https://doi.org/10.7289/V5/TM-OAR-PSD-317

NOAA Technical Memorandum OAR PSD – 317

SAN FRANCISCO BAY INTEGRATED FLOOD FORECASTING PROJECT SUMMARY REPORT

Jungho Kim, Lynn E. Johnson, Tim Coleman and Rob Cifelli
NOAA Earth System Research Laboratory – Physical Science Division

Liv Herdman, Rosanne Martyr-Koller, Juliette Finzi-Hart, Li Erikson and Patrick Barnard
USGS Pacific Coastal and Marine Science Center

Earth System Research Laboratory
Physical Sciences Division
Boulder, Colorado
December 2017

noaa NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION / Office of Oceanic and Atmospheric Research

https://doi.org/10.7289/V5/TM-OAR-PSD-317

NOAA Technical Memorandum OAR PSD – 317

SAN FRANCISCO BAY INTEGRATED FLOOD FORECASTING PROJECT SUMMARY REPORT

Jungho Kim, Lynn E. Johnson, Tim Coleman and Rob Cifelli
NOAA Earth System Research Laboratory – Physical Science Division

Liv Herdman, Rosanne Martyr-Koller, Juliette Finzi-Hart, Li Erikson and Patrick Barnard
USGS Pacific Coastal and Marine Science Center

Earth System Research Laboratory
Physical Sciences Division
Boulder, Colorado
April 2018

UNITED STATES
DEPARTMENT OF COMMERCE

Secretary Penny Pritzker
Department of Commerce

NATIONAL OCEANIC AND
ATMOSPHERIC

Dr. Kathryn Sullivan
Under Secretary for Oceans and
Atmosphere / Administrator

Office of Oceanic and

Craig McLean
Assistant Administrator for
Oceanic and Atmospheric
Research

Notice

Citation

Herdman, L. J. Kim, , L.E. Johnson, T. Coleman, R. Cifelli, R. Martyr-Koller, J. Finzi-Hart, L. Erikson and P. Barnard. 2018. San Francisco Bay Integrated Flood Forecasting Project - Summary Report. NOAA Technical Memorandum PSD-317, NOAA Printing Office, Silver Spring, MD, 37 pp.   https://doi.org/10.7289/V5/TM-OAR-PSD-317

Available at: http://docs.lib.noaa.gov/noaa_documents/OAR/PSD/TM_OAR_PSD_317.pdf

Table of Contents

List of Figures

Abstract

San Francisco Bay is a highly urbanized estuary and the surrounding communities are susceptible to flooding along the bay shoreline and inland rivers and creeks that drain to the Bay. An integrated forecast model is being developed for predicting flooding in Bay area tributaries and estuaries. This project involves state-of-the-art coupling of a NWS Distributed Hydrologic Model (DHM) with the USGS Coastal Storm Modeling System (CoSMoS). Results presented here are for a prototype focused on the interaction of the Napa River watershed and the San Pablo Bay. Discharges from the DHM are meteorologically driven and dynamic, allowing for identification of flash flood threats for model grids interior to the Bay tributaries. The DHM tributary flows are input to the CoSMoS model which in turn simulates flooding extent in the receiving estuary. We utilize Delft3D-FM, a hydrodynamic model based on a flexible mesh grid, to calculate water levels that account for tidal forcing, seasonal water level anomalies, surge and in-Bay generated wind waves derived from the wind and pressure fields of a NWS forecast model.

This report focuses on assessment of the various flood forecast information products generated by the integrated flood forecast modeling system. The tributary DHM generates forecast information for each grid that are portrayed as discharge, flow hydrographs (peak flow, time-to-peak, duration of high flow), soil moisture, and flood recurrence level. The CoSMoS portrays flood inundation and timing, and duration. Both models can help identify flood impact features such as road-stream crossings, and other critical facilities. A workshop was held with state, federal and local agency staff involved with flood forecasting and warning, and flood mitigation. As part of the workshop, we asked participants to review Hydro-CoSMoS outputs and rate how useful these products would be for theirs jobs. Results of these reviews are presented, and discussion is directed to how users' assessments could influence design of the real-time operational system to be implemented.

Executive Summary

A joint National Oceanic and Atmospheric Administration (NOAA) and U.S. Geological Survey (USGS) project linking a watershed distributed hydrologic model and a coastal hydrodynamic model for the Napa basin and San Pablo Bay region of San Francisco was completed in 2014-2017. The aim of the project was to demonstrate interoperability between the two modeling systems to assess the impact of tributary inflows on coastal storm flooding in and around the mouth of the Napa River.

The project used the National Weather Service (NWS) Research Distributed Hydrologic Model (RDHM) and the USGS Coastal Storm Modeling System (CoSMoS) to simulate a flood scenario in the Napa and San Francisco Bay. The RDHM is a gridded version of the NWS legacy hydrologic model based on the so-called Sacramento procedures. It is a conceptual model which represents surface and subsurface hydrologic processes as a collection of tanks which store and release incident precipitation in a non-linear manner. The RDHM model reflects terrain characteristics of slope and direction in each grid, which for this application was approximately 4 km. It routes excess precipitation across the grid and onto adjacent downstream grids as it accumulates surface runoff throughout the watershed. Previous research involving the Russian-Napa Rivers has documented the accuracy of the RDHM when compared to gauged flows, with generally good results when the forcing precipitation fields are accurate.

CoSMoS is a fully dynamic hydraulic model which represents the combined influences of oceanic tides, atmospheric pressure and winds throughout San Francisco Bay. This project involved input of the Napa River watershed inflows to San Pablo Bay, which is a sub-embayment in the north portion of San Francisco Bay. CoSMoS is based on the hydrodynamic modeling software DFlowFlexibleMesh from Deltares (DflowFM) which implements a finite volume method of conservation of mass and conservation of momentum on a staggered unstructured grid. CoSMoS can represent the extent of land inundation arising from coastal storms and tributary inflows. Given a high-resolution DEM (~2 m) CoSMoS resolves water depths up into the tributary to the full extent of tidal and storm surge influence.

The project successfully demonstrated the interaction of the two models, dubbed the Hydro-CoSMoS system, using a storm scenario of moderate precipitation occurring over the Napa watershed coincident with coastal storm surge and wind conditions over SF Bay. The scenario represented storm conditions that have historically occurred in the region and which have resulted in watershed and coastal flooding, but are not considered extreme. Coupling of the watershed flows as input to the coastal model was accomplished using standard file exchange procedures within the Flood Early Warning System (FEWS) context. Simulation of the watershed allowed portrayal of forecast flood hydrographs, peak flows and their frequency equivalent (e.g. 1 % recurrence level), soil moisture levels, and built facilities at risk (e.g. bridge crossings) for each grid. Simulation of the SF Bay and San Pablo Bay allowed portrayal of the time variability of water depths and currents, maximum depths, duration of flooding, and built facilities at risk.

A Table-Top Exercise (TTE) was conducted as the culmination of the project to represent products of the Hydro-CoSMoS system as they might be with fully integrated real-time forecast operations. The TTE was held at the Flood Operations Center in Sacramento and included participants from a variety of local, state, and federal organizations. Participants used several types of computer interfaces, including a clickable PDF, to navigate the scenario and interpret the impacts and consider their responses. The TTE provided opportunity for users' feedback on the type and format of information and how it was conveyed. This information is expected to be useful in the design and deployment of a near real-time, fully coupled watershed-coastal modeling system for San Francisco Bay.

1. Introduction

1.1 Background

The San Francisco Bay (SF Bay) area is highly urbanized, and communities are susceptible to flooding along the bay shoreline and inland rivers and creeks that drain to the Bay. A prototype forecast system that couples watershed and oceanic models was developed to demonstrate capabilities for forecasting watershed and coastal flooding in this complex urban environment. This collaborative project involved linkage of the National Weather Service (NWS) Distributed Hydrologic Models (DHM) with the United States Geological Survey (USGS) Coastal Storm Modeling System (CoSMoS) The coupled modeling system has been dubbed Hydro-CoSMoS. A prototype for the Napa River basin and Napa Estuary was demonstrated at a “Table-Top Exercise (TTE)” held June 13, 2017 at California Department of Water Resources (CaDWR) office in Sacramento.

1.2 Objectives

Objectives of this demonstration project were to:

- Apply the watershed and coastal flood forecasting models to the Napa River watershed and estuary,
- Identify appropriate meteorological data for forcing the models,
- Calibrate the models to establish that they accurately represent forecasts of flood runoff and coastal inundation areas and depths,
- Couple the two models at an interface that allows flood depths to be predicted by the hydraulic influence of both tides and watershed driven flows,
- Develop visualizations that portray the timing, magnitude and extent of flooding,
- Communicate the flood forecast model outputs to flood forecasters and flood emergency response managers, and,
- Assess the flood forecast products and system requirements to provide guidance for buildout of a complete San Francisco Bay flood forecasting system.

1.3 Case Study – Napa River Basin and Estuary

San Francisco Bay is an urbanized estuary that opens to the ocean at the 2km wide mouth of the Golden Gate (37.8° N, 122.5° W) and extends inland to the Sacramento and San Joaquin rivers and deltas. The Bay is at a maximum depth near the opening of the Golden Gate (113m) and shallows as the channel goes inland to San Pablo Bay (with channel depths of 11 to 24 m) (Barnard et al 2013). The Napa River drains into this shallow sub-embayment, which is dominated by tidal mud flats. The Napa River watershed is 1,100 km^2 and is a mix of urban (9%), agricultural (35%), grassland (15%) and forests (40%) with the area adjacent to the bay being restored to wetland habitat. It extends from the Mayacamas Mountains to the north and empties into the San Pablo Bay west of the Carquinez straight. The watershed is bounded by relatively steep terrain surrounding the long narrow valley that is 43 km long and 8 km wide at its widest point (Dusterdorf et al 2014). The City of Calistoga is in the northern end of the watershed and the city of Napa sits at the southern, tidally influenced end, with Vallejo, CA located on the eastern side of the river where it meets the Bay (Figure 1).

The case study conducted on the Russian-Napa River basins in California has involved forcing a distributed hydrologic model with California Nevada River Forecast Center (CNRFC) gridded precipitation fields. The Russian River watershed encompasses 1,485 sq. mi. within Sonoma and Mendocino Counties, California. The Napa River basin, located just east of the Russian River basin, encompasses approximately 426 square miles. These are two of the most flood-prone rivers in the State of California because of their unique geography and proximity to the coast, which together produce climatologically heavy wintertime rainfall. Total population in the study area is approximately 700,000. Primary water uses are for domestic supply and irrigation of (predominately) vineyards. Also, there are efforts to re-establish endangered fisheries habitat in the basins.

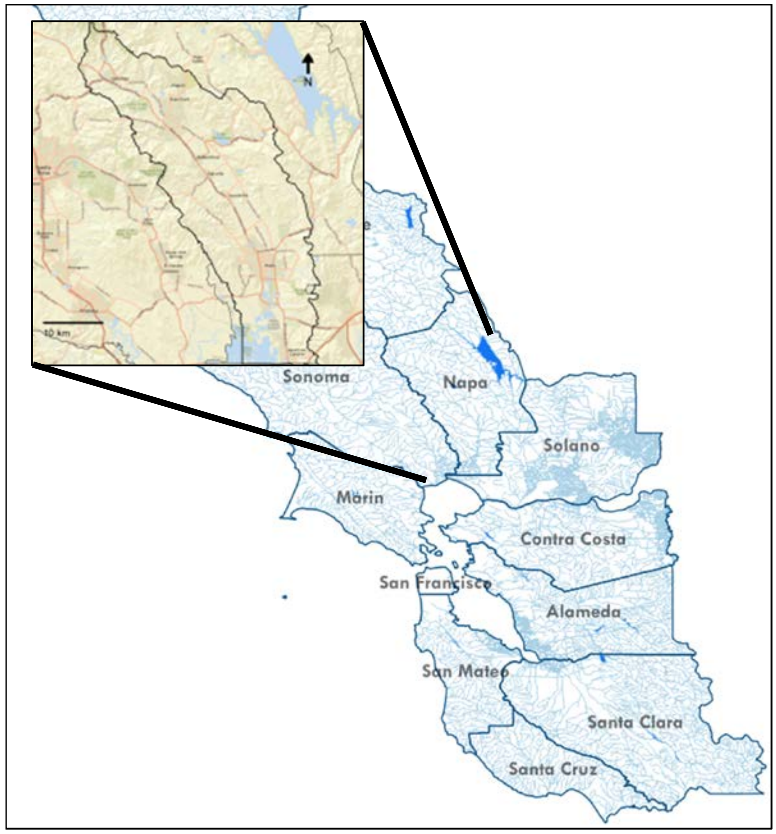


Figure 1 Map of San Francisco Bay region with Napa River watershed draining from the north into San Pablo Bay.

For the Napa River basin, the DHM involved forecasted precipitation and surface runoff computations for each grid, and routing of the surface flows to the basin outlet. A real-time prototype has been established and operated during the past two winter storm seasons. The grid flows can be visualized as the flood recurrence interval equivalent (e.g. 100-year flood level), and on-line users can click on a grid to obtain the forecast runoff hydrograph. Flood impact features, such as road-stream crossings, could also be identified as a warning aid for emergency responders. The river basin outflows are then input to the CoSMoS model which forecasts estuary flood inundation depths.

For the coastal application, we utilized Delft3D-FM, a hydrodynamic model based on a flexible mesh grid, and SWAN, a spectral wind-wave model, to calculate water levels that account for tidal forcing, seasonal water level anomalies, storm surge and in-Bay generated wind waves derived from the wind and pressure fields of a NWS forecast model. The flooding extent is determined by overlaying the resulting maximum water levels onto a 2-m digital elevation model of the estuary that resolves the extensive levees and tidal marshes.

The Table Top Exercise was intended to inform staff with the CaDWR, NWS, and Bay area counties about the capabilities of the coupled watershed and coastal flood prediction system, and to seek feedback on how they would like to see forecast products per their needs. The feedback will help design the system for the upcoming Advanced Quantitative Precipitation Information (AQPI) system to be deployed for the entire 9 county San Francisco Bay area.

1.4 Outline of report

This report summarizes the demonstration project. The watershed hydrologic and coastal flood forecasting models are described in Section 2. Section 3 presents the case study, which involves a scenario of hydrometeorological conditions representative of storm events in the San Francisco Bay area.

2. Integrated Flood Forecast System - Hydro-CoSMoS

2.1 Distributed Hydrologic Model

2.1.1 Research Distributed Hydrologic Model (RDHM)

The NWS-Office of Hydrologic Development (OHD, now the Office of Water Prediction (OWP)) Research Distributed Hydrologic Model (RDHM) was applied to develop the prototype SF Bay Integrated Flood Forecast System (Hydro-CoSMoS). RDHM was used to simulate the tributary flows and the overall movement of water through the watershed. Advantages of the distributed model are associated with the spatial detail of flow predictions at any location throughout the basin, which can inform efforts for flood mitigation, water supply, irrigation and ecosystem management. RDHM represents the general functionality of the class of distributed hydrologic models (DHMs) operating on a gridded data structure.

The overall objective of this project, supported through NOAA's Physical Sciences Division and the California Department of Water Resources (Ca-DWR), was to assess the accuracy of the distributed hydrologic modeling approach in representing surface hydrologic processes, including flood events and low flows (Johnson et al 2016). It was also intended to examine how the DHM approach may be applied in support of NWS hydrologic forecasting services, as well as related water management purposes.

The RDHM is a conceptual hydrologic prediction model which can be used to account for runoff, streamflow, soil moisture, snowmelt, evapotranspiration, and various hydrologic states during storm events and inter-storm periods. The required inputs are precipitation and temperature. RDHM computes the water balance between precipitation and infiltration for each grid, and routes both surface and subsurface water flow based on conceptual representations of terrain, soils, vegetation, and the influences of these on infiltration and evapotranspiration.

The OHD provided base data sets on terrain and channel networks, soils, and the default parameters for the RDHM model. The CNRFC provided the primary datasets on precipitation fields. Additional precipitation data was derived from the Multi Radar – Multi Sensor (MRMS), an operational system that provides a suite of gridded quantitative precipitation estimation (QPE) products at ~ 4km spatial and hourly temporal resolution.

Results of the DHM modeling activities are summarized in general terms here (after Johnson et al 2016).

- The default data sets for defining the RDHM grid structure and model parameter values provide a workable foundation for the simulation model.
- RDHM has been shown to provide so-called "natural" surface flow estimates that are reasonably accurate when the precipitation forcings are accurate (e.g. location, timing and intensity), the land surface and subsurface parameters are tuned to portray the hydrologic response (e.g. soil moisture and evapotranspiration dynamics), and water management influences are minimal.

2.1.2 RDHM in CHPS-FEWS

The RDHM was implemented in the NWS CHPS-FEWS (Community Hydrologic Prediction System-Flood Early Warning System) computing environment, which allows a streamlined, near-real time data ingest and simulation capability. The CHPS-FEWS has been configured to ingest multiple QPE and Quantitative Precipitation Forecasts (QPF) forcings; including radar-rainfall products generated by the MRMS system.

Implementation within a CHPS-FEWS computing environment facilitates automated RDHM model execution and near-real time data ingest. The DHM model executes without assimilation using the gridded CNRFC QPE as the observed precipitation forcing and with forecasts based on the HRRR dataset, extended to 48 hours with Weather Prediction Center (WPC) and Global Forecast System (GFS) precipitation fields. A simulation is automatically run every hour using 48-hour old states and forecast out to 48 hours.

2.1.3 Hydrometeorological Visualization Tool

A Hydrometeorological Visualization Tool (HVT, Figure 2) produces web-oriented displays of RDHM output that provide animations of precipitation, flood runoff and soil moisture, and ancillary GIS mappings of flood impact features.

The HVT was developed using a Google Maps interface so that it can be widely deployed and accessed using a commonly available platform familiar to most users. HVT builds on existing functionality for loading RDHM grid data into Google Maps. This functionality loads the RDHM grid data from the NetCDF format using routines written in Python scripts and NCL to convert the data into a raster image and KML file, which is then displayed in Google Maps in continuous animation using Javascript. An itemized description of HVT functions is summarized in general terms here:

- The tool was made available online via the web, without requiring software downloads by the user. The tool displays GIS layers along with DHM grid results in raster KML format overlaying a Google Maps view of the study region.
- RDHM data were automatically loaded into the interface as data are made available by CHPS-FEWS, which was available 24-7 during the prototyping periods.
- Data available in the HVT were obtained by import from the CHPS-FEWS and include: a) Gridded surface flows for the DHM domain (i.e. Russian-Napa Rivers) for each time step (4-km grid, 1-hr), b) Gridded soil moisture levels for DHM domain (4-km grid, 1-hr), c) Gridded precipitation amounts for

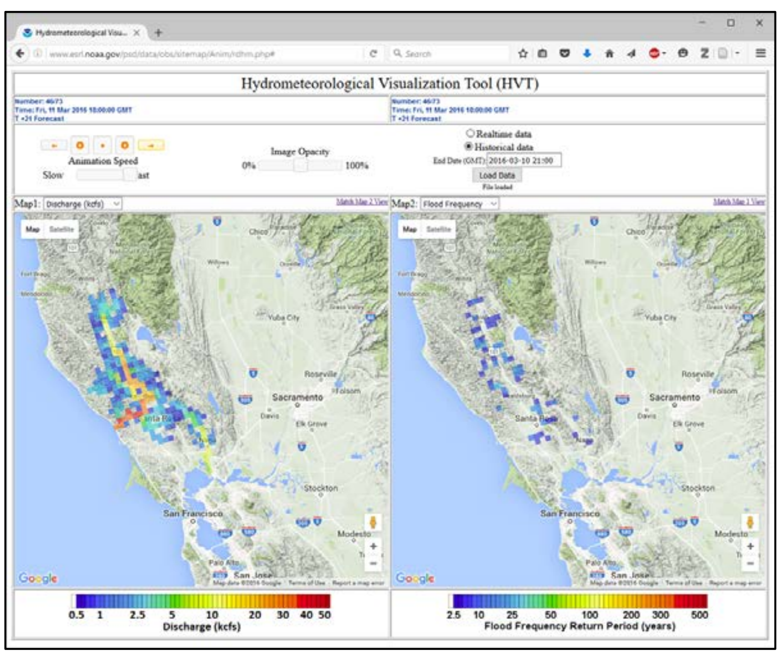


Figure 2 HVT displays animations of (a) grid surface flows, and (b) flood flow frequency equivalent.

the DHM domain (4-km grid, 1-hr), and d) Gridded surface flows were converted to their flood frequency equivalent (e.g. 20-yr flood frequency level, Figure 3).

- By default, the tool animates RDHM results over the past 24 observations and 48-hour forecast hours in an endless loop until users specify a specific range of dates. These animations provide a quick snapshot of precipitation and other specified variables in the region. The user can select which variable they want to see animated in this fashion.

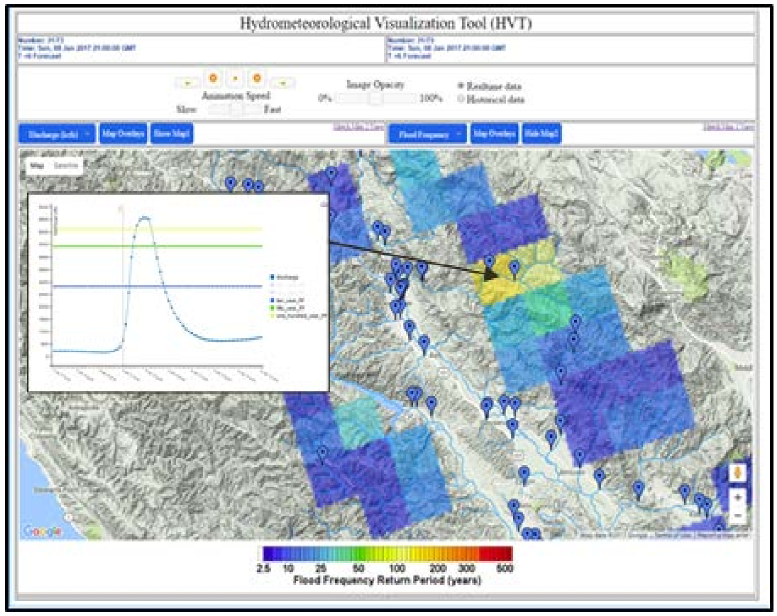


Figure 3 HVT displays time series of flows at a user selected grid. The hydrograph indicates the flood frequency levels associated with that grid.

- Users can look at specific day/time combinations and interact with the RDHM data for specific grids. Popups provided for specific grid points allow users to view and interact with the data in graph and tabular format.

- Overlay of grids of flood frequency levels can provide locations where flash flood emergency responders are needed. This capability is provided for all streams, including small tributaries, which currently have no flood information or flow gage rating curves.

- The HVT displays at-risk road crossings (Figure 4) and other flood impact features (e.g. schools and health care facilities) on user request.

2.1.2 National Water Model

During this project, the National Water Model (NWM) was introduced as the new DHM for the NOAA NWS. Because of the timing of the NWM implementation relative to the project timeline, it was deemed prudent to continue with RDHM. In the future development of Hydro-CoSMoS, we will conform with the standards of the NWM to enhance forecasting capability for operational purposes. The NWM delivers streamflow forecasts on the 2.7

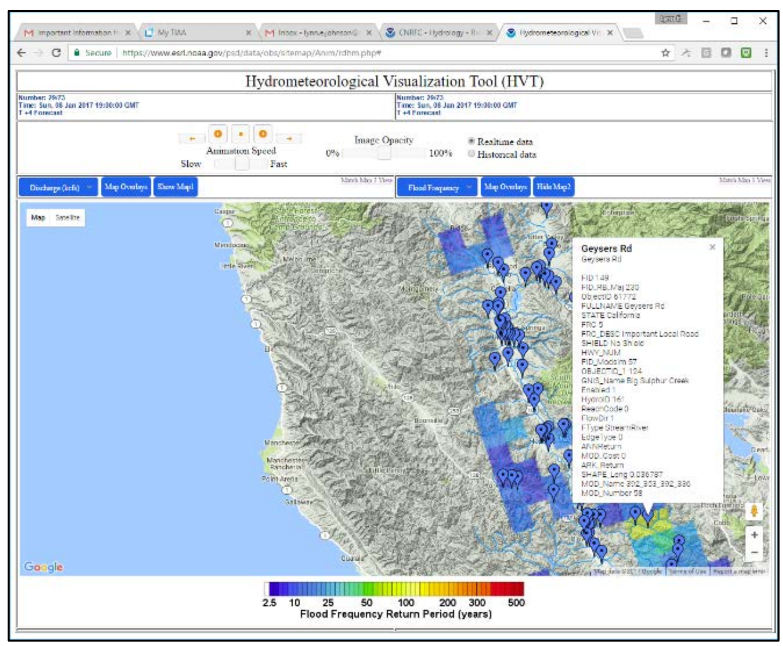


Figure 4 HVT user can interrogate (mouse click) a grid to identify road-stream intersections at risk for flooding.

million river reaches of the USGS National Hydrography Dataset (NHDPlus v2) as well as gridded analyses of a host of other hydrologic variables across the Nation. NWM is a hydrologic model that simulates observed and forecast streamflow over the entire continental United States (CONUS). The NWM will provide complementary hydrologic guidance at current NWS River Forecast Center (RFC) forecast locations and significantly expand guidance coverage and type in underserved locations (http://water.noaa.gov).

2.2 CoSMoS

2.2.1 Overview

The Coastal Storm Modeling System (CoSMoS, https://walrus.wr.usgs.gov/coastal_processes/cosmos/) is a dynamic modeling approach that has been developed by the USGS to allow more detailed predictions of coastal flooding due to both future sea level rise and storms integrated with long-term coastal evolution (i.e., beach changes and cliff/bluff retreat) over large geographic areas (100s of kilometers). In general, CoSMoS is a framework that takes large scale oceanic conditions and scales them using regional and local models to generate high resolution hazard predictions (P. Barnard et al 2014, Figure 5). CoSMoS represents all the relevant physics of a coastal storm (e.g., tides, waves, and storm surge), which are then scaled down to local flood projections for use in community-level coastal planning and decision-making. Rather than relying on historic storm records, CoSMoS uses wind and pressure from global climate models to project coastal storms under changing climatic conditions during the 21st century.

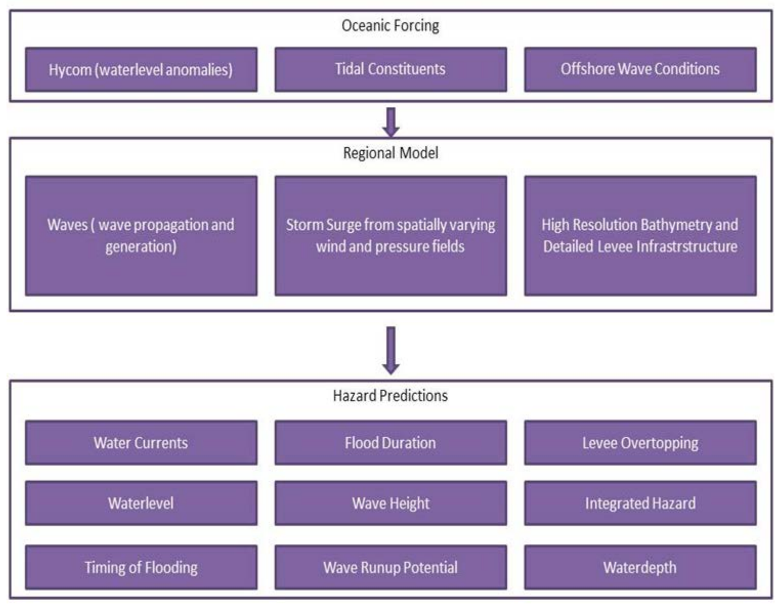


Figure 5 Cosmos Structure

In this implementation of CoSMoS, the oceanic forcing is forced by astronomic tidal constituents as described by Topex/Poseidon 7.2 (Dushaw et al 1997), and additional regional water level anomalies are obtained from an operational 7-day forecast run of the Hybrid Coordinate Ocean Model (HyCOM) by the Naval Research Laboratory at 1/12-degree resolution (Cummings and Smedstad, 2013; Cummings, 2005; Fox et al., 2002). The offshore wave conditions are found from an operational 3-day wave forecast furnished by the Coastal Data Information Program, Integrative Oceanography Division, operated by the Scripps Institution of Oceanography. The wave forecast is a combination of the NOAA Wavewatch III model for deep water and CDIP's spectral refraction wave model for shallow water (O'Reilly et al., 2016; Tolman, 1998). The coupled hydrodynamic-wave model simulates the forecast period in approximately 40 minutes using 64 processors on a high-performance computing cluster.

For the regional model, we used the hydrodynamic modeling software DFlowFlexibleMesh from Deltares (DflowFM) which implements a finite volume method of conservation of mass and conservation of momentum on a staggered unstructured grid (Kernkamp et al., 2011). Our set up for San Francisco Bay includes a domain that extends 90 km offshore of the Golden Gate and to Point Arena in the north and

Monterey in the south (300 km). There are 202,842 grid cells in the domain with the size of the grid cells ranging from 4 km at the ocean side to as small as 5 meters in the coastal region near the Napa watershed. (Figure ure 1) This model is coupled to a structured grid wave model, Simulating Waves Nearshore (SWAN). SWAN solves the spectral energy density balance and accounts for wave propagation in time and space, shoaling, refraction due to current and depth with frequency shifting due to currents and non-stationary depth. It allows for wave generation by wind, white capping, bottom friction and depth-induced breaking. It also computes wave-induced set-up. The SWAN grid has 134,200 cells and covers approximately the same area as the DFLOWFM grid. The currents and waves interact by having communication between SWAN and DFlowFM at a 20-minute interval.

The bathymetry in the regional models was determined by averaging the closest four depth points from a 2-m digital elevation model (Foxgrover et al., 2011 and 2014). Fixed weirs are used to represent regional levees (SFEI, 2016) in the model. Fixed weirs are defined at the velocity points and block flow between the two adjacent computational cells, when water levels are below the specified height of the fixed weir, without reducing the total wet surface and the volume of the model. This allows us to represent levees which have sub-grid dimensions, but are large enough to change flow patterns and flood extents. Major river discharges are, unless directly simulated as in the Napa River case, set to typical winter (November through March) values. Water levels are initialized from a non-storm condition.

2.2.2 CoSMoS Products

There were many products that resulted from the CoSMoS framework, including flooding depths and extents, currents, water level, timing and duration of flooding, wave heights and wave run-up potential, levee overtopping and an integrated hazard metric. Flooding extents and depths (Figure 6) were determined by interpolating water levels (a direct output of the regional model) onto a 2m resolution grid and subtracting the DEM. The currents and wave heights are direct outputs of the regional model. These results were output on hourly intervals, from which we can determine the spatial extent of the timing of initial flooding, the timing of the maximum flooding and the duration of the flooding. Given computational time constraints we were unable to directly compute the wave run up, but by using our detailed bathymetry and some standard wave run- up formula from the engineering literature (van Der Meer 2002; EurOtop 2016) we could make estimates of wave runup in the domain which can contribute to extended flooding. The water levels can be compared to the digitized levee network (SFEI) to predict potential levee overtopping. Finally, we computed many integrated hazard metrics that included time integration of currents and water depth to find the locations which will be most impacted in a storm event, either through very fast currents, extremely deep water or extremely long flood duration, or some combination of the three.

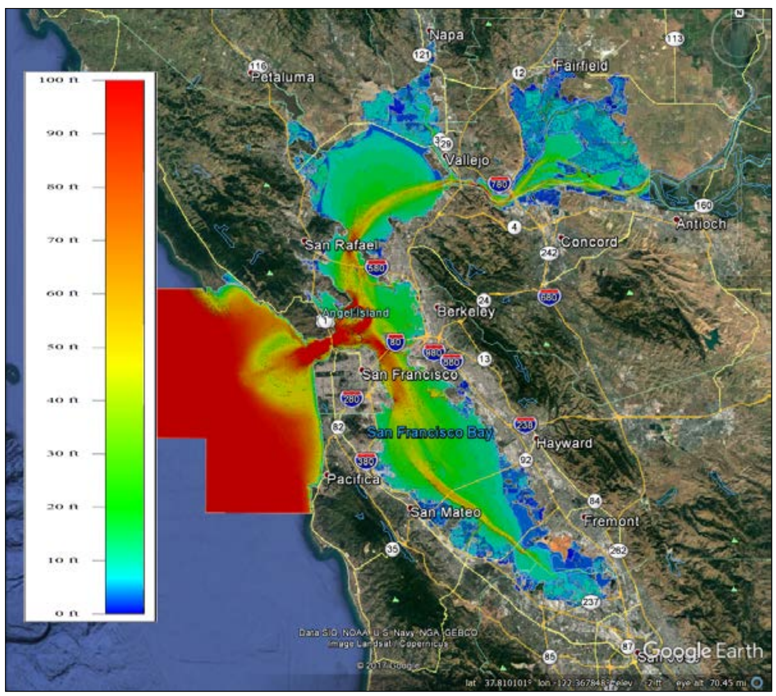


Figure 6 CoSMoS simulated maximum depth for San Francisco Bay.

Examples of these types of results are all shown in the Clickable PDF used in the TTE.

In previous CoSMoS work, projections of multiple storm scenarios (daily conditions, annual storm, 20-year- and 100-year-return intervals) were provided under a suite of sea-level rise scenarios ranging from 0 to 2 meters (0 to 6.6 feet), along with an extreme 5-meter (16-foot) scenario. This allows users to manage and meet their own planning horizons and specify degrees of risk tolerance.

3. Case Study

3.1 Flood Scenario

The project partners created a realistic storm scenario to demonstrate the use of the Integrated San Francisco (SF) Bay Coastal Flood Forecast Model (i.e. Hydro-CoSMoS) to emergency responders and planners for the Napa River region. Like the ArKstorm scenario (Porter et al 2010), this scenario is based on a combination of actual events that have occurred in the SF Bay area and consists of two components: the watershed and the coast. For the watershed, soil moisture and precipitation conditions were input into the watershed using a NOAA-NWS distributed hydrologic model (DHM), providing projections of fluvial-related flooding. For the coast, flooding was projected from waves, winds and atmospheric pressure modeled by using the USGS Coastal Storm Modeling System (CoSMoS) in SF Bay. The storm scenario combined these two components to provide projections for the watershed and coastal area for the Napa River basin and estuary.

3.2 Watershed Storm Scenario

3.2.1 Background

For the watershed storm scenario, we chose a storm event that happened over Napa County on December 23, 2012. This storm event had 58.3 mm (2.29 in) rain corresponding to 1-to-2-year return period for 12-hour precipitation. However, CNRFC issued a flood warning because of the high peak flow (13,100 cubic feet per second at 08:00 PST, December 24, 2012) corresponding to 5-year return period for streamflow. In addition, the soil moisture condition was 46% saturation, higher than normal soil moisture condition (23% saturation). This storm was then scaled-up to reflect a more significant flooding event, as described below.

To scale this storm to a more extreme event we modified the rainfall and soil moisture conditions. We estimated the 25-yr recurrence interval rainfall fields through NOAA Atlas 14 and MRMS data based on the radar products and scaled the 2012 storm to reflect the spatial-temporal characteristics of rainfall fields. We also increased the maximum soil moisture condition to 51% based on an actual storm event happened on March 27, 2012.

3.1.2 Watershed Scenario Pre-processing

The methodology for this study involved pre-processing to generate a distributed rainfall field in T-year recurrence intervals, estimation of antecedent moisture condition (AMC) as soil moisture, and implementation of flood frequency analysis to calculate T-year recurrence intervals from the simulated runoff flows. Figure 7 shows a flowchart of the methodology.

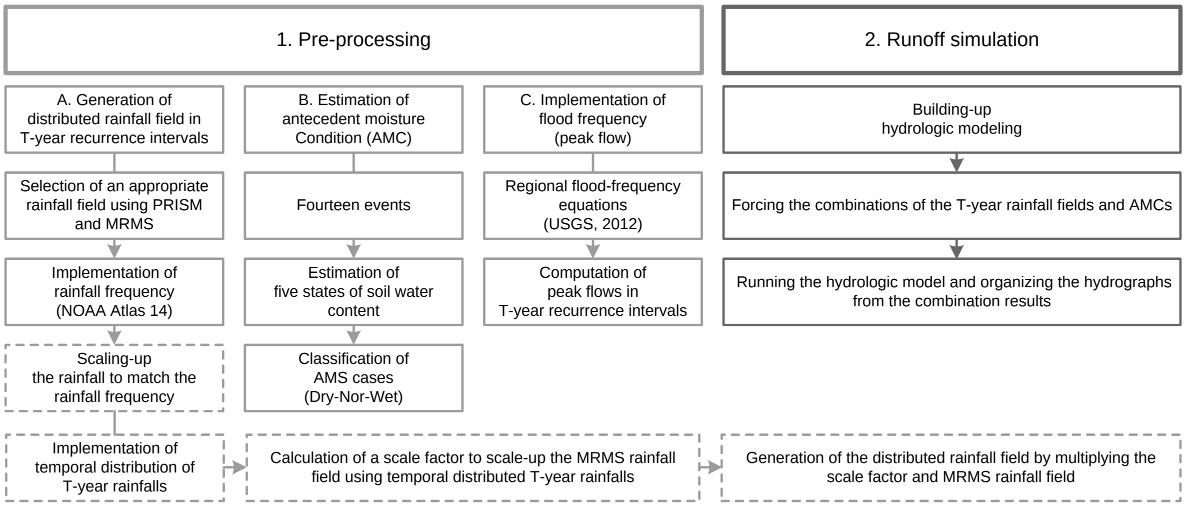


Figure 7 Flowchart of the methodology to establish the watershed scenario.

Generation of the distributed rainfall fields in T-year recurrence intervals was the first step (Figure 7). Pre-processing of the rainfall input considered the spatial distribution of MRMS radar-based rainfall field data, which can provide the spatial distribution features of the actual rainfall field. It also considered rainfall frequency to reflect various rainfall scales with T-year recurrence intervals. For the rainfall scaling, this study referenced NOAA Atlas 14 which contains rainfall frequency estimates for the United States with associated 90% confidence intervals. In this study, we selected the 25- year recurrence interval as the rainfall scale.

To generate T-year distributed precipitations, a simple assimilation approach is applied. In the assimilation approach, the spatiotemporal distributions of the target storm (Figure 8) and T-year precipitations are required. The target storm plays a role in providing spatial and temporal distributions and its duration for generating T-year distributed precipitation fields. If the target storm has a duration of 12 hours, for example, the specific T-year distributed precipitation in hourly time step consists of 12 of distributed precipitation fields equal to the target storm. Temporal distribution of precipitation, also, follows the target storm. The temporal distribution of the target storm is extracted using hourly areal average precipitation (AAP). The hourly AAPs are used to temporally distribute T-year precipitation as total amount of the precipitation is for 12 hours. The AAP is calculated from Eq. (1), and the temporal distribution of T-year precipitation is resolved as same as the target storm by using Eq. (2).

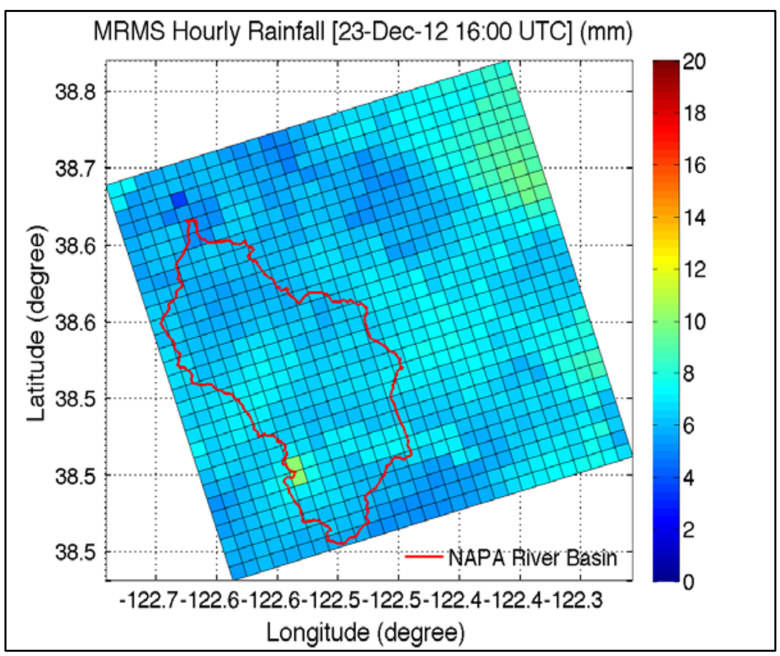


Figure 8 A sample Multi/Radar and Multi/Sensor rainfall field.

$$AAP\left(R_G(t)\right)=\left[\sum_{j=1}^{m}\sum_{i=1}^{n}R_G\left(t,i,j\right)\right]\times\frac{1}{n\times m} \tag{1}$$

$$R_F(t)=R_F\times\frac{AAP\left(R_G(t)\right)}{\sum_{i=1}^{duration}AAP\left(R_G(i)\right)} \tag{2}$$

$$F_{scale}(t,i,j)=\frac{R_G\left(t,i,j\right)}{AAP\left(R_G\left(t\right)\right)} \tag{3}$$

$$R_{FG}\left(t,i,j\right)=R_F\left(t\right)\times F_{scale}(t,i,j) \tag{4}$$

where, AAP is the areal average precipitation, $R_G(t)$ is gridded precipitation field (e.g. MRMS QPE products) at time t, $R_G(t,i,j)$ is each grid value in the gridded precipitation field, and n and m indicate a number of grids in row and column. $R_F(t)$ is the temporally resolved hourly T-year precipitation, R_F is T-year precipitation corresponding to specific recurrence interval. F_{scale} is scale factor for each grid value at time t. $R_{FG}(t,i,j)$ is each grid value in T-year distributed precipitation fields.

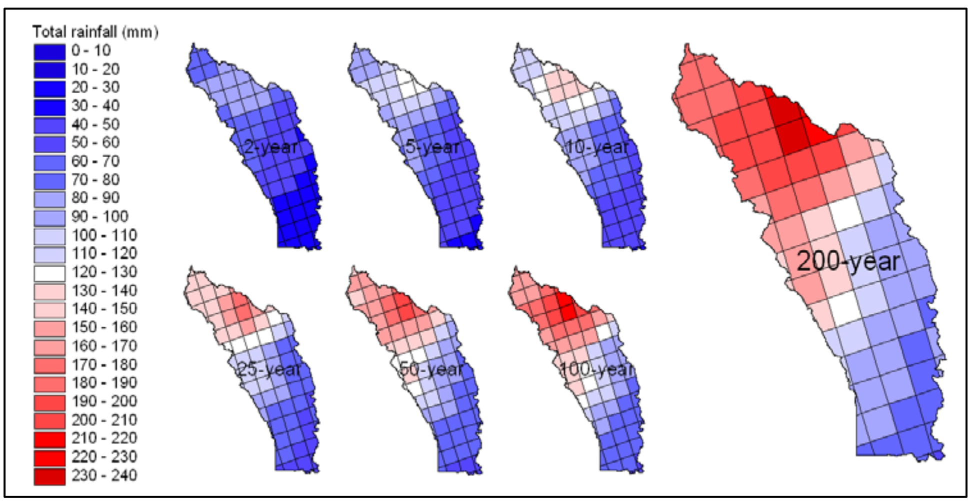


Figure 9 Radar-based distributed rainfall fields in T-year recurrence intervals (2-200 years) in the NAPA River basin.

The assimilation approach for distributed precipitation fields (using MRMS QPE products) and T-year precipitation is implemented using scale factors to match hourly precipitation amount of the distributed precipitation fields with the hourly T-year precipitation temporally resolved. In this process, the scale factor is calculated from Eq. (3) for each time step (t) and at each grid (i, j) of MRMS QPE data. From Eq. (3), MRMS QPE fields at each time step are normalized using the AAP value for whole girds. And then the MRMS QPE fields are scaled-up by multiplying the scale-factor to the normalized MRMS QPE field through using Eq. (4). So, the areal average value of the scaled-up precipitation field would be equal to the temporally resolved hourly T-year precipitation at the same time step. Through this step, T-year distributed precipitation can be generated for the duration of a target storm. Figure 9 shows the accumulated rainfall field generated for the 2-200 T-year recurrence intervals in the Napa River basin. In this study, the 25-year recurrence interval was used to simulate the hydrograph and generate flood runoff.

As a second process in pre-processing, 14 sets of five states of soil water content were estimated from a total of 14 rainfall events. This study used soil moisture states in the SAC-SMA model to estimate soil moisture conditions for the actual storm events to create an Arkstorm-like scenario. The SAC-SMA model has five soil moisture states to reflect an antecedent moisture condition (AMC) according to soil layer and moisture. The five states represent the amount of water retained in the upper/lower zone. The amount varies over the depth and for different types of soil. In the upper zone, the soil moisture state is rapidly decreased due to subsurface runoff by free water, and the tension water is reduced by evaporation (or evapotranspiration). In the lower zone, free water content consists of both supplemental and primary. Figure 10 shows the capacity of the five soil moisture states used in Napa River basin.

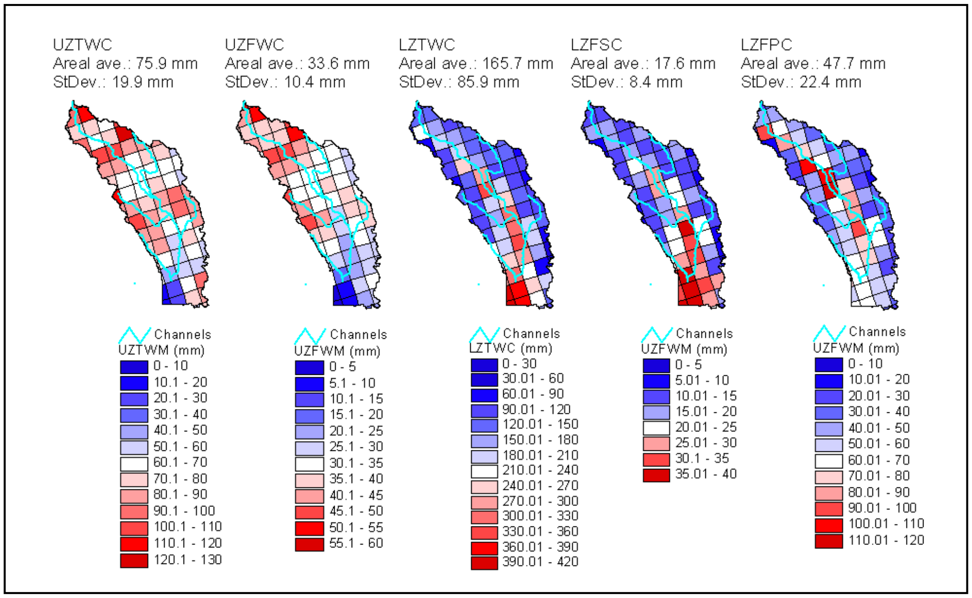
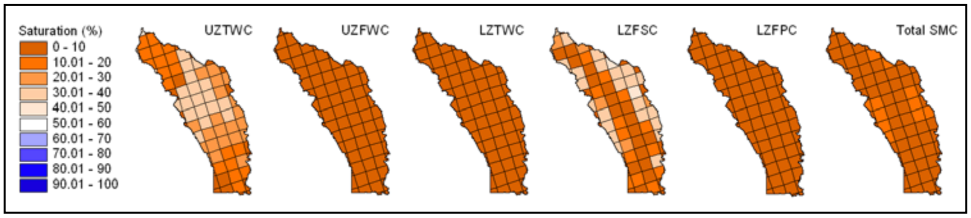


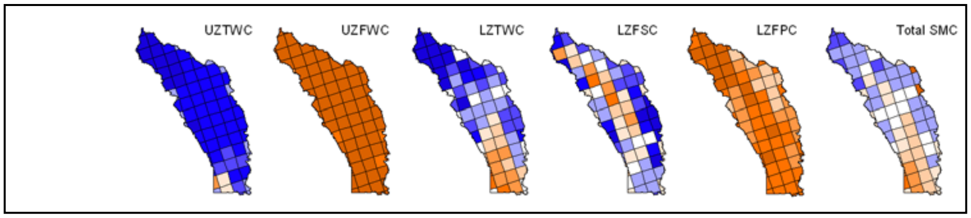
Figure 10 Capacity of initial states associated with soil moisture contents in the SAC-SMC Model

Figure 11 shows the five soil moisture states for both dry and wet conditions in the Napa River basin. For this study, we used the wet AMC condition to simulate a hydrograph for coupling with the CoSMoS model. The third process in pre-processing was to decide the flood frequency equations to derive T-year recurrence intervals from peak flows. In this study, the regression equations developed for coastal basins of California were referenced (USGS 2012). These equations involve the drainage area and mean annual precipitation for each grid cell, and were applied to derive the T-year recurrence interval for the simulated peak flow.

The flood runoff simulation was implemented using the 25-year recurrence interval of the generated rainfall fields and the wettest AMC condition. Therefore, one hydrograph arising from the combination was simulated, the peak flows were translated to their T-year flood frequency recurrence interval. According to the hydrograph result, maximum flood frequencies in the overall watershed were around the 100-year level at time corresponding to 36 hours of the simulation. Figure 12 shows the spatial distribution of streamflow and the resultant hydrograph from a selected location (Figure 12, red circle).



(a) Driest case (Event#10, UTC 11/19/2014 02:00)



(b) Wettest case (Event#03, UTC 03/27/2012 06:00)

Figure 11 Antecedent moisture contents (AMC) and its saturation in the driest and the wettest case.

3.3 Coastal Storm Scenario

3.3.1 CoSMoS Storm Scenario

For this scenario, we wanted to choose a storm that, while extreme, represented a reasonable and plausible event (Figure 13). The atmospheric and wave conditions were chosen to match historical conditions that created an observed 50-year return period non-tidal water level at the San Francisco gage station located on the south-east side of the golden gate. Water level data were analyzed from 1890 to present-day to determine the non-tidal residuals and the 50-year return period non-tidal water level was found to be near 44 cm (1.44 ft). Non-tidal water levels reached a peak of 44.1 cm at 4 pm on February 6, 1998. The wind, barometric pressure and wave conditions from that time were taken as representative conditions for a 50-year storm.

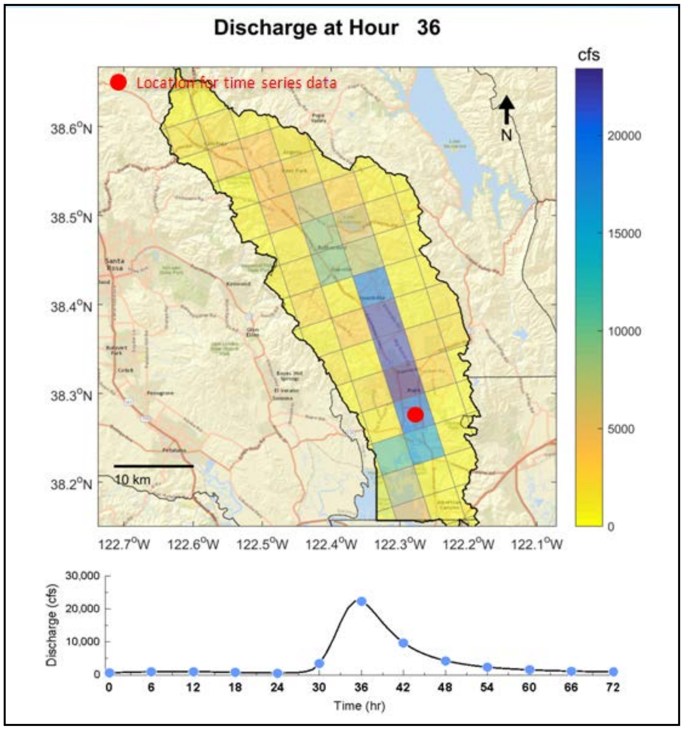


Figure 12 Spatial distribution of streamflow and a hydrograph for coupling with CoSMoS.

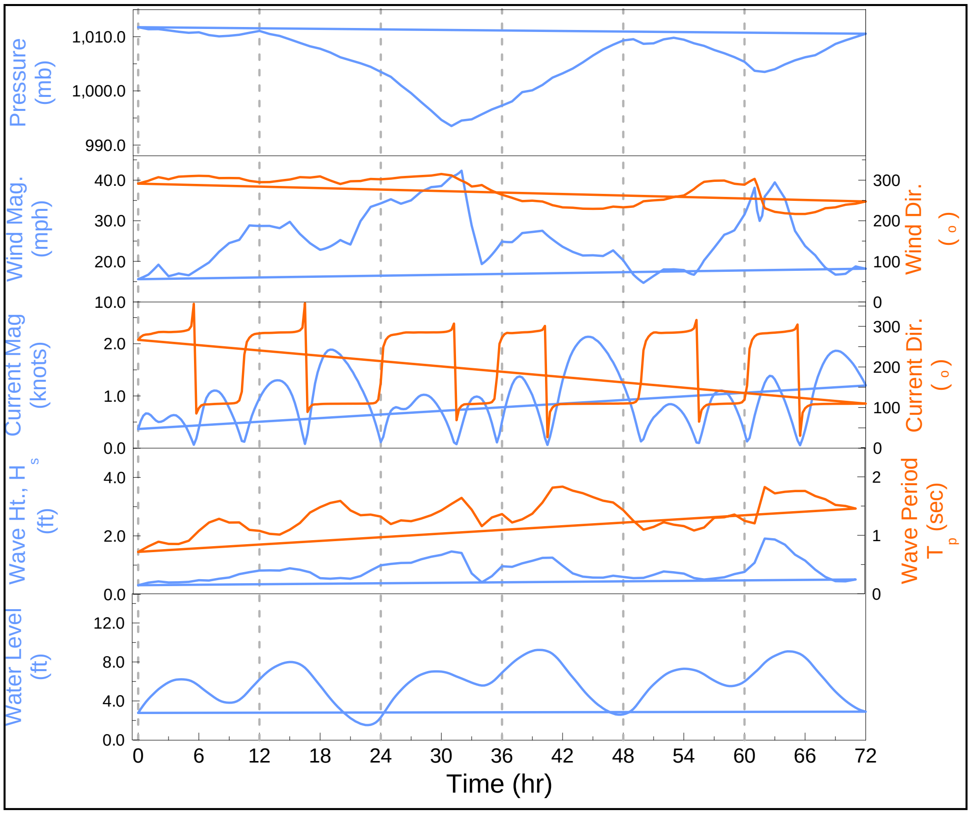


Figure 13 Summary of meteorological and hydrodynamic conditions at the Napa River mouth for the 72-hour coastal storm scenario.

During this 50-year storm wind speeds ranged from 4-12 ms-1 (9- 27 mph) and were predominantly from the south-west direction. The atmospheric pressure reached a low of 984mb in this storm. Offshore waves ranged from 3.4-8.2 m (11.2-26.9 ft) significant wave height and had a peak period of 20s with most of the energy coming from the west. These atmospheric storm and wave conditions were applied to a spring tidal period from November 2010. These tides represented slightly higher high tides and slightly lower low tides (i.e. a larger tidal range) but they are not as significant as king tides which occur later in the winter.

Additional effort was directed to defining the bathymetry of the Napa River near the City of Napa, as there has been recent construction of a flood bypass channel. Preliminary simulation indicated that tidal and storm surge influences would be felt at this location and further upstream. Field investigation provided details on the bypass channel configuration.

3.3.2 CoSMoS Storm Scenario Results

CoSMoS was used to simulate the coastal storm scenario to obtain water level and current variations for the 72-hour simulation period. Simulation results were generated for the SF Bay regional scale, and the San Pablo – Napa River local scale. Outputs included the spatial distribution of a) winds and pressure, b) wave heights, c) current speeds, and d) water depths. Figure 14 shows the maximum water depth for the local scale which extends up into downtown Napa.

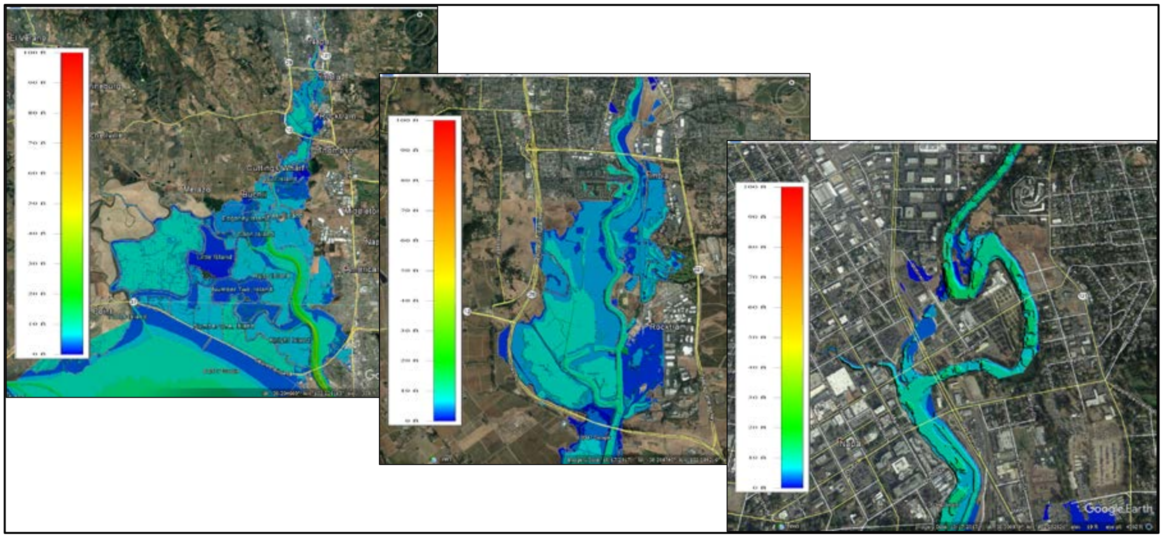


Figure 14 CoSMoS simulated maximum depth for San Pablo Bay and upstream to City of Napa.

CoSMoS also provided various flood hazard indices which involve CoSMoS and DHM model output data characterizing flood magnitude, extent and criticality. The Hazard Index involves time integration of currents and water depth to find the locations which will be most impacted in a storm event, either through very fast currents, extremely deep water or extremely long flood duration, or some combination of the three. Flood indices included: a) time to first flood, b) duration of flooding, c) time of maximum depth, d) maximum depth, and e) hazard index (a combination of depth and velocity). Critical facilities were mapped in conjunction with maximum flood depth, these included a) fire stations, b) schools, c) wastewater treatment plants, and d) roads (Figure 15).

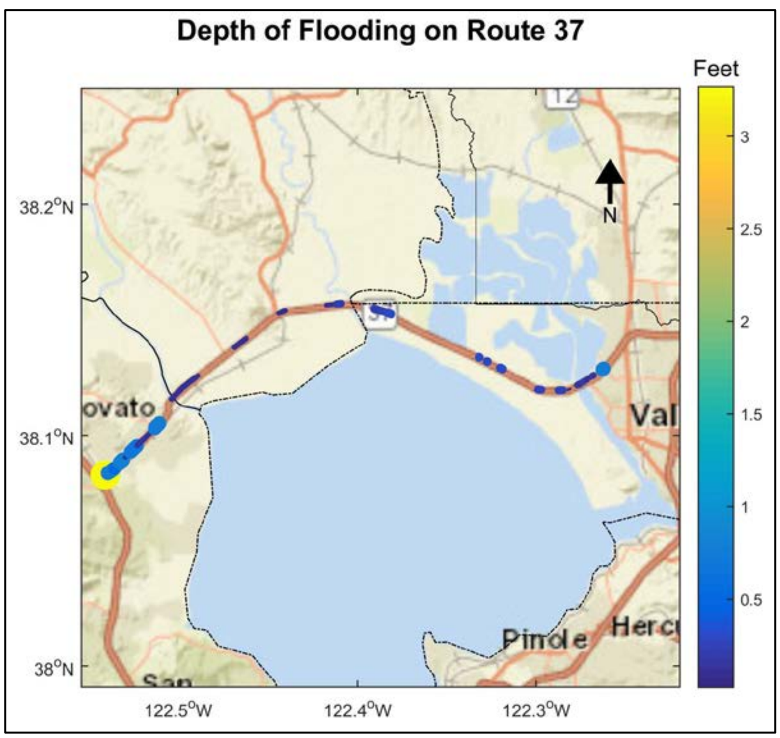


Figure 15 Coastal storm impact as depth of flooding for Route 37

3.4 Coupling the Watershed and Coastal Models

The general framework for the coupling of the models is housed in the Flood Early Warning System (FEWS), which is an open shell system for managing input/output communications that is extensively used in NWS forecasting products and for handling real-time time-series data (Figure 16) (http://oss.deltares.nl/web/delft-fews/).The coupling process involved retrieval of weather forecasts which are required to run CoSMoS, defined below, and provide the inputs for the distributed hydrological model.

The hydrological model was run for each watershed to provide a time series of discharge for the river which is passed to CoSMoS. The CoSMoS framework incorporated weather predictions and river discharge to ultimately make real time predictions that can be compared to recent observations. For this implementation we were only including the Napa River watershed, but this framework using FEWS can easily be extended to include more watersheds.

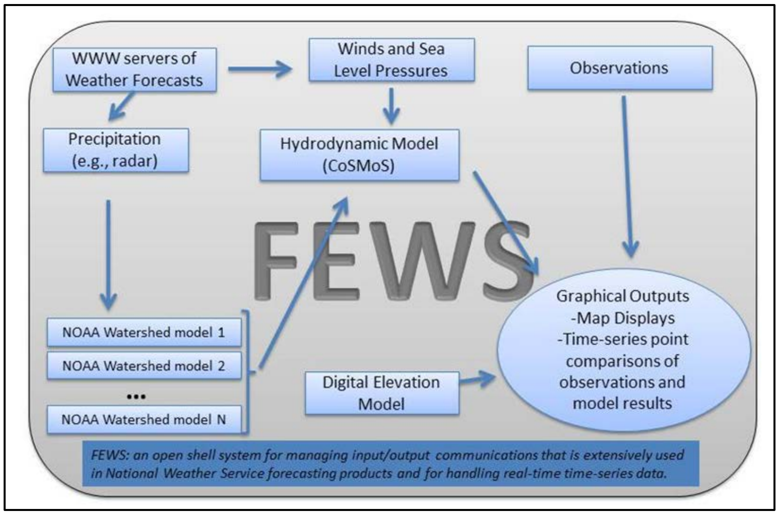


Figure 16 Flow chart of the coupling framework within FEWS.

4 Tabletop Exercise

4.1 Objectives of the Exercise

A table-top exercise (TTE) was created to advance users' understanding of the Hydro-CoSMoS modeling system, the various flood forecast products, and to inform design of a fully operational watershed-coastal flood forecasting system. TTEs are used in meetings to discuss a simulated emergency, in this case an event as defined by the watershed and coastal flood scenario (described above). They help increase understanding of technical details and information products, clarify roles and responsibilities, and identify additional mitigation and preparedness needs. These exercises typically result in action plans for continued improvement of the flood forecasting system. The Federal Emergency Management Agency (FEMA) has an Emergency Planning Exercises web page which provides guidance and resources (https://www.fema.gov/emergency-planning-exercises). For this TTE, members of the flood forecasting and emergency response community were asked to review and discuss the flood forecasting information and actions they would take, testing their understanding of the modeling outputs and emergency response plans in an informal, low-stress environment.

The TTE was held on June 13, 2017 at the CaDWR Flood Operations Center (FOC) in Sacramento, CA. The FOC is an advanced computing and networking facility used by the CaDWR and NWS CNRFC before and during flood events to assess risks, and coordinate flood response actions and communications with the various local, state and federal agencies and citizens. The FOC has a collection of networked computers and teleconferencing equipment by which to display hydrometeorological forecasts and current conditions.

4.2 Table Top Exercise Participants

The exercise involved attendees from a variety of local, state, and federal agencies on-site, as well as webinar remote access for at-distance participants. Participants in the exercise included a collection of managers and staff of the following organizations; see the appendix for a complete list of participants.

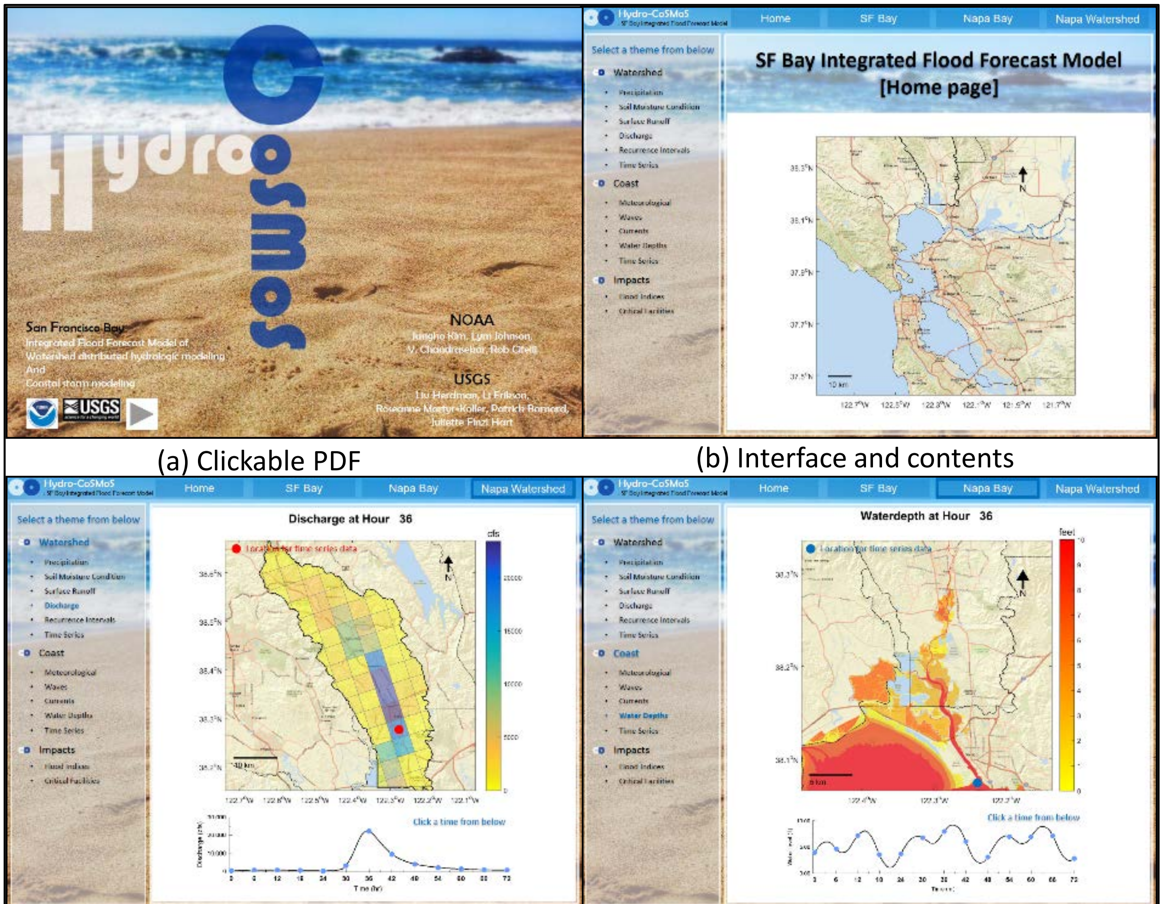
- Federal:
    - NWS CNRFC
    - NWS WFOs at Monterrey, Sacramento and Eureka
    - NOAA ESRL PSD Hydromet Modeling and Applications
    - USGS Pacific Coastal and Marine Science Center

- California DWR:
    - Flood Planning Group
    - Flood Operations
- California Dept. Transportation
- County Flood Response Agencies
    - Contra Costa County
    - Marin County
    - Napa County
    - Sonoma County
- Bay Area Flood Protection Agencies Association
- University of California - Davis

4.3 Clickable PDF

To facilitate demonstration of the functionality of the Hydro-CoSMoS system a “clickable PDF” document was created to provide an interactive medium for exploration of watershed and coastal model data and forecasts (Figure 17). The document was provided to participants beforehand, and was presented and reviewed at the outset of the exercise sessions. Users of the PDF were able to browse through the various flood model products in a manner like how they might be exposed to flood forecasts in real time. For instance, hydrological and meteorological data and flood forecast information products were time sequenced over the forecast period of 72 hours as described in the scenario above.

The clickable PDF had three main sections focused on the Watershed, Coast and Flood Impacts, depicting three regional scales: the entire SF bay, the smaller Napa – San Pablo Bay and the Napa watershed (Figure 17). The SF Bay view shows the largest map with the entire SF Bay area including watersheds. The Napa Bay map shows the model results on the map area focused on the estuary between watershed and bay. The Napa watershed shows of the entire Napa watershed with the spatial distributed cells based on the DHM gridding scheme. Users choose a map type depending on their preferred map scale and region of interest. The clickable PDF provided time series data at several specific locations and the model results were overlaid onto a geopolitical map of the San Francisco bay region. Over the watershed, the model results provide the map of precipitation, soil moisture condition, surface runoff, discharge and recurrence intervals, at 6 hourly intervals over a forecast from 0 to 72 hours. The coast region shows meteorological data such as wind and pressure, as well as model results for waves, currents, and water depths. The impacts represent the flood impact results from the Hydro-CoSMoS system and provides practical information to support decision making from users.



(a) Clickable PDF (b) Interface and contents

(c) Example: discharge in the watershed (d) Example: water depth in the coast

Figure 17 Clickable PDF

4.4 Description of Tabletop Exercise

During the workshop, workshop participants were guided through a tabletop exercise (TTE) that was designed to have them interact with the information and provide feedback on the usefulness and usability of the products developed and included in the clickable PDF.

The flow of the TTE involved the following activities:

Step 1: The scenario (as described above) was outlined for the participants (Figure 18).

Step 2: Participants in the room and on the phone, were given 15 minutes to review the data via the PDF. They were guided through reviewing the 400+ page PDF by using a format similar to the pre-exercise survey (Figure 19). Following the small group exercise, participants were asked to provide their feedback in a large group discussion. Notes were captured on flip charts (Figure 20).

Step 3: Information was provided to participants about flooding that had occurred during the winter of 2017 along a stretch of Route 37 in Napa County (Figure 21). Participants were then guided to assess the impacts to a stretch of Route 37 in Napa County based on Hydro-CoSMoS modeling and outputs. The participants were asked to consider the following questions to determine the usefulness of the example products:

1. Have you used information similar to this information before? If yes, what is the source?

2. What physical scale would you want this information?
3. Are the time intervals appropriate?
4. How else would you like to see this information displayed?
5. Does it matter the scale of the event? (i.e. Does a bigger event require different info than a smaller event)

During group discussion, representatives from Napa County provided insight into how the 2017 flooding was addressed, which information they used at the time, and how the information provided by the Hydro-CoSMoS model could enhance their response capabilities in the future.

Step 4. The entire group discussed overall impressions of the modeling system and outputs/products and identified next steps for the project.

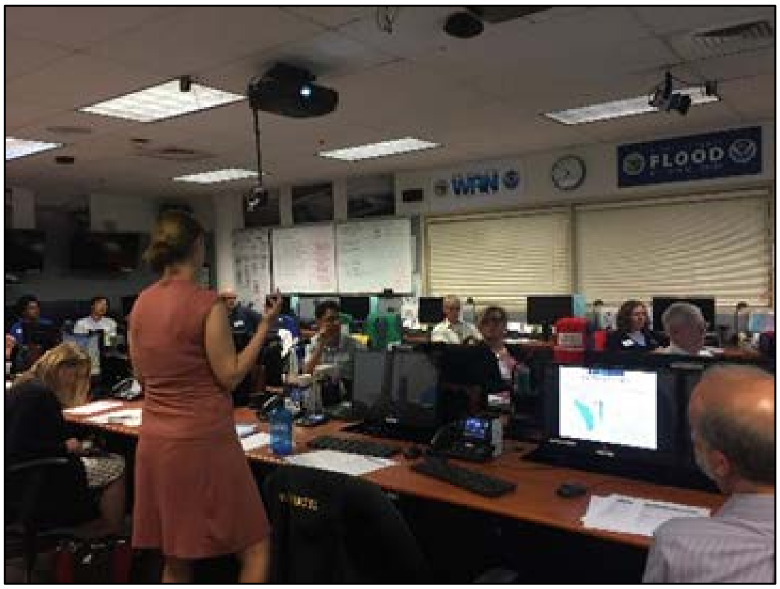
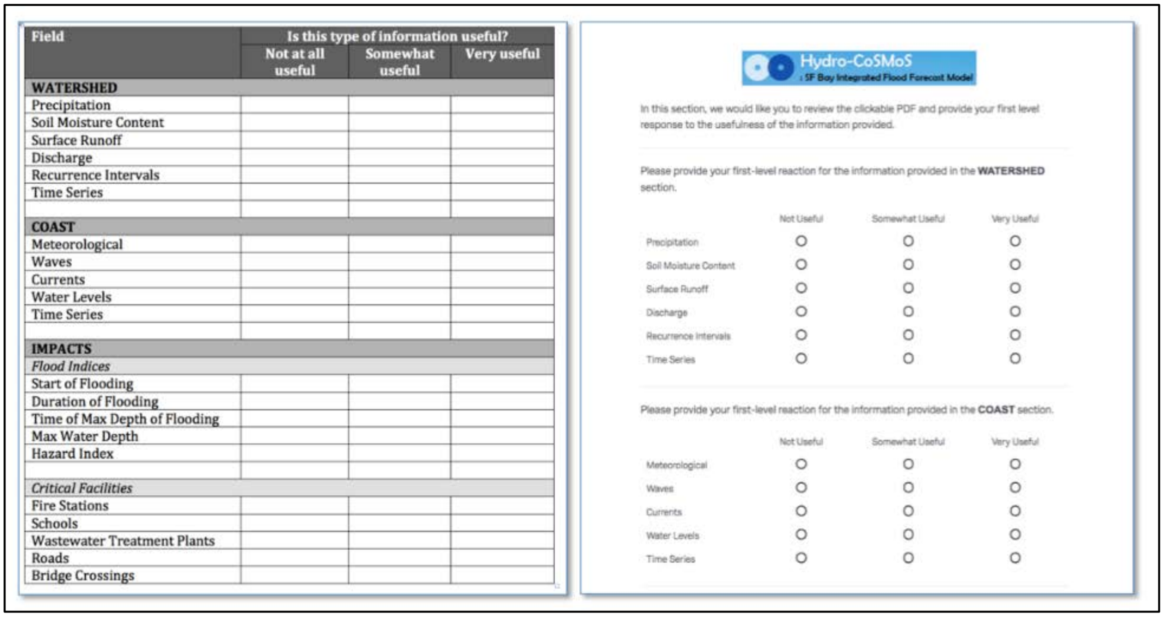


Figure 18 Tabletop exercise held at the CaDWR Flood Operations Center demonstrating the integrated coastal flood forecasting model.



Field	Is this type of information useful?		
	Not at all useful	Somewhat useful	Very useful
WATERSHED			
Precipitation			
Soil Moisture Content			
Surface Runoff			
Discharge			
Recurrence Intervals			
Time Series			
COAST			
Meteorological			
Waves			
Currents			
Water Levels			
Time Series			
IMPACTS			
Flood Indices			
Start of Flooding			
Duration of Flooding			
Time of Max Depth of Flooding			
Max Water Depth			
Hazard Index			
Critical Facilities			
Fire Stations			
Schools			
Wastewater Treatment Plants			
Roads			
Bridge Crossings			

Hydro-CoSMoS
: SF Bay Integrated Flood Forecast Model

In this section, we would like you to review the clickable PDF and provide your first level response to the usefulness of the information provided.

Please provide your first-level reaction for the information provided in the **WATERSHED** section.

	Not Useful	Somewhat Useful	Very Useful
Precipitation	○	○	○
Soil Moisture Content	○	○	○
Surface Runoff	○	○	○
Discharge	○	○	○
Recurrence Intervals	○	○	○
Time Series	○	○	○

Please provide your first-level reaction for the information provided in the **COAST** section.

	Not Useful	Somewhat Useful	Very Useful
Meteorological	○	○	○
Waves	○	○	○
Currents	○	○	○
Water Levels	○	○	○
Time Series	○	○	○

Figure 19 User survey forms for tabletop exercise. (Left) Participants in the room were provided a hard copy printout in which they could indicate the usefulness of each model product. (Right) Those on the phone, were provided a link to an online survey in which they could also provide real-

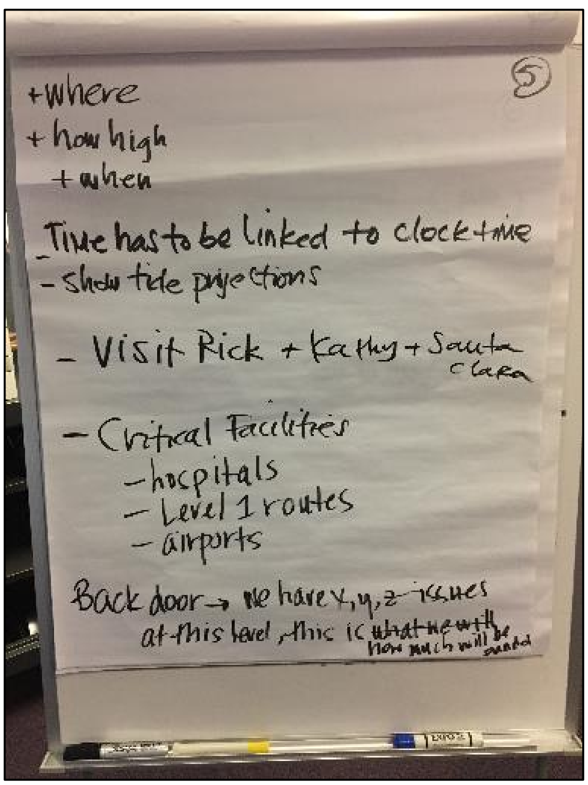


Figure 20 Photo of flip chart page. These were used to record group discussion comments.

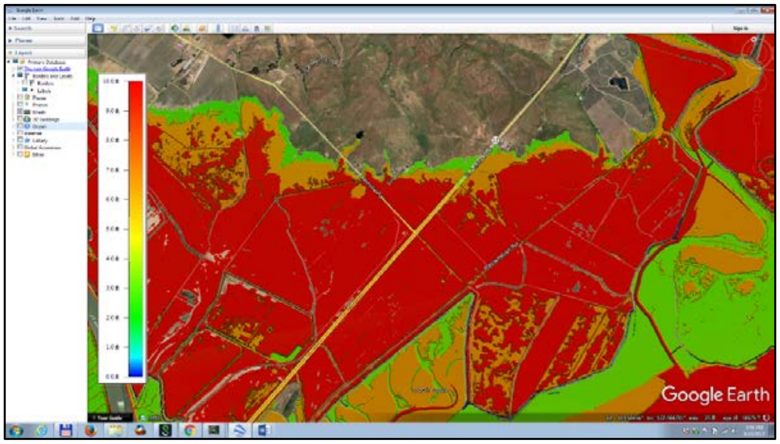


Figure 21 Screen shot of Google Earth view of flood potential over HWY 37 that was available for participants to explore and view during the Table Top Exercise.

5. User Survey of Watershed and Hydro-CoSMoS Products

5.1 Background

Two user surveys were conducted to assess various aspects of the Watershed DHM and Hydro-CoSMoS functionality and products. The purpose of the surveys was to document user satisfaction with the models for flood and flash flood operations experimental products or services and to collect suggestions for improvements.

The general context is that of a forecaster, or anyone, who is involved with determining flood and flash flood threats, issuing watches and warnings, and/or organizing for flood mitigation response. The process, illustrated in Figure 22 below, involves a sequence of information gathering, assessment, decision making and follow-up. With this guide in mind, the survey addresses information products that precede an event, including recent observed and modeled rainfall and soil moisture. Forecast rainfall would then be reviewed to identify magnitude and lead time. Then, the various DHM and Hydro-CoSMoS products would be reviewed to identify time and locations of flood and flash flood threats. The prototypes also provide products that identify at-risk facilities, such as bridge crossings, where mitigation actions might be directed.

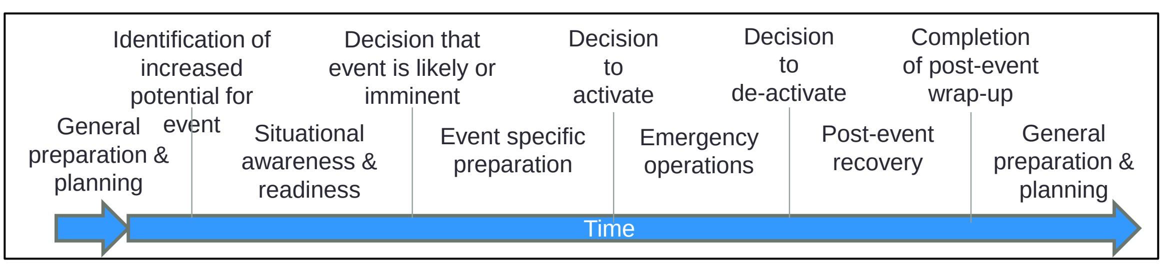


Figure 22 Major weather event decision cycle (after Morss and Ralph 2007)

Some questions involved assignment of a numeric ranking to quantify whether the respondent thinks the product is useful or not. These questions are usually followed by an optional comment box, so the respondent can include supplementary remarks and questions.

5.2 Watershed Distributed Hydrologic Model Survey

For the Watershed DHM project we established an Advisory Panel (AP) comprised of NWS staff and other users having interest in the DHM for flash flood operations. Five intended user groups were identified and a user-centered approach involving identification of users' needs and requirements was outlined. The user groups included the 1) NWS California-Nevada River Forecast Center (CNRFC), 2) NWS Weather Forecast Office – San Francisco-Monterrey (WFO-MTR), 3) Emergency Management Agencies (EMAs), 4) General Public, and 5) National Marine Fisheries Service (NMFS). A user-centered approach involving identification of users, and their needs and requirements, led to design of the interface and forums.

Retrospective assessments were conducted where the basic functionality of our distributed hydrologic model for flash flood operations (DHM for FFO) was demonstrated and feedback solicited from the Advisory Panel. The demonstration involved a GoToMeeting forum whereby the various CHPS-FEWS and HVT functions were shown, and comments by participants recorded. Rough transcriptions of these comments have been extracted from the recording and organized according to the primary flash flood services elements identified by the Flash Flood Summit (OWP 2015), namely 1) Observation and Monitoring, 2) Modeling, 3) Forecasting and Characterization, 4) Communication, and 5) Concept of operations.

An on-line survey was also conducted which obtained user ratings on the various gridded and related watershed forecast products, and comments on these. The forum comments are below, and the online survey results are tabulated in Appendix A.

- Quantitative Precipitation Estimation (QPE)
    - QPE data sources include WSR-88D, MRMS, CNRFC QPE, spotter reports, etc; all of which are collected and viewed in either AWIPS or internet browser.
    - Accuracy of precipitation fields is paramount. Forecasters' need some way to assess accuracy of differing precipitation products used as input to DHM. The display needs some error bars or ground gage data to compare.
    - Local ALERT-type rain gage data, coop reports, CoCoRaHS, and local media weather reports (e.g. radar imagery) are helpful. Looking at stream gage data is also very helpful.
    - CNRFC QPE is rated Somewhat to Very Much Helpful for flash flood location and magnitude. QPE is useful for "warming up" the DHM to establish initial states.
    - The MRMS is a system with automated algorithms that quickly and intelligently integrate data streams from multiple radars, surface and upper air observations, lightning detection systems, and satellite and forecast models. MRMS QPE has high resolution and can be set up to use alternate field data as available.
    - Russian-Napa River basins are largely blocked from radar coverage, so radar-rainfall products are not very accurate unless ground truth involved.

- Quantitative Precipitation Forecast (QPF)
    - The GFS has quite coarse resolution making it a poor choice for flash flood forecasting. It has an approximate horizontal resolution of 13 km for the first 10 days and 27 km from 240 to 384 hours (16 days). It produces forecast output every hour for the first 12 hours, three hourly through day 10 and 12 hourly through day 16.
    - HRRR QPF seems to be preferred but may have latency problems. The Rapid Refresh (RR or RAP) is a numerical weather prediction (NWP) model. The model is designed to provide short-range hourly weather forecasts for North America. The grid points are spaced every 13 kilometers (8.1 mi). The model runs once each hour, with forecasts given hourly out to 18 hours.
    - The HRRR is a NOAA real-time 3-km resolution, hourly updated, cloud-resolving, convection-allowing atmospheric model, initialized by 3-km grids with 3-km radar

assimilation. Radar data is assimilated in the HRRR every 15 min over a 1-hr period adding further detail to that provided by the hourly data assimilation from the 13-km radar-enhanced Rapid Refresh.
  - QPF rated Somewhat to Very Much helpful for FF location and magnitude; rated Not at All to Somewhat Helpful for FF lead time.
  - Availability of rain gage data is important as input to rainfall field mapping.
  - A concern is that rain gage data may be delayed in transmission so not available.
  - Local agencies' ALERT gage readings are routinely obtained by the WFO-MTR, but there are few ALERT stations in the Russian-Napa River basins.
- Soil Moisture Grid Display
  - Soil moisture data was rated Very Much Helpful for assessing watershed initial conditions.
  - Some commented it is the most useful new data set available. However, others commented that the soil moisture data can be misleading and late. SM data is not being assimilated into DHM model. One commented that it is much better to monitor rate of runoff from particular stream gages to get a feel for how saturated the soils are.
- DHM Discharge Grid Display
  - The DHM approach is of great interest as it provides hydrologic forecasts for all grid locations, including ungaged locations.
  - Flash floods are events which occur in less than 6 hours of intense rain, thus making small tributaries having rapid response a primary concern. The CHPS-FEWS-DHM computes at a 1-hr time step. Even for precipitation forecasts issued at larger time steps, the CHPD-FEWS interpolates the data down to a 1-hr time step. This contrasts with the official NWS CNRFC forecasts which are developed for selected locations on the main stem of the major rivers which have response times of greater than 6 hours.
  - DHM discharge rated Somewhat to Very Much helpful for FF location and magnitude. The (4 km) grid cell seems very coarse to accurately predict flash flooding, but would be useful for predicting potential threats. DHM discharge had varied responses per helpfulness for FF impacts. Need rating curves or some other means to determine how deep the water is, which is only available at gages sites.
- DHM Flow Frequency Grid Display
  - DHM flow frequency grid was rated Somewhat to Very Much helpful for FF magnitude; less so for FF location and impacts.
  - The flow frequency grid display provides a more qualitative rendering of model output to show levels of flash flood threat
  - Most understood the TF concept very well, but some did not.
  - Provides context if user is not familiar with typical flow levels. Useful for impacts and for a check on the forecast (do I really want to forecast a 100-year event).
  - Normalizing the flow levels to their flood frequency equivalent, the threshold frequency (TF) was strongly endorsed.
- DHM Discharge Hydrograph Displays
  - The hydrograph provides a more quantitative rendering of model output to show flood flow levels and stages. Interrogation by mouse click rated Somewhat to Not at All difficult for obtaining hydrograph.
  - Most rated the DHM flow hydrograph display as Very Much helpful for FF location, magnitude, duration, and lead time.
  - Comparison with USGS gage flows was considered very helpful. Rating curves are available for all USGS and most other gaging stations which can provide information on water depth.

    - Water level (flood inundation) would be even more helpful. Need to have some sort of E-19 data with these gages or locations to know what the impacts are. The DHM does not yet provide detailed flood inundation mapping information.
- DHM Impact Features Displays
    - Overlay of the grid onto the Impact Features layer provides useful utility for identifying features at risk to public safety.
        - The bridge crossings layer allows interrogation by users to get name and other metadata about the location. Color coding of bridge crossings based on the TF level was endorsed. Need to have some sort of E-19 data with these gages or locations to know what the impacts are.
        - The 4-km grid may be too coarse for precise portrayal of impact feature risk. The demonstration showed one grid with 4 impact features interior. Questions arose pertaining to:
            - Which impact feature should receive attention by responders?
            - What flow level is represented in the grid when there are multiple streams interior?
        - The prototype was not designed to portray flood inundation maps. The DHM outputs such as flow rate could be used as input to a more detail flood plain hydraulic model to accomplish this.
- DHM Accuracy
    - The DHM was rated Sometimes to Frequently accurate enough for flash flood magnitude, location, timing, and impacts.
    - It would be helpful for improved temporal resolution.
    - Better than not, all depends on accuracy of weather model inputs.
    - Need improved calibration, and regulation modeling.
    - All agree that DHM performance statistics can guide use of DHM products.
- DHM Forecasting Operations
    - Adding this into a forecaster's arsenal will undoubtedly help improve situational awareness of a rainfall event.
    - Maintenance of the data feeds requires continuing attention. Changes in data formats, upgrades to computer operating systems, and other software and system issues are commonplace.
    - The CHPS-FEWS-DHM system is complicated and designed to be operated by a highly trained expert having understanding of meteorology and hydrology, and the various capabilities for managing such data and the functions incorporated into the system.
    - There is not time for a WFO forecaster to work the CHPS-FEWS-DHM system to obtain flash flood information. The system must work automatically and provide forecast products in an automatic and timely manner.
    - The WFO-MTR Service Hydrologist has capability for using the CHPD-FEWS-DHM system during 2 to 3-day ahead preparations for flash flood operations, but not during an event. Preparations may involve setting up the DHM, selecting input and output datasets and conducting calibration/verification activities.
    - Procedures for working with DHMs have not been established. These include:
        - Establishing calibrations and QA/QC for precipitation and DHM precursors.
        - Developing some way to “nudge” the DHM to obtain more accurate simulations?
- Concept of Operations:
    - The HVT web service was considered a good way to provide flash flood information to NWS forecasters and a wider audience involving local emergency response agencies.

        - Capability for a user to interact with the DHM outputs to obtain actionable information is required. The demonstration was useful in showing a user interrogation of the DHM grids to identify the flash flood criticality, and to obtain metadata about the specific location.
    - We can help highlight areas of concern for excessive rainfall to EMs and the public through partner emails or social media messaging before the event.
    - I could see that a product like this would be useful for county emergency responders during to help flood response planning. (Helpful) to support personal decision-making. (Helpful to) identify areas of risk, timing of risk, and general level of event.
    - Another piece of the puzzle but not the answer.
    - Latency of the product can be very long and for flash flooding need to run hourly if needed with new gridded QPE and QPF. Can't have 1-3 hr latency of model data feeding the RDHM.
    - Need to have the model forecast and the obs for the gages in the display so we can see how the model is doing near real-time.
    - The "Who" for DHM forecasting has not been defined.
    - Migration of the RFC and WFO organizational structure and responsibilities for flash flood services has not been defined.
    - The DHM soil moisture grid data are being used to inform development of RFC Guidance at several regions.
    - The CNRFC expressed interest in developing a new way to forecast flash flood threats without dependence on simplified RFC Guidance methods.
    - There is sensitivity to DHM flow predictions being made for the same main stem locations where the CNRFC also makes forecasts. This sensitivity can be mitigated using the TF approach for representing flash flood threats.

5.3 Table Top Exercise Survey

A second survey was conducted prior to and during the TTE workshop; attendees were provided access to the Clickable PDF as well as a link to a questionnaire. The goal of the questionnaire was to provide a guided format for participants to review the clickable PDF and provide initial responses to the initial modeling outputs developed. In the questionnaire, respondents were asked information about their organization, their needs for coastal, estuarine and watershed flooding information, and what types of flooding information and products they currently use. They were then asked to review the clickable PDF and provide initial first-level responses to the usefulness of the various products.

The discussion throughout the TTE provided valuable information for the project partners. Some of the comments addressed the outputs provided in the clickable PDF, but most of the comments addressed how to make the Hydro-CoSMoS information relatable and usable by the largest number of end-users. Results of the survey are tabulated in the Appendix; we highlight some of the key findings below.

- Needs for Coastal Flood Forecasts
    - NWS forecasters use radar data, flash flood guidance, rainfall reports, and river data for their warning decision making.
    - County-level staff are concerned with storm surge into flood control channels and protecting communities and ecosystem restoration projects thereby. Some counties track flood threats and issue warnings.
- Flood Data Sources:
    - Most use NWS warnings, including from the WFO and the CNRFC. Some track precipitation reports (public and private), spotter reports (phone, email,, social media, and news media), USGS stream gages.
    - Some county staff have their own precipitation and stream gage networks.
- Watershed Forecasts:

- Participants indicated that the timing needs to be linked to local time. Hourly projections at a minimum during an event are preferred.
    - The time series outputs (i.e. hydrographs) were generally deemed to be helpful.
    - Local responders want to see information at a finer scale (e.g. 250m) than currently provided by the Napa Watershed modeling.
    - Precipitation information rated Very Helpful.
    - Soil moisture rated Somewhat Helpful.
    - DHM surface runoff rated Not Useful to Somewhat Useful.
    - Recurrence interval rated Very Useful by most, but some rated Not Useful.
    - Time series unanimous Very Useful. Would like to see flood stage.
    - Relate water flows to citizen experience.
        - Use storms of record (preferably within a 10-year window) to allow some comprehension of projected storm event.
        - Depth and velocity of flow relate to danger.
- Coastal Flood Forecasts:
    - Meteorological data rates Somewhat Useful. Helps establish context.
    - Wave forecasts rated unanimous Very Useful.
    - Currents forecast rated Somewhat Useful; some rated Not Useful.
    - Water level forecasts rated Somewhat Useful to Very Useful.
    - Time series forecasts rated Very Useful.
    - Suggest overlay FEMA Floodplain for reference; also recent flood inundation levels.
- Coastal Flood Indices:
    - People primarily want to know - Where, How High and When.
    - Consider describing projections as “ankle deep” “knee deep” etc. Indicate flood stage.
    - Incorporate tide projections so that responders can be aware of the confluence of tides with flooding projections.
    - Need to consider audience – is it Emergency Managers and First Responders or someone else?
    - Need to consider point of products – newscast or police with blow horn saying need to evacuate?
    - (Would be good to have) local corroboration of projected flooding.
    - Flood indices uniformly rated Somewhat to Very Helpful, including those for a) Start of Flooding, b) Duration of Flooding, c) Time of Max Depth, d) Max Water Depth, and e) Hazard Index (although some confusion on what it means).
- Impacts – Critical Facilities:
    - Identification of fire stations, schools and wastewater treatment plants rated Somewhat Useful. Suggest include hospitals and airports.
    - Identification of roads and road crossings (bridges) rated Very Useful.
    - Identify key locations for each region...to help bring context to flood projections.
    - EOC locations could be included in an internally (non-public) available layer - but that would not be good to include a public layer.
    - Forecasters have hydro-database (E-19).
    - Develop database service of user-generated content.
    - Need to narrow in on the audience for each product or output. Are the outputs geared to first responders or others?

6. Summary and Conclusions

6.1 Summary

The San Francisco Bay Integrated Flood Forecasting Project to demonstrated the feasibility of linking tributary and coastal storm models in San Francisco Bay. The demonstration was based on a direct coupling of the discharge from the watershed model into the coastal model, a first step toward a more advanced coupling. A TTE was conducted at the culmination of the project, to engage potential stakeholders and end users and solicit feedback on the kinds of information needed from an integrated flood forecasting system in the Bay area.

6.2 Conclusions

- The prototype Hydro-CoSMoS was deployed and demonstrated capability to provide watershed and coastal flood information at scales and at locations not currently served by NWS operations.
- The DHM was interfaced to WFO precipitation forcing datasets available in real-time at the WFO and NOAA Physical Sciences Division in Boulder, CO. RDHM outputs were generated using hydrologic modeling software such as CHPS/FEWS and DHM products disseminated using web services. These precipitation data feeds were used to assess potential improvements in runoff predictions with the distributed modeling approach.
- The DHM prototype and interactions with our Advisory Panel supported examination a concept of operations, requirements specification, and toolkit for DHM implementation and application for NWS flash flood operations.
- Coordination was accomplished with the NWS agencies involved with hydrologic operations in assessment of the RDHM for WFO operations, including the WFO-MTR, CNRFC, NWC and Western Region.
- Assessment of the DHM implementation was conducted to determine how best to implement the model to support flood forecast operations, identify constraints and opportunities for enhanced flood and water management applications which could be sustained by WFO/RFC DHM operations.
- The assessments provided useful feedback on local needs, which model outputs are useful and usable, and how best to communicate the various model outputs. Participants expressed interest in continued discussions as the Hydro-CoSMoS model continues to be built out for Napa and the other watersheds in the SF Bay.
- Integrating coastal storm and fluvial events is of growing importance, and coastal models operate best at a regional scale making this multi-watershed with one coastal modeling system a highly efficient approach.
- The project was successful in showing how tributary flows could be used to inform the coastal storm model during a flooding scenario.
- The demonstrations of prototypes provide a basis for a larger project to fully couple the models and provide forecasts in real-time for the entire SF Bay region.
- By joining together regional resources a tool can be built that will help all areas, notwithstanding local staffing limitations.
- As with all operational models, we also confront the challenge of balancing desired resolution and computational resources.
- Interaction with many local authorities in design of system is helpful in optimizing usefulness, and allows validation in locations with little data by tapping local knowledge base and experience.

- The assessments provided an opportunity for the model developers to interact with the end-users of their information, providing valuable information to help guide continued model development and to inform what model outputs are most relevant to end-users.
- Similarly, the assessments provided an opportunity for the end-users to become familiar with this emerging tool and to gain an initial level of understanding prior to advancement to real-time operations. This helps develop an engaged end-user who will be more likely to utilize the model products once it is running operationally.
- The assessments also enabled the project team to learn about other potential end-users and leverage the results of this these exercises to engage subsequent end-users in the SF Bay region and other counties in CA.

7. Acknowledgements

This project was supported by a grant from the California Department of Water Resources under the guidance of Dr. Michael Anderson, State Climatologist. The FEWS implementation of RDHM and prototyping of near real-time simulations was part of a grant provided by the NOAA Office of Oceanic and Atmospheric Research (OAR), Office of Weather and Air Quality (OWAQ), FY2015 US Weather Research Program, Hydrometeorology Testbed (HMT) and Hazardous Weather Testbed (HWT) Grant Award # NA15OAR4590151. The NOAA Physical Sciences Division provided resources to supplement project support from DWR, ancillary data sets, and access to the CHPS-FEWS system for the DHM forecasts.

Project personnel who have collaborated in developing the prototype flood forecast system include ESRL-PSD’s Jungho Kim, Lynn Johnson, Tim Coleman and Rob Cifelli. Riverside, Inc’s James Halgren and John Park contributed to implementation of the distributed hydrologic model. USGS coastal modeling staff include Liv Herdman, Rosanne Martyr-Koller, Juliette Finzi Hart, Li Erikson and Patrick Barnard.

8. References

Barnard , Patrick L., David H. Schoellhamer, Bruce E. Jaffe, Lester J. McKee, 2013. Sediment transport in the San Francisco Bay Coastal System: An overview, Marine Geology, Volume 345.

Barnard, P. L., van Ormondt, M., Erikson, L.H., Eshleman, J., Hapke, C., Ruggiero, P., Adams, P. N., and Foxgrover, A. C., 2014. Development of the Coastal Storm Modeling System (CoSMoS) for predicting the impact of storms on high-energy, active-margin coasts. Natural Hazards, 31 p., doi: [10.1007/s11069-014-1236-y](10.1007/s11069-014-1236-y)

Cummings, J.A., and O. M. Smedstad. 2013: Variational Data Assimilation for the Global Ocean. Data Assimilation for Atmospheric, Oceanic and Hydrologic Applications vol II, chapter 13, 303-343.

Cummings, J.A., 2005: Operational multivariate ocean data assimilation. Quart. J. Royal Met. Soc., Part C, 131(613), 3583-3604.

Dusterhoff, S. D.; Beagle, J.; Collins, J. N.; Doehring, C. 2014. Initial Protocol to Identify and Delineate the Head of Tide Zone in San Francisco Bay Tributaries. San Francisco Estuary Institute: Richmond, CA.

EurOtop, 2016. Manual on wave overtopping of sea defences and related structures. An overtopping manual largely based on European research, but for worldwide application. Van der Meer, J.W., Allsop, N.W.H., Bruce, T., De Rouck, J., Kortenhaus, A., Pullen, T., Schüttrumpf, H., Troch, P. and Zanuttigh, B., www.overtopping-manual.com.

Fox, D.N., W.J. Teague, C.N. Barron, M.R. Carnes, and C.M. Lee, 2002. The Modular Ocean Data Assimilation System (MODAS). J. Atmos. Ocean. Technol., 19, 240-252.

Halgren, J., L. Johnson, T. Coleman and R. Cifelli. 2015: RDHM-CHPS Research-to-Operations Demonstration, Russian-Napa River Basins, CA. Poster for 6th NOAA Testbed and Operational Proving Ground Workshop. April 14.

Johnson, L.E. 1995: DARE Hydrologic Evaluations (1990-1992) - Assessment of Hydrologic Forecasts. NOAA Technical Memorandum. Forecast Systems Laboratory. Boulder, Colorado. June. 70 pp.

Johnson, L.E. 1995: DARE Hydrologic Evaluations (1990-1992) - Evaluation of Hydrologic Training. NOAA Technical Memorandum. Forecast Systems Laboratory. Boulder, Colorado. June. 50 pp.

Johnson, L.E., C. Hsu, R. Zamora, and R. Cifelli, 2016. Assessment and Applications of Distributed Hydrologic Model - Russian-Napa River Basins, CA. NOAA Technical Memorandum PSD-316, NOAA Printing Office, Silver Spring, MD, 101 pp. doi:10.7289/V5M32SS9 (http://dx.doi.org/10.7289/V5M32SS9)

Johnson, L.E., P. Kucera, C. Lusk, W. Roberts. 1998: Usability Assessments for Hydrologic Forecasting Decision Support System..Journal American Water Resources Association. April.

Kernkamp, H. W. J., Van Dam, A., Stelling, G. S., De Goede, E. D., 2011: Efficient scheme for the shallow water equations on unstructured grids with application to the continental shelf. Ocean Dynamics 61, 1175–1188.

Lusk, C., L.E. Johnson, P. Kucera, W. Roberts. 1999: Process and Methods Used to Evaluate Prototype Operational Hydrometeorological Workstations. (with P. Kucera, C. Lusk, W. Roberts). Bulletin American Meteorological Society.v80, N1, pp. 57-66.

Morss, R. E., and F. M. Ralph, 2007: Use of information by National Weather Service forecasters and emergency managers during CALJET and PACJET-2001. Weather and Forecasting, 22(3), 539-555.

Nielsen, J., 1993: Usability Engineering. Academic Press, Inc.ISBN 0-12-518406-9.

O'Reilly, W. C. et al., 2016. The California coastal wave monitoring and prediction system Coastal Eng., v116, Oct. 2016, pp118-132.

Pelle, A., L. Johnson, R. Cifelli, G. Tootle 2015: Threshold Frequency Estimation for the Russian-Napa Rivers, CA. Poster at American Geophysical Union Annual Conference. December.

Porter, Keith, Wein, Anne, Alpers, Charles, Baez, Allan, Barnard, Patrick, Carter, James, Corsi, Alessandra, Costner, James, Cox, Dale, Das, Tapash, Dettinger, Michael, Done, James, Eadie, Charles, Eymann, Marcia, Ferris, Justin, Gunturi, Prasad, Hughes, Mimi, Jarrett, Robert, Johnson, Laurie, Dam Le-Griffin, Hanh, Mitchell, David, Morman, Suzette, Neiman, Paul, Olsen, Anna, Perry, Suzanne, Plumlee, Geoffrey, Ralph, Martin, Reynolds, David, Rose, Adam, Schaefer, Kathleen, Serakos, Julie, Siembieda, William, Stock, Jonathan, Strong, David, Sue Wing, Ian, Tang, Alex, Thomas, Pete, Topping, Ken, and Wills, Chris; Jones, Lucile, Chief Scientist, Cox, Dale, Project Manager. 2010: Overview of the ARkStorm scenario: U.S. Geological Survey Open-File Report 2010-1312, 183 p. and appendixes. https://pubs.usgs.gov/of/2010/1312/

Roberts,W.F., L.E. Johnson, P.C. Kucera, C.M. Lusk, and D.C. Walker. 1995: Real-time Forecast Exercise for WFO-Advanced., 1996: NOAA Tech. Memorandum ERL FSL-18, Forecast Systems Laboratory, Boulder, CO.

Smith, M., and Coauthors, 2013: The distributed model intercomparison project – Phase 2: Experiment design and summary results of the western basin experiments. J. Hydrol., 507, 0, 300-329.

Tolman, H. L., 1998: A New Global Wave Forecast System at NCEP. In: _Ocean Wave Measurements and Analysis, Vol. 2, (Ed: B. L. Edge and J. M. Helmsley), ASCE, 777-786.

van der Meer J.W. 2002: Technical Report Wave Run-up and Wave Overtopping at Dikes, Technical Advisory Committee on Flood Defence, Delft, The Netherlands.

9. ACRONYMS

- AWIPS Advanced Weather Interactive Processing System
- CaDWR California Department of Water Resources
- CHPS-FEWS Community Hydrologic Prediction System-Flood Early Warning System
- CNRFC California Nevada River Forecast Center
- CoSMoS Coastal Storm Modeling System
- DEM Digital Elevation Model
- DHM Distributed Hydrologic Model
- DHM-TF Distributed Hydrologic Model - Threshold Frequency
- EM Emergency Manager/Management
- FEMA Federal Emergency Management Agency
- FEWS Flood Early Warning System
- FFG Flash Flood Guidance
- FFO Flash Flood Operations
- FOC Flood Operations Center
- GIS Geographic Information System
- GFS Global Forecast System
- GUI Graphical User Interface
- HMT Hydrometeorology Testbed
- HVT Hydrometeorological Visualization Tool
- Hydro-CoSMoS Integrated San Francisco Bay Coastal Flood Forecast Model
- HRRR High Resolution Rapid Refresh
- IWRSS Integrated Water Resources Science and Services
- MPE Multi-sensor Precipitation Estimation
- MRMS Multi/Radar and Multi/Sensor
- NCEP National Centers for Environmental Prediction
- NEXRAD Next generation radar
- NHD National Hydrography Dataset
- NOAA National Oceanic and Atmospheric Administration
- NWM National Water Model
- NWS National Weather Service
- OAR Office of Oceanic and Atmospheric Research
- OHD Office of Hydrologic Development
- OWP Office of Water Prediction
- QPE Quantitative Precipitation Estimation
- QPF Quantitative Precipitation Forecast
- RDHM Research Distributed Hydrologic Model
- RFC River Forecast Center
- SF Bay San Francisco Bay
- TF Threshold Frequency
- TTE Table Top Exercise
- USACE U.S. Army Corps of Engineers
- USGS U.S. Geological Survey
- WFO Weather Forecast Office
- WPC Weather Prediction Center

Appendix A – Watershed Reflective Assessment Survey Results

DHMforFFO Questionnaire Responses

Question Topic	Subtopic	% Ratings by Category: Not at all (1)	Some what (3)	Very much (5)	Weighted Score	Comments
Please describe your job and needs for flash flood forecasts.	All respondents are members of Advisory Panel, predominately NWS WFO forecasters. A few are hydrologic modelers involved with R&D and local flash flood warning operations.					
What QPE data source(s) do you use to assess current rainfall amounts? Please list the QPE product(s) you use and where you access it/them.	WSR-88D, MRMS, CNRFC QPE, spotter reports, etc. All of which are collected and viewed in either AWIPS or internet browser. Other QPE sources mentioned include local ALERT-type rain gage data, coop reports, cocorahs, and local media weather reports (e.g. radar imagery).					
Thinking about the CNRFC QPE display above, please rate how helpful the QPE grid displays are for flash flood detection and forecasting.	Detecting the location of a flash flood threat?	0%	67%	33%	3.7	QPE rated as Somewhat to Very Much helpful for flash flood location.
	Determining the magnitude of a flash flood event?	0%	100%	0%	3.0	All rated QPE as Somewhat helpful for flash flood magnitude.
	Assessing the accuracy of precipitation forcings?	20%	40%	40%	3.4	Varied responses for QPE for precip accuracy assessment.
Please provide additional comment(s) about the QPE data you may use.	Standard 6-hr time increment has limited value for FF operations. Multiple responses note that need 1-hr (or less) precip data having short latency to assess flash floods. To assess the accuracy of precipitation forcings, the display needs some of errors or data to compare ground gage data. Looking at stream gage data is also very helpful.					
What QPF data source(s) do you use to assess current rainfall amounts? Please list the QPF product(s) you use and where you access it/them.	AWIPS has numerous QPF products. Examples include the CNRFC QPF, HRRR, and/or local media weather forecasts. Need very short term forecasts for flash floods.					
Please rate how helpful the QPF grid displays are for flash flood detection and forecasting.	Detecting the location of a flash flood threat?	0%	60%	40%	3.8	QPF rated Somewhat to Very Much helpful for FF location
	Determining the magnitude of a flash flood event?	0%	80%	20%	3.4	QPF rated Somewhat to Very Much helpful for FF magnitude
	Determining the lead time of a flash flood event?	33%	67%	0%	2.3	QPF rated Not at All to Somewhat helpful for FF lead time.
Please provide additional comment(s) about the QPF data you may use.	QPF is the most important element of FF forecast system. 6-hr time scale too coarse. Need real-time obs data to corroborate.					
Please rate how helpful the DHM soil moisture (SM) grid displays are for flash flood detection and forecasting.	Detecting the location of a flash flood threat?	0%	67%	33%	3.7	SM rated Somewhat to Very Much helpful for FF location.
	Determining the magnitude of a flash flood event?	0%	100%	0%	3.0	SM rated Somewhat helpful for FF magnitude
	Determining the watershed conditions for flood runoff?	17%	17%	67%	4.0	Most rated SM rated as Very Much helpful for watershed conditions.
Please provide additional comment(s) about the soil moisture product.	Soil moisture seems to be driven in these distributed models by recent rains. They are not assimilating soil moisture data. Thus they can be off greatly. So give little credence to these. Much better to monitor rate of runoff from particular stream gages to get a feel for how saturated the soils are. Most useful new gridded dataset available. Currency/latency day to day must be reliable.					

DHMforFFO Questionnaire Responses

Question Topic	Subtopic	% Ratings by Category: Not at all (1)	Some what (3)	Very much (5)	Weighted Score	Comments
Please rate how helpful the DHM discharge grid displays are for flash flood detection and forecasting.	Detecting the location of a flash flood threat?	0%	67%	33%	3.7	DHM discharge rated Somewhat to Very Much helpful for FF location.
	Determining the magnitude of a flash flood event?	0%	83%	17%	3.3	Most rated DHM discharge rated as Somewhat helpful for FF magnitude
	Determining the impacts of a flash flood event?	17%	50%	33%	3.3	Varied responses for DHM discharge grids as helpful for FF impacts.
Please provide additional comment(s) about the discharge grid display.	This (4 km) grid cell seems very coarse to accurately predict flash flooding, but would be useful for predicting potential threats. A model like this needs to earn its way into the forecast process. One would have to look at this type of output for many events and self calibrate to see what the false alarms and detection rates are. Also will it translate to other areas readily with different precip regimes...convection.					
Please rate how helpful the DHM flow frequency grid displays are for flash flood detection and forecasting.	Detecting the location of a flash flood threat?	17%	50%	33%	3.3	Varied responses for DHM flow frequency grids as helpful for FF location.
	Determining the magnitude of a flash flood event?	0%	50%	50%	4.0	DHM flow frequency rated Somewhat to Very Much helpful for FF magnitude.
	Determining the impacts of a flash flood event?	0%	83%	17%	3.3	Most rated DHM flow frequency as Somewhat helpful for FF impacts.
	How well do you understand the flood frequency characterization?	0%	33%	67%	4.3	Most rated the DHM flood frequency grids are Very Much undertandable.
Please provide additional comment(s) about the flood frequency grid display.	I am not sure I fully understand what this display is showing. Provides context if user is not familiar with typical flow levels. Useful for impacts and for a check on the forecast (do I really want to forecast a 100 year event).					
Please rate how helpful the DHM discharge hydrograph displays are for flash flood detection and forecasting.	Detecting the location of a flash flood threat?	20%	0%	80%	4.2	Most rated the DHM flow hydrograph display as Very Much helpful for FF location.
	Determining the duration of a flash flood threat?	0%	50%	50%	4.0	DHM flow hydrograph rated Somewhat to Very Muchhelpful for FF duration
	Determining the magnitude of a flash flood event?	0%	0%	100%	5.0	DHM flow hydrograph rated Very Much helpful for FF impacts.
	Determining the lead time of a flash flood event?	17%	17%	67%	4.0	Most rated DHM flow hydrograph as Very Much helpful for FF lead time.
	Is it difficult mouse clicking the flow grid to obtain a hydrograph?	60%	40%	0%	1.8	Interrogation by mouse click rated Somewhat to Not at All difficult for obtaining hydrograph.
Please provide additional comment(s) about the flow hydrograph display.	If accurate this type of output seems very useful. Good fingertip references. Water level (flood inundation) would be even more helpful. Need to have some sort of E-19 data with these gages or locations to know what the impacts are. Flooded intersection or closed bridge or flooded houses. Not familiar with these locations makes it difficult to know impacts.					

DHMforFFO Questionnaire Responses

Question Topic	Subtopic	% Ratings by Category: Not at all (1)	Some what (3)	Very much (5)	Weighted Score	Comments
Please rate how helpful the DHM impact features displays are for flash flood and impact assessment.	Detecting the location of a flash flood threat?	0%	33%	67%	4.3	DHM impact features rated Somewhat to Very Much helpful for FF location.
	Determining the impacts of a flash flood event?	0%	50%	50%	4.0	DHM impact features rated Somewhat to Very Much helpful for FF impacts
	Is it a burden to interrogate by mouse clicking the impact icon?	67%	33%	0%	1.7	Most rate interrogation by mouse click rated as Not at All difficult for obtaining impact features.
	Do you feel it is appropriate for NWS to provide this product/service?	17%	33%	50%	3.7	Varied responses on appropriateness for NWS to provide impact feature info.
Please provide additional comment(s) about the flood impact features displays.	Good fingertip references. Water levels and elevations of bridge decks would be even more helpful. Need to have some sort of E-19 data with these gages or locations to know what the impacts are.					
In your opinion, how often would you expect the DHM forecasts to be accurate enough to support your job?	Magnitude of flood	17%	33%	50%	3.7	How often DHM forecasts accurate for flood magnitude rated Rarely, to Sometimes, to Frequently.
	Location of flood	17%	33%	50%	3.7	How often DHM forecasts accurate for flood location rated Rarely, to Sometimes, to Frequently.
	Time of flood	17%	50%	33%	3.3	How often DHM forecasts accurate for time of flood rated Rarely, to Sometimes, to Frequently.
	Impacts of flood	17%	33%	50%	3.7	How often DHM forecasts accurate for flood impacts rated Rarely, to Sometimes, to Frequently.
In general, do you believe the DHM forecasts are accurate enough to support your needs?	Response	50%	0%	50%	3.0	DHM accuracy to support your needs rated No and Yes equally.
What could be done to improve DHM accuracy and usability?	It would be helpful for improved temporal resolution. Adding this into a forecaster's arsenal will undoubtedly help improve situational awareness of a rainfall event. Uncertainty analysis information about forcings and soil moisture. Need improved calibration, and regulation modeling. Better than not, all depends on accuracy of weather model inputs. Needs to be able to assimilate observations like radar rain rates and soil moisture. It needs a longer calibration to get a more distributed rainfall climatology. Ability to re-run allows better precip inputs in evolving real-time.					
Please tell us how much you agree or disagree with the statements below (check a single column box for each statement).	DHM performance statistics can guide use of DHM products.	0%	0%	100%	5.0	All agree that DHM performance statistics can guide use of DHM products.
	Need to provide options to modify DHM parameters.	17%	67%	17%	3.0	Need to provide options to modify DHM parameters - Most neither disagree or agree.
	Need capability to re-run DHM for local watersheds.	0%	67%	33%	3.7	Need capability to re-run DHM for local watersheds - Most neither disagree or agree, but some agree.
Tell us how you would use the information provided in this product/service (e.g., information only, to support personal decision-making, to support flash flood response decision making, etc)?	We can help highlight areas of concern for excessive rainfall to EMs and the public through partner emails or social media messaging before the event. I could see that a product like this would be useful for county emergency responders during to help flood response planning. (Helpful) to support personal decision-making. (Helpful to) identify areas of risk, timing of risk, and general level of event. Another piece of the puzzle but not the answer. Latency of the product can be very long and for flash flooding need to run hourly if needed with new gridded QPE and QPF. Can't have 1-3 hr latency of model data feeding the RDHM. Need to have the model forecast and the obs for the gage in the display so we can see how the model is doing near real-time.					
Do you have any additional input regarding the concept of operations or any other aspect of DHM use for support of FF operations?	No comments on ConOps					

Appendix B – Hydro-CoSMoS Tabletop Exercise Agenda

Tabletop Exercise: SF Bay Integrated Flood Forecast Model

Location: Sacramento Flood Center, 3310 El Camino Avenue Room 200

Date: Tuesday, June 13th, 2017 Time: 09:00 – 12:00 PDT

Objectives:

- Present initial results of SF Bay Integrated Flood Forecast Model
- What it is & how it works
- Understand end-user information needs for products and services

Check-In (08:45-09:00)

Greeting (09:00-09:15)

Part I Project Overview (09:15-10:30):

- Opening Remarks – Mike Anderson (10 min.)
- Prototype for SF Bay Advanced Quantitative Precipitation Information - Rob Cifelli (15 min.)
- Watershed distributed hydrological model – Jungho Kim (20 min.)
- CoSMoS model – Rose (20 min.)

Q & A / Discussion (10 min.)

Short Break (10 min)

Part II Pilot Study Scenario: Napa Watershed – San Pablo Bay (10:40-12:00):

- Model Scenario Exercise (65 min)
  - Introduction of scenario: Route 37 and Napa basin flood impacts due to confluence of heavy precipitation, river flooding, and storm surge (Liv)
  - Review impacts of recent January flooding that included long term closure of Route 37 (Juliette – very short 5 min and allow for some comments from Napa folks in the rooms)
  - Small group exercise: attendees use model products to plan their response before, during and after the event, each group will be facilitated by a NOAA/USGS team member
    - What information is most useful?
    - What information is mission critical?
    - Is there a different way that you would like to see the data presented?
    - How you might use this? What decisions would this inform?
    - Does the scale of the event matter (i.e. typical winter storm vs. extreme event)?
    - What other information do you use and are there other products you'd like to see developed?
  - Full group discussion:
    - Lessons learned from small group exercise
- Next Steps and Wrap Up (15 min)

Appendix C – Hydro-CoSMoS Tabletop Exercise Survey Results

Tabletop Exercise Questionnaire Responses

Question Topic	Subtopic	% Ratings by Category: Not Useful (1)	Some what (3)	Very Useful (5)	Weighted Score	Comments
Please describe your job and needs for flash flood forecasts.	Respondents included a mix of NWS forecasters, CaDWR flood managers, and several county-level flood response agency staff. A few are hydrologic modelers involved with R&D and local flash flood warning operations.					
Please describe your needs for flood forecasts.	NWS forecasters use radar data, flash flood guidance, rainfall reports, and river data for their warning decision making. County-level staff are concerned with storm surge into flood control channels and protecting communities and ecosystem restoration projects thereby. Some counties track flood threats and issue warnings.					
What sources do you currently typically consult for this type of information?	Most use NWS warnings, including from the WFO and the CNRFC. Some track precipitation reports (public and private), spotter reports (phone, email,, social media, and news media), USGS stream gages. Some county staff have their own precipitation and stream gage networks.					
Please provide your first-level reaction for the information provided in the WATERSHED section. Note that the WATERSHED data included DHM input factors that contribute to flood magnitude, such as precipitation (current and forecast). Saturated soil moisture levels can exacerbate flood runoff. Surface runoff is the local runoff from a single grid, Discharge is the cumulative runoff at a grid from all upstream grids. Time series is the flow hydrograph which forecasts the peak flow and time-to-peak, and the duration of high water.	Precipitation	0%	40%	60%	4.2	Precipitation information rated Very Useful.
	Soil Moisture Content	0%	80%	20%	3.4	Soil moisture rated Somewhat Useful.
	Surface Runoff	40%	40%	20%	2.6	Grid runoff rated Not Useful to Somewhat Useful.
	Discharge	0%	40%	60%	4.2	Cumulative discharge rated Useful.
	Recurrence Intervals	20%	20%	60%	3.8	Recurrence interval rated Very Useful by most, but some rated is Not Useful.
	Time Series	0%	0%	100%	5.0	Time series unanimous Very Useful.
Additional comments on the WATERSHED section.	Use local clock time for time series. Hourly time step preferred. Show flood stage. Refer to flood of record and/or recent flood levels (e.g. Napa River 1986 storm of record). DHM 4 km grid too coarse; need 250 m grid for watershed. Local responders used to more fine-scale information. Need to better define discharge and runoff. CFS is not communicable – make it more relatable.					

Tabletop Exercise Questionnaire Responses

Question Topic	Subtopic	% Ratings by Category: Not Useful (1)	Some what (3)	Very Useful (5)	Weighted Score	Comments
Please provide your first-level reaction for the information provided in the COAST section. Note that COAST data include the CoSMoS model Meteorological forcing data (winds, barometric pressure), as well as gridded model forecasts such as Waves, Currents, and Water Levels. Time series show the forecast water level heights over time at a point, so the peak height, time-to-peak and duration of high water.	Meteorological	20%	60%	20%	3.0	Met.data rated Somewhat Useful, with range of Not Useful to Very Useful.
	Waves	0%	100%	0%	3.0	Wave forecasts unanimous rated Somewhat Useful.
	Currents	20%	80%	0%	2.6	Currents forecast rated Somewhat Useful; some rated Not Useful .
	Water Levels	0%	60%	40%	3.8	Water level forcasts rated Somewhat Useful to Very Useful.
	Time Series	0%	40%	60%	4.2	Time series forecasts rated Very Useful.
Additional comments on the COASTAL section.	Show tide projections. Overlay FEMA Floodplain for reference; also recent flood inundation levels.					
Please provide your first-level reaction for the information provided in the FLOOD INDICES section. Note that FLOOD INDICES involve CoSMoS and DHM model output data characterizing flood magnitude, extent and criticality. The Hazard Index involves time integration of currents and water depth to find the locations which will be most impacted in a storm event, either through very fast currents, extremely deep water or extremely long flood duration, or some combination of the three.	Start of Flooding	0%	50%	50%	4.0	Flood start time rated Somewhat to Very Useful.
	Duration of Flooding	0%	0%	100%	5.0	Flood duration rated unanimous Very Useful.
	Time of Max Depth of Flooding	0%	0%	100%	5.0	Time of Max Depth of Flooding rated unanimous Very Useful.
	Max Water Depth	0%	25%	75%	4.5	Max Water Depth rated Very Useful.
	Hazard Index	0%	50%	50%	4.0	Hazard Index rated Somewhat to Very Useful. Some confusion on what it means.
Additional comments on the FLOOD INDICES section.	People primarily want to know - Where, How High and When. Consider describing projections as “ankle deep” “knee deep” etc. Need to consider audience – is it Emergency Managers and First Responders or someone else? Need to consider point of products – newscast or police with blowhorn saying need to evacuate? Local corroboration of projected flooding.					
Please provide your first-level reaction for the information provided in the IMPACTS - CRITICAL FACILITIES section. These data involve identification of built facilities that are of concern to flood responders.	Fire Stations	0%	75%	25%	3.5	Fire stations rated Somewhat Useful.
	Schools	0%	75%	25%	3.5	Schools rated Somewhat Useful.
	Wastewater Treatment Plants	0%	50%	50%	4.0	Wastewater treatment rated Somewhat to Very Useful.
	Roads	0%	20%	80%	4.6	Roads data rated Very Useful.
Additional comment(s) about the CRITICAL FACILITIES data you may use.	Suggest include hospitals and airports. Bridges subject to flooding. Identify key locations for each region...to help bring context to flood projections. EOC locations could be included in an internally (non-public) available layer - but that would not be good to include a public layer. Forecasters have hydro-database (E-19). Develop database service of user-generated content.					