show HEC-RAS 2D to have a slight statistical advantage over TUFLOW in terms of precision. While TUFLOW produced more accurate results when compared to observed data, HEC-RAS 2D is also a free, readily available model that the U.S engineering community is very familiar with. Earlier in this report, it was discussed that the HEC-RAS 2D simulation time only became reasonable for multiple model iterations when the computational mesh size was increased. This should only be done when high-resolution terrain, such as LiDAR, is available. Therefore, the TUFLOW model with use of GPUs is suggested as the hydraulic model of choice when only low-resolution terrain is available to achieve multiple model iterations in a short response time frame.

4. Assess Recommendation 3 further through additional pilot studies that use disaster events other than Hurricane Harvey as the baseline event.

Due to the naturally wide-ranging conditions of flood events it is recommended that additional pilot studies be completed to assess how well the model results compare to observed data for other flood events. A recent event, such as Hurricane Florence (2018) that has available observed data could provide a more complete picture of how well the use of forecast data predicts actual flood inundation areas. In addition, Recommendation 3 is based solely on the results of this study, which showed TUFLOW to produce more accurate but less precise results than HEC-RAS 2D when compared to observed data. This supports further investigation to determine whether that trend remains constant in other geographies and with other types of flood events.

5. Establish on-call provider teams.

Multiple teams of modelers experienced with the selected model/s of choice should be assembled, and contract vehicles should be established to get modeling underway as soon as a flood threat is identified. Teams should be geographically dispersed around the Nation so staff and the facilities that are selected to model a particular event can be located outside the area that will be impacted by the event. The SME organizations described in Section 4.1 are a logical starting point. Although FEMA has existing relationships with many of these organizations, additional agreements may be necessary for them to be able to start work without a time-consuming contract modification or interagency agreement.


An official document should be published outlining the adopted processes to serve as a guidance document for the on-call provider teams. The document should outline the data sources, input parameters, assumptions, and modeling methods to be used for a rapid response analysis. The document will serve as a cookbook to facilitate a faster response and also ensure consistency of the approach among all the modeling teams. Portions of this report can serve as the basis for the guidance document. The USACE Emergency Management Branch performs a similar function for USACE-operated infrastructure (dams, levees, locks). The USACE’s protocol could also help inform the guidance document although FEMA is concerned with a much larger size and range of impact areas and will not always have as much data at hand for some areas.
7. Establish training for on-call providers.

After teams are in place and a guidance document has been compiled, training should be conducted for all providers to ensure that each provider understands not only the process but also team member roles and responsibilities. A strong understanding of the protocol will expedite data gathering and modeling when every minute counts. Training should be provided via webinar and recorded and should happen well in advance of the flood threat. It should closely follow the guidance document for consistency.

8. Compile a FEMA GIS library of easily accessible data needed by the on-call providers for this type of work.

Compiling data to build the necessary models can be a time-consuming first step in rapid response. FEMA should consider building a GIS library of pertinent data, including topography and land use. This library should be reviewed and updated as new datasets become available, at least annually. It would be prudent to time regular updates to occur prior to the beginning of hurricane season each year.

9. Establish a GIS portal viewer to enable the disaster response community to view the results.

Emergency managers use a host of resources to respond to flooding, including their own experience. The results of rapid response modeling will be a powerful tool for them if they can readily access and understand the data. GIS datasets must be served with a robust and intuitive website that does not require logins or other impediments to access. Many local officials and residents use the USGS Advanced Hydrologic Prediction Services (AHPS) web service (https://water.weather.gov/ahps/forecasts.php) to view flood gage forecasts. Linking the rapid response GIS platform to this site would be a natural way for users to find the data. Also, understanding the traffic load that this site provides during flood events will help FEMA estimate the load that its site will face. Inclusion of a comment form is also recommended to receive user feedback.

10. Conduct an outreach campaign for the disaster response community.

It is vital that local first responders understand the process and also the resulting data. They will need to know that the data exist and how to access the data. Consideration should be given to ease of use for emergency managers with varying technical skills and resources. Emergency managers usually welcome such tools enthusiastically. Outreach documentation including fact sheets for accessing and using the data will need to be developed and should be incorporated into routine communication with target users. For example, during Discovery meetings, which are often attended by emergency managers, a brief introduction of the dataset should be discussed and the audience pointed to resources for more information.

FEMA will also need to work with CTPs or State/County Emergency Management offices to activate this type of outreach campaign. Existing flood warning systems can be used to piggyback this new data. For example, adding a link on the USGS AHPS web service would quickly get the information out to users of the gage forecasts. These are routinely used by not only community officials but also the public.
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