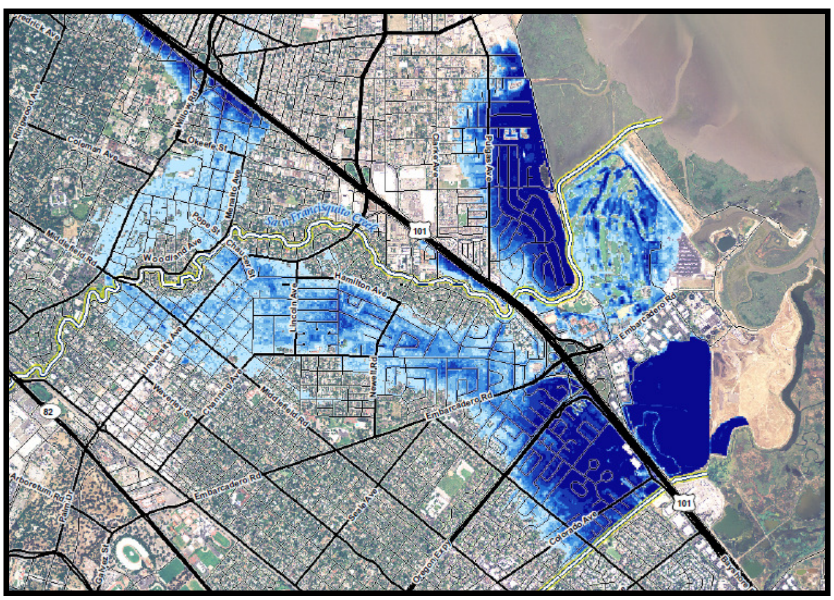
Final Report

San Francisquito Creek
Hydraulic Modeling and Floodplain Mapping

Volume II: Floodplain Modeling and Mapping

Prepared For:

U.S. Army Corps of Engineers
San Francisco District



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1. INTRODUCTION

The study reach of San Francisquito Creek is located within a densely urbanized area on the border of Santa Clara and San Mateo Counties, California. The study is a complex flood control project intending to update the existing floodplains along the Creek from Highway 280 to San Francisco Bay.

San Francisco District of the U.S. Army Corps of Engineers (USACE) sub-contracted Northwest Hydraulic Consultants, Inc. (NHC) to conduct hydraulic modeling and mapping of the floodplain inundation limits of breakout flood flows from San Francisquito Creek for a series of flood events having return periods of 500, 250, 100, 50, 25, 10, 5, and 2 years. Noble Consultants, Inc. (NCI) was a primary contractor to the USACE and was responsible for the identification of breakout locations along the Creek and development of breakout hydrographs using a 1-dimensional (1-d) unsteady HEC-RAS model. NHC's work included 2-dimensional (2-d) computer modeling of overland flows and generation of floodplain inundation maps. Overland flows were simulated using 2-d computer model FLO-2D (version 2007.06). 2-d models were developed for different floodplain areas along San Francisquito Creek using topographic data provided by the USACE and hydrologic data developed by NCI (see Volume I: Channel Hydraulic Modeling Report).

This report documents NHC's modeling approach and the assumptions used in model development, describes computational parameters and model sensitivity analyses, and discusses results from computer simulations. Inundation maps developed by this study are attached in the appendix.

2. STUDY AREA

The San Francisquito Creek watershed has an area of about 47 square miles, extending from Skyline Boulevard in the Santa Cruz Mountains (elevation 2,200 ft) to San Francisco Bay (NHC and JSA 2004). The watershed boundary is shown in Figure 1. Rural areas and open space characterize the upper part of the watershed, which is hilly and rugged. The lower watershed includes the densely populated cities of East Palo Alto, Menlo Park, and Palo Alto and towns of Portola Valley and Woodside located in relatively flat-lying areas.

San Francisquito Creek begins as overflow from the Searsville Lake Dam built in 1892 in Stanford University's Jasper Ridge Biological Preserve. The Creek flows generally northeastward for 14 miles from its source to its terminus in San Francisco Bay about 2.5 miles south of the Dunbarton Bridge. The major tributaries are Bear, Corte Madera, and Los Trancos Creeks.

San Francisquito Creek is typically dry in summer and is subject to periodic flooding during winter heavy storm events. Notable floods on the Creek with peak flows exceeding 5,000 cfs have occurred in 1894, 1895, 1911, 1955, 1982, and 1998 (USACE 1972, Kittleson et al. 1996, CRMP 1997, Cushing 1999, NHC and JSA 2004). According to USACE (1972), between 1910 and 1972 San Francisquito Creek overflowed its banks eight times – in 1911, 1916, 1919, 1940, 1943, 1950, 1955 and 1958. As described by CRMP (1997), during the flood of 1955 (which had an estimated peak flow at the USGS gage at Stanford University of 5,560 cfs) the Creek overtopped its banks in several locations, including the bridges at Middlefield Road, Pope/Chaucer Street, Highway 101, and two locations along the low levees upstream of Highway 101. This flood inundated about 1,200 acres of commercial and residential property and about 70 acres of agricultural land. Also inundated were the Palo Alto Airport and Golf Course. In 1958, an estimated flow of 4,460 cfs measured at the USGS gage caused a levee failure downstream of Highway 101 with subsequent flooding of the Palo Alto Airport, City Landfill, and Golf Course to depths of up to 4 ft. In addition, water backed up behind the Highway 101 Bridge, causing overbanking upstream of the highway. In 1982, the Creek overflowed near Alpine Road, at University Avenue, and downstream of Highway 101, causing extensive damage to private and public property.

The flood of record on San Francisquito Creek occurred in 1998 with a peak flow of 7,200 cfs at the Stanford University gage (Cushing 1999, NHC and JSA 2004). During this flood event, the Creek overtopped its banks, affecting approximately 1,700 residential and commercial structures in the in the cities of Palo Alto, Menlo Park and East Palo Alto. The Creek's levees were also damaged.

Levees and channel modifications now contain flows that previously overtopped the banks earlier in the 20th century. As described by USACE (1972) and Cushing (1999) overflow now mostly occurs along the lower part of the Creek, downstream of Middlefield Road, during extreme floods.

3. DESCRIPTION OF COMPUTER MODEL FLO-2D

Overland flooding in the study area was simulated using computer model FLO-2D (version 2007.06). FLO-2D is a quasi 2-d volume conservation model that simulates channel flows and overland flows including unconfined flows over complex topography and roughness, split channel flows, and urban flooding (FLO-2D Software Inc 2009). The model numerically routes a flood hydrograph while predicting the area of inundation and floodwave attenuation. FLO-2D uses the full dynamic wave momentum equation and a central finite difference routing scheme with eight potential flow directions to predict the progression of a flood hydrograph over a system of square grid elements.

FLO-2D can be applied to simulate a variety of complex flood problems including:

- River overbank flooding
- Unconfined alluvial fan and floodplain flows
- Urban flooding

- Flood insurance studies
- Flood mitigation design

FLO-2D is a hydraulic model approved by Federal Emergency Management Agency (FEMA) for riverine studies and unconfined flood analyses. The following descriptions provide a brief overview of the main features of the model pertinent to river overland flooding.

3.1. Surface Topography

FLO-2D requires two sets of data for any flood simulation, a digital terrain model (DTM) and an inflow hydrograph. The potential flow surface topography is represented by a square grid system. The grid elements (or grid cells) are assigned elevations from an interpolation of the DTM points. A processor program GDS (grid developer system) generates grid system and assigns the elevations. The grids are uniform in size throughout the model domain. The GDS superimposes a grid system over the DTM points and interpolates grid cell elevations using DTM point filters. It automatically generates the FLO-2D floodplain and other data files to start an overland flood simulation. Images can be imported to the GDS to assist graphical editing. Any size grid cell can be used in the model, but the computational time step is governed by wave celerity and small grid cells will require small time steps and long model run times. A typical square grid cell size will range from 10 ft to 500 ft. The number of grid cells is unlimited. However, if the number of grid cells exceeds 100,000, the model simulation may be very slow and may take days to weeks to run.

3.2. Surface Roughness

For flow less than 0.2 ft deep (where the flow depth is on the order of the surface irregularities), a default value of shallow flow Manning's roughness coefficient of 0.2 is used in FLO-2D. For flow depth between 0.2 and 0.5 ft, the shallow flow roughness coefficient is reduced by half. To improve the timing of the floodwave progression through the grid system, a depth variable roughness is assigned for flow depths ranging from 0.5 ft to 3 ft. For depth in excess of 3 ft, a user-defined Manning's roughness value is used.

3.3. Inflow Hydrographs

Inflow hydrographs can be designated for either channel or floodplain nodes. The number of inflow hydrograph nodes is unlimited.

3.4. Routing Algorithm Stability and Volume Conservation

Computational time steps are determined by FLO-2D and typically range from 1 to 30 seconds. The time step is incremented or decremented according to strict flood routing numerical stability criteria. Numerical stability is linked to volume conservation. The key to any successful flood routing model is volume conservation. When the model accurately conserves volume the model runs faster and tends to produce more reliable results. Volume conservation is tracked and is reported both during the simulation and in summary output files.

3.5. Overland Flow Simulation

Unconfined overland flow is modeled two-dimensionally and is routed through the grid system based on topography, roughness, and obstructions. Overland flow is computed in eight directions (4 compass directions and 4 diagonal directions). In-channel flow can also be simulated (one-dimensionally) in FLO-2D, with the channel geometry represented by cross-sections. However, this study was concerned with overland flows only.

3.6. Hydraulic Structures, Levees, Buildings and Flow Obstructions

Hydraulic structures (such as bridges, culverts, weirs) can be simulated by user specified discharge rating curves or rating tables assigned to appropriate grid elements. Levees can be represented by specifying crest elevations for any combination of the eight grid cell flow directions. Streets can be modeled as shallow rectangular channels with a width and curb height. Floodplain storage loss due to buildings and other flow obstructions on a grid cell basis can be incorporated into a flood model using area reduction factors (ARF). A portion of a grid cell or the entire cell can be removed from potential inundation during the flood simulation. Reduced flood storage forces more flow downstream. The flow exchange between grid cells can be partially or entirely obstructed with a flow width reduction factor (WRF) for any or all of the eight flow directions.

3.7. Model Output, Results and Mapping

The floodwave progression over the flow surface can be viewed along with a plot of the inflow hydrograph while the model is running. The main output results from a flood simulation include maximum water surface elevation for each grid cell within the computational domain, maximum flow depth and velocity, velocities vectors, and flow depth and velocity at the end of the simulation. The simulation results can be viewed graphically in the MAPPER post-processor program. MAPPER automatically generates and saves shape files of flood plots for viewing in ArcGIS.

4. DATA SOURCE

To develop 2-d models of the floodplain areas along San Francisquito Creek and to simulate overland flooding, San Francisco District of the USACE provided the following data: County of Santa Clara's 2006 LiDAR based 5 ft by 5 ft grid digital elevation model (DEM) for the study area, aerial imagery, highway median barrier data, and sound walls locations. NCI used an unsteady 1-d HEC-RAS model of San Francisquito Creek to determine reaches where levee overtopping occurs during different flood events and to develop breakout flow hydrographs for these reaches. According to the NCI's model results, levee overtopping occurs in several locations in the upper reach of San Francisquito Creek between Highway 280 and Junipero Serra Boulevard and in multiple locations along the lower reach of the Creek downstream of Highway 82. In the upper reach, the valley of the Creek is confined by high grounds and in-channel flows and overland flows are hydraulically interconnected. Therefore, flood inundation maps for the upper Creek were developed using water surface elevation data from the NCI's HEC-RAS model.

NHC used the USACE's topographic and NCI's hydrologic data to develop 2-d models of the lower floodplain areas of San Francisquito Creek where overland flows are conveyed away from the Creek's channel and therefore are disconnected from in-channel flows. NCI's breakout flow hydrographs obtained for the lower reach of the Creek for the 500-, 250-, 100-, 50-, and 25-year flood events are shown in Figures 2-6. Breakout flow characteristics are summarized in Table 1. According to the NCI's data, no levee overtopping occurs here during the 10-, 5-, and 2-year flood events. Results from the 2-d models were used to develop flood inundation maps along the lower reach of San Francisquito Creek.

5. FLO-2D MODEL DEVELOPMENT

The model development components included development of the model geometry and hydraulic boundary conditions. The following sections describe in detail the methods, approximations, and assumptions used in developing the FLO-2D models of the study area.

5.1. Model Geometry

The intent of the 2-d modeling was to simulate overland flooding on the floodplain areas of San Francisquito Creek. Due to the large size of the Creek's floodplain area, individual FLO-2D models were developed for two separate flood prone areas located on the left floodplain (designated "North 1" and "North 2") and one flood prone area on the right floodplain (designated "South"). The modeled floodplain areas are shown in Figure 7.

The main assumption in the FLO-2D model development was that breakout flows do not return back to the channel of San Francisquito Creek. The ground generally slopes away from the Creek and in most areas the berms and levees extend along the Creek banks. Therefore, the Creek's channel was excluded from the model domains by setting model boundaries along Creek banks/levees. Modeling of in-channel flows, infiltration and evaporation losses, and water outflow into storm water drainage systems were not required by the USACE. Model computational domains included anticipated inundation areas and extended from the most upstream breakout locations all the way down to the bay lands. The downstream model boundaries generally coincided with the levees running along the shoreline and providing hydraulic control to overland flows. If subsequent model runs indicated that the simulated inundation area was limited by the computational domain (i.e. simulated flow hit the model boundary and water surface elevation at this location exceeded local ground elevation), the computational domain was increased and model run was repeated. Land areas included in the final versions of the models ranged from 831 to 2,247 acres. The FLO-2D models developed and model main parameters are summarized in Table 2.

The model grid cell size was selected using methods prescribed in the FLO-2D user's manual and scope of work. The resulting grid cell size was set to 30 ft by 30 ft throughout the modeled areas. This grid cell size was sufficiently small to represent relatively small-scale topographic details (such as streets and highways) and at the same time provided manageable run times. The number of grid cells in the models ranged from 40,476 to 108,774. An average ground elevation within each grid cell was computed from the USACE's DEM data. Due to averaging of surface topography within model grid cells, there could be areas where narrow dikes and roads were poorly or not resolved in the model geometry. However, it is believed that such small-scale features did not affect overall flooding patterns.

A global Manning's roughness coefficient of 0.04 was assigned to all grid cells in all the models. This value was within the 0.02-0.05 range suggested in the FLO-2D user's manual for asphalt and concrete and within the 0.04-0.10 range suggested for grassland and open floodplain areas. The value of 0.04 was believed to be generally representative of the urbanized areas modeled for flow depths greater than 3 feet. No local site-specific roughness values were used because of the complexity of the urban area and absence of relevant information. The specified roughness value of 0.04 was applied for flow depths in excess of 3 ft. For depths below 3 ft, roughness value was calculated by FLO-2D automatically and depending on the depth was between the user-defined value of 0.04 and default shallow roughness value of 0.2.

In order to include floodplain storage capacity reduction due to buildings and other structures, an Area Reduction Factor (ARF) was assigned to each grid cell. NHC delineated sub-regions of similar land use types using aerial imagery. Grid cells within each sub-region were assigned ARF values based on the density of structures within each sub-region. Land types and corresponding ARF values used in this study are summarized in Table 3. ARF sub-regions were specified not to block major highways and streets. Most highways and streets appeared in the 2-d models as topographical depressions and were important conveyors of overland flows.

Due to the very large size of the modeled areas, highly complex character of the urban environment, complex flooding pattern (which was often difficult to anticipate), absence of relevant data, and time and budget constrains, no width reduction factors were specified and no individual street, drainage ditch, small levee, or hydraulic structure were modeled explicitly. Overland flow in the models was entirely governed by the land surface topography as contained in the DEM. The only additional features which (per request from the USACE) were included in the models were a 3.5 ft high concrete median barrier running along portions of Highway 101 and highway noise walls. The highway median barrier and noise walls were specified on a grid cell basis using shape files provided by the USACE. Grid cell elevations in the model were increased by 3.5 ft along the median barrier. The highway noise walls were modeled by blocking appropriate grid cells.

5.2. Hydraulic Boundary Conditions

In FLO-2D inflow points are specified on a grid cell basis, while NCI's breakout hydrographs were developed for rather extended levee reaches (see Table 1) which included a few breakout locations. To provide a more realistic and more uniformly distributed inflow into the floodplain in the 2-d models, NHC used water surface and levee profiles from the NCI's HEC-RAS model to determine specific locations where levee overtopping occurred within the breakout reaches specified by NCI. The reach-specific breakout hydrographs developed by NCI (shown in Figures 2-6) were evenly distributed between these overtopping locations in the FLO-2D models. The flow breakout locations used in the FLO-2D models are shown in Figure 7.

In most cases, flood flows propagate toward the Bay and pond at the outboard levees running along the shoreline. However, some levees are not high enough to contain all the flood waters. If overtopping of the most downstream levee was expected (which was the case for the South floodplain area), model grid cells along this levee were assigned actual levee crest elevations (in many cases levee crest elevations were averaged with adjacent ground elevations during the generation of the 2-d grid) and outflow points were specified on the outside of the levee to simulate spillage of flood waters into the bay area.

5.3. Model Runs

The developed models were not calibrated due to the absence of relevant calibration data. The models were used to route flood flows from the breakout locations through the urban areas as they progressed toward San Francisco Bay. The simulation time step in the model runs was variable and was adjusted by FLO-2D automatically in order to provide numerically stable solutions. The simulation time was set to a minimum of 18 hrs from the beginning of the flood. This simulation time was sufficiently long so that most overland flood waters reached the downstream model extent or accumulated in local depressions and no significant water flow occurred at the end of the simulations. Model run times ranged from a few hours for small flood events to a few days for large flood events.

6. RESULTS

Maximum flood inundation depths predicted by the NHC's FLO-2D models for the lower floodplain areas of San Francisquito Creek and by the NCI's HEC-RAS model for the upper reach of the Creek were post-processed and mapped in GIS. Examination of the modeling results revealed that for the 500- and 250-year flood events the FLO-2D models showed inundation of a few small open areas located behind high internal levees at the downstream extents of the floodplain areas North 1 and North 2. Simulated maximum inundation levels were actually below the elevations of these levees which due to their narrow width were poorly resolved in the model geometry. These inundated areas were excluded from the mapped results and the simulated maximum inundated areas and floodplain storage volumes were adjusted accordingly. Given the relatively small size of these excluded areas, their effect on simulated flooding characteristics in the study area is assumed to be insignificant.

The floodplain inundation maps developed as part of this study are located in the Appendix. Overland flood volumes, floodplain storage volumes, and maximum inundated areas simulated by the FLO-2D models are summarized in Table 4. Below is a brief discussion of overall flooding pattern simulated along lower San Francisquito Creek by the FLO-2D models.

6.1. 500-Year Flood

According to the FLO-2D model results, the 500-year flood events will cause widespread flooding along the lower reach of San Francisquito Creek. Flooding patterns are highly non-uniform due to dense urban environment and complex interaction of various overland flow paths.

In the floodplain area North 1, the ground surface slopes away from San Francisquito Creek. As a result, overland flows from the left bank breakouts located upstream of Middlefield Road and upstream of Pope Street travel away from the Creek's channel and then flow in a wide band in the north-eastern direction along the streets and as a sheet flow through residential areas to Highway 101. At Highway 101, flood waters pond in front of the highway noise walls and the median barrier. Some flows spill north over the barrier in the vicinity of Willow Road, but the majority of the flow propagates north-westerly along the highway. Flows spilling over the highway travel north through residential areas and then turn north-west and inundate commercial and industrial areas located south of Highway 84. North-westerly flows along the Highway 101 barrier reach a railroad crossing in the vicinity of Marsh Road, overtop the median barrier, and spread into industrial and commercial areas between Highway 101 and Highway 84. Some flood waters eventually spill over Highway 84 into industrial areas on the west side of the highway and into adjacent drainage canals running along the bay lands. The total inflow volume from the Creek into the floodplain area North 1 is 835 acre-ft. The maximum inundated area is about 709 acres. Maximum inundation depths in this floodplain area are generally within 1-2 ft in most built-up areas with sheet overland flow, up to 2-5 ft in ponded areas upstream of highways and levees, and are as deep as 15-20 ft in a topographic depression at Highway 101 in the vicinity of the railroad crossing in Menlo Park. Maximum flow velocities are generally less than 2-3 ft/s.

Outflows into the floodplain area North 2 occur both upstream and downstream of Highway 101. Outflows from the left bank breakouts located upstream of Highway 101 are less extensive and cause minor flooding of the predominately commercial area located between the Creek and the highway. No overland flow spills from here over Highway 101. Overland flows from the left bank breakouts, located downstream of Highway 101, inundate vast residential areas of East Palo Alto on the north side of the highway and generally east of Clarke Avenue. Some waters spill over low sections of the outboard levee into San Francisco Bay. The total inflow volume from the Creek into the floodplain area North 2 is 856 acre-ft, of which approximately 765 acre-ft is contained within the floodplain area and 91 acre-ft is conveyed into the Bay. The maximum inundated area is about 231 acres. Maximum water depths here are generally within 3-5 ft, with depths up to 10-15 ft some deep topographic depressions. Maximum velocities of overland flows here are generally within 1-3 ft/s.

The South floodplain area is subject to the most severe flooding during the simulated 500-year flood event. The ground surface in this area generally slopes away from San Francisquito Creek.

Overland flows from the right bank breakout locations upstream of Middlefield Road and upstream of Chaucer Street are conveyed in a wide band easterly and then south-easterly through a network of streets and densely populated areas of Palo Alto and inundate large residential areas between San Francisquito Creek and Matadero Creek. Additional inflow into this area occurs from the breakouts located immediately upstream of Highway 101. Flood waters pond at Highway 101, overtop the highway in the vicinity of Matadero Creek, and spread into open land and commercial areas on the north side of the highway. Modeling results indicate that flood waters ponded in the open land area overtop low portions of the outboard levee, spill into Matadero Creek, and are conveyed to the Bay. No water spills into Matadero Creek upstream of Highway 101 because of floodwalls running along the Creek. Flood waters from the breakouts located downstream of Highway 101 inundate the Palo Alto Airport and Golf Course. Additional flow into the airport area is conveyed from the open land area over Embarcadero Road. The total inflow volume from the Creek into the South floodplain area is 3,216 acre-ft, of which 2,333 acre-ft is contained within the floodplain boundaries and 883 acre-ft is conveyed into the Bay. The maximum inundated area is 1,134 acres. Maximum flow depths are up to about 1-4 ft between the Creek channel and Embarcadero Road on the south side of Highway 101, up to 5-8 ft in the area between Embarcadero Road and Matadero Creek on the south side of Highway 101, up to 7-10 ft in the open area north of Highway 101, and up to 3-5 ft at the Palo Alto Airport and Golf Course. Maximum velocities of overland flows range from around 1-3 ft/s in areas of shallow flooding to 3-6 ft/s in areas of deep flooding, particularly along streets, in the residential area between Embarcadero Road and Matadero Creek on the south side of Highway 101, and in the open land area north of Highway 101.

The total inflow volume from San Francisquito Creek into the floodplain during the 500-year flood event is 4,907 acre-ft, of which 3,933 acre-ft is contained within the floodplain and 974 acre-ft spills over outboard levees and is conveyed to San Francisco Bay. The total inundated floodplain area (including the left and right floodplains) is computed at 2,074 acres.

6.2. 250-Year Flood

The overland flooding pattern simulated for the 250-year flood event is generally similar to that obtained for the 500-year event. However, due to the lower outflows from the Creek onto the floodplain areas, flooding extent and inundation depths are slightly less extensive.

In the floodplain area North 1, overland flows propagate north-easterly toward Highway 101 and pond at the highway. Some flood water spills over the highway median barrier in the vicinity of Willow Road and are conveyed further north through residential and commercial areas and then north-west over the railroad and along Highway 84. The majority of flood waters, however, travel north-westerly along Highway 101, spill over the highway median barrier in the vicinity of the railroad crossing, and spread into commercial and industrial areas between Highway 101 and Highway 84. Some flood waters overtop Highway 84 and spill into industrial areas on the west side of the highway and into adjacent drainage canals. The total volume of inflow from the Creek into the floodplain area North 1 is 545 acre-ft. The maximum inundated area is 509 acres. Maximum floodplain inundation depths range from around 0.5-1.5 ft in most residential areas with sheet flow to 2-5 ft in ponded areas upstream of highways and up to 15-20 ft in the topographic depression at Highway 101 in the vicinity of the railroad crossing. Maximum flow velocities are generally less than 1-2 ft/s for the most part of the area.

In the floodplain area North 2, flows from the left bank breakouts located upstream of Highway 101 cause minor localized flooding and are all contained in front of the highway. Outflows from the breakouts below Highway 101 inundate vast residential areas of East Palo Alto located north of the highway and east of Clarke Avenue. Some waters spill over low sections of the outboard levee into the Bay. The total inflow volume to this area is 741 acre-ft, of which about 673 acre-ft is contained within the floodplain area and 68 acre-ft is conveyed into the Bay. The maximum inundated area is 220 acres. Maximum water depths range from 1-5 ft in the residential areas up to 7-15 ft in topographic depressions at the outboard levee. Maximum stream velocities through the residential areas are generally within 1-3 ft/s.

On the South floodplain, flows from the right bank breakouts located upstream of Middlefield Road, upstream of Chaucer Street, and upstream of Highway 101 inundate vast areas between San Francisquito Creek and Matadero Creek, overtop Highway 101, flood the open land area on the north side of the highway, and spill over the outboard levee into Matadero Creek and over Embarcadero Road to the airport area. Overland flows from the breakouts located downstream of Highway 101 are conveyed to the Palo Alto Airport and Golf Course. The total inflow from the Creek into the South floodplain is 2,307 acre-ft, of which 1,990 acre-ft is contained within the floodplain boundaries and 317 acre-ft is conveyed into the Bay. The maximum area inundated on the South floodplain is 1,073 acres. Maximum water depths are around 1-3 ft in the residential areas between San Francisquito Creek and Embarcadero Road, 3-7 ft in the ponded areas along Matadero Creek, 7-9 ft in the open land area north of Highway 101, and up to 3-5 ft in the airport and golf course area. Maximum flow velocities are around 1-3 ft/s in areas of shallow flooding and are up to 3-6 ft/s in areas of deep flooding.

The total inflow volume from the Creek into the floodplain during the 250-year flood event is 3,593 acre-ft. Of this volume, 3,208 acre-ft is contained within the floodplain boundaries and 385 acre-ft is conveyed over outboard levees to the Bay. The total floodplain area inundated during the 250-year flood event is about 1,802 acres.

6.3. 100-Year Flood

In the floodplain area North 1, overland flows propagate as a sheet flow north-easterly toward Highway 101, pond at the highway median barrier, travel north-westerly along the highway, spill over the highway at the railroad crossing, and spread into commercial and industrial areas between Highway 101 and Highway 84. Some flows spill over Highway 101 in the vicinity of Willow Road and causes minor flooding in residential and commercial areas on the north side of the highway. The total volume of inflow from the Creek into the floodplain area North 1 is 273 acre-ft. All the overland flows are contained within the floodplain boundaries. The maximum inundated area is 345 acres. Maximum water depths are generally less than 1 ft in areas of sheet flow, around 2-4 ft in ponded areas at highways, and are up to 7-16 ft in the ground depression at Highway 101 in the vicinity of the railroad crossing. Maximum flow velocities are generally less than 1-2 ft/s.

In the floodplain area North 2, outflows from the left bank breakouts located upstream of Highway 101 are all contained on the south side of the highway, causing minor flooding of adjacent commercial areas. Outflows from the breakouts below Highway 101 inundate vast residential areas located north of the highway and east of Clarke Avenue. The total volume of inflow into the floodplain area North 2 is 562 acre-ft. All the overland flows are contained within the floodplain boundaries. The maximum inundated area is 208 acres. Maximum inundation depths range from 1-5 ft in the residential areas to 5-12 ft in topographic depressions along the outboard levee. Maximum flow velocities are generally within 1-3 ft/s.

On the South floodplain, the inundated area include vast residential areas between San Francisquito Creek and Matadero Creek north of Highway 101, open land area on the north side of Highway 101, and the Palo Alto Airport and Golf Course area. No water spills over the outboard levee into Matadero Creek or the Bay. The total volume of inflow into the South floodplain area is 1,258 acre-ft. All the overland flows are contained within the floodplain storage volume. The maximum inundated area is 917 acres. Maximum flow depths are up to about 1-3 ft in the inundated residential areas between San Francisquito Creek and Embarcadero Road and in the airport/golf course area and increase up to 3-7 ft in the ponded areas along Matadero Creek. Maximum flow velocities range from around 0.5-2 ft/s in areas of shallow flooding up to 2-5 ft/s in areas of deep flooding.

The total overbank inflow from the Creek into the floodplain during the 100-year flood event is 2,093 acre-ft. All the overland flood waters are contained within local floodplain storage areas. The total floodplain area inundated during the 100-year flood event is about 1,410 acres.

6.4. 50-Year Flood

In the floodplain area North 1, overland flows travel as sheet flow from the left bank breakout locations north-easterly toward Highway 101 and then spread in a narrow band north-westerly on the south side of the highway toward the railroad crossing. The inundation area extends to Marsh Road. Some water spills over the highway median barrier in the vicinity of Willow Road and the railroad crossing and spreads into adjacent areas on the north side of Highway 101. The total volume of overbank inflow into the floodplain area North 1 is 92 acre-ft. All the overland flows are contained within the floodplain boundaries. The maximum inundated area is 154 acres. Maximum water depths are generally less than 1 ft in areas of sheet flows, 1-4 ft in ponded areas at Highway 101, and 5-14 ft in the ground depression at the highway in the vicinity of the railroad crossing. Maximum flow velocities are generally less than 1-2 ft/s.

In the floodplain area North 2, most significant flooding occurs north of Highway 101, with minor flooding on the south side of the highway. The total volume of overbank inflow into the floodplain area North 2 is 376 acre-ft. All the overland flows are contained within the floodplain boundaries. The maximum inundated area is 173 acres. Maximum water depths are up to 1-4 ft in built-up areas and up to 5-10 ft in depressions along the outboard levee. Maximum flow velocities are generally within 0.5-2 ft/s.

On the South floodplain, flood waters from the right bank breakouts located upstream of Middlefield Road, upstream of Chaucer Street, and upstream of Highway 101 are conveyed as sheet flow south-easterly through residential areas. These flows pond at Highway 101 between Embarcadero Road and Matadero Creek levee, overtop the highway, and spill into the open land area on the north side of the highway. Flows from the breakouts located downstream of Highway 101 inundate the golf course and the airport. The total volume of overbank inflow into the South floodplain area is 485 acre-ft. The maximum inundated area is 602 acres. Maximum water depths range from around 0.5-2 ft in areas of transit sheet flow to 2-5 ft in topographic depressions and ponded areas, particularly between Embarcadero Road and Matadero Creek on the north side of Highway 101. Maximum overland flow velocities are about 0.5-2 ft/s.

The total overbank inflow from the Creek into the floodplain during the 50-year flood event is 953 acre-ft, which is contained within the floodplain boundaries. No overland flow spills into the Bay. The total floodplain area inundated during the 50-year flood event is about 929 acres.

6.5. 25-Year Flood

In the floodplain area North 1, left bank breakout flows upstream of Pope Street propagate north through residential areas and pond at Highway 101. No water spills north over the highway. The total volume of inflow from the Creek into the area North 1 is about 11 acre-ft. The maximum inundated area is about 44 acres. Maximum inundation depths are generally less than 1 ft in the residential areas and up to 1-3 ft in the ponded area at Highway 101. Maximum flow velocities are on the order of 1-2 ft/s along the streets and generally less than 0.5 ft/s through the residential areas of sheet flooding.

In the floodplain area North 2, the residential area located north of Highway 101 between Pulgas Avenue and San Francisquito Creek is inundated. The total inflow volume into this area is about 219 acre-ft. The maximum inundated area is about 133 acres. Maximum water depths are up to 1-3 ft in the residential area and up to 4-9 ft in topographic depressions located at the levee running along the Creek and the bay lands. Maximum overland flow velocities in the residential area are generally around 0.5-1.5 ft/s.

On the South floodplain, flows from the breakouts located upstream of Chaucer Street and upstream of Highway 101 are conveyed in the south-easterly direction through the network of streets and residential areas and accumulate in local topographic depressions at Oregon Expressway and on the south side of Highway 101. No water spills north over Highway 101. Flows from the breakouts located downstream of Highway 101 travel east and north onto the golf course and the airport. The total inflow volume from the Creek to the south floodplain is about 144 acre-ft. The maximum inundated area is approximately 350 acres. Maximum water depths are generally less than 0.5-1 ft in areas of sheet flow and are up to 2-4 ft in topographic depressions and ponded areas. Maximum overland flow velocities are generally around 0.5-2 ft/s.

The total overbank inflow from the Creek into the floodplain during the 25-year flood event is 374 acre-ft. All the overland flood waters are contained within local floodplain storage areas. The total floodplain area inundated along San Francisquito Creek during the 25-year flood event is about 527 acres.

7. SENSITIVITY ANALYSES

FLO-2D relies on a number of user-defined input parameters to perform hydrodynamic computations. Recommended value ranges are available for these parameters, but selection of the final value is dependent on the specific application and the modeler's judgment. The validity of the selected values is usually checked by comparing model results with measured flow data. If necessary, the model parameters are then adjusted to obtain the best agreement between the modeled and measured data. This process of adjusting model input parameters is called "model calibration". However, no detailed flood inundation calibration data are available for the study area. Sensitivity analyses were therefore performed on a range of modeling parameters to evaluate the reasonableness of the model results. The parameters tested included Manning's roughness coefficient and model grid cell size. Sensitivity analyses consisted of changing selected modeling parameters (while keeping other modeling parameters unchanged) and assessing the change in the simulated results.

Sensitivity analyses were conducted using the model of the South floodplain of San Francisquito Creek and the 100-year flood event. Variations in results due to the change in modeling parameters were assessed by comparing computed maximum inundated areas, inundation depths, and overall flooding patterns. Results of the sensitivity runs are presented in Table 5 and discussed below. Given the similar topographic relief, floodplain conditions, and overall character of flooding (shallow urban flooding with localized ponding), it is believed that sensitivity of the results obtained for the other models and other flood events are likely to be comparable to that obtained for the South floodplain for the 100-year flood event. The project scope, budget and time constraints did not permit additional sensitivity analyses for all the models and all the flood events simulated.

7.1. Manning's Roughness Coefficient

A single representative value of Manning's roughness coefficient of 0.04 was used in the main model. It is known, however, that this parameter may vary within quite significant limits depending on many local factors which are difficult to define a priori without direct stream flow measurements. To determine the effect of changing surface roughness coefficient on simulated flooding characteristics, sensitivity runs were performed using roughness coefficients of 0.02 and 0.06. The Manning's coefficient of 0.02 corresponds to simple, plane surface conditions, while the coefficient of 0.06 is close to the generic value for overland flow suggested in the FLO-2D user's manual.

The sensitivity runs show that reduction of the Manning's roughness coefficient from 0.04 to 0.02 increases floodplain flow conveyance and results in a 4.3% reduction of the maximum inundated area (from 917 acres to 878 acres). On the contrary, increase of the roughness coefficient from 0.04 to 0.06 reduces flow conveyance and causes a 2.6% increase in the maximum inundated area (from 917 acres to 941 acres). Changes in maximum inundation depths are minor (generally less than 0.1-0.3 ft). The computed overall flooding pattern does not change noticeably when varying surface roughness. On the whole, given the complex surface topography and heavily urbanized character of the model area, differences in the modeling results caused by varying surface roughness appear to be rather insignificant.

7.2. Grid Cell Size

The model grid cell size for the main modeling run was set to 30 ft. To determine the effect of the gird cell size on computed flooding characteristics, sensitivity runs were conducted using 50 ft and 20 ft model grids.

Analysis of the sensitivity test results revealed that increase of the grid cell size from 30 ft to 50 ft causes a 2.1% reduction in the maximum inundated area (from 917 acres to 898 acres). The difference in the simulated maximum inundation depths is insignificant for most of the modeled area, except for the open land area north of Highway 101 where the 50 ft grid model shows depths 0.5-1 ft greater compared to the 30 ft grid model. The overall flooding pattern remains practically unchanged. Although using smaller model grid sizes generally produces more accurate predictions (due to better resolution of the bed surface topography), the differences in the flooding extent and inundation depths between the finer 30 ft grid model and the coarser 50 ft grid model appear to be insignificant. Therefore, both these grid cell sizes can be used for the study area and will likely produce very similar results.

Reduction of the grid cell size from 30 ft to 20 ft causes a 1.6% increase in the maximum inundated area (from 917 acres to 932 acres). The maximum depths are generally very similar, except for the open land area north of Highway 101 where the 20 ft grid model predicts depths about 0.5 ft less than the 30 ft grid model. The overall flooding pattern does not change significantly. The observed changes in flood characteristics are due to the better representation of the small-scale topographic features (particularly streets, levees, and local ground undulations) in the finer gird model. However, the model run time for the 20 ft grid model was over three days, comparing to about one day for the 30 ft grid model and only a few hours for the 50 ft model. Given the time constraints and a large number of modeling scenarios, use of the grid cell size smaller than 30 ft appears to be impractical from the point of view of manageable model run time. Therefore, use of the 30 ft to 50 ft grid models of the study floodplain areas appears to be the best balance between modeling details and efficiency.

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Table 1. Breakout flow characteristics for simulated flood events on San Francisquito Creek.

Breakout location	Station #	Outflow direction	Peak flow (cfs)				
			500-yr	250-yr	100-yr	50-yr	25-yr
Within 550 ft u/s of Middlefield	22337.71-22892.1	Left (north)	1,025	628	206	1	0
Within 770 ft u/s of Middlefield	22337.71-23111	Right (south)	3,134	2,257	1,097	81	0
Within 590 ft u/s of Pope/Chaucer	17836.92-18425.2	Left (north)	517	477	415	314	93
Within 590 ft u/s of Pope/Chaucer	17836.92-18425.2	Right (south)	1,433	1,339	1,177	913	333
Within 1,100 ft u/s of Hwy 101	9131.4-10229.1	Left (north)	42	37	28	15	1
Within 800 ft u/s of Hwy 101	8230.6-8530, 8931.3-9030.6	Right (south)	269	232	195	177	126
Within 2,360 ft d/s of Hwy 101	5404.2-7762	Left (north)	768	722	672	638	550
Within 2,360 ft d/s of Hwy 101	5404.2-7762	Right (south)	251	227	204	192	161

Table 2. FLO-2D models main parameters.

Modeled floodplain area	Area (acres)	Grid cell size (ft)	No. of grid cells	Manning's roughness coefficient	Minimum simulation time (hrs)
North 1	2,247	30	108,774	0.04	18
North 2	831	30	40,476	0.04	18
South	2,100	30	101,370	0.04	18

Table 3. Area Reduction Factors for different land types for use in FLO-2D model (adopted from USACE 2007 and NHC 2008).

Land use type	Area Reduction Factor (ARF)	Land use type	Area Reduction Factor (ARF)
Dense residential	0.4	Commercial	0.5
Open residential	0.2	Rural / agricultural	0
Downtown	0.7	Dense vegetation	0
Park areas	0	Default floodplain value	0
Industrial	0.6	Large individual buildings	1

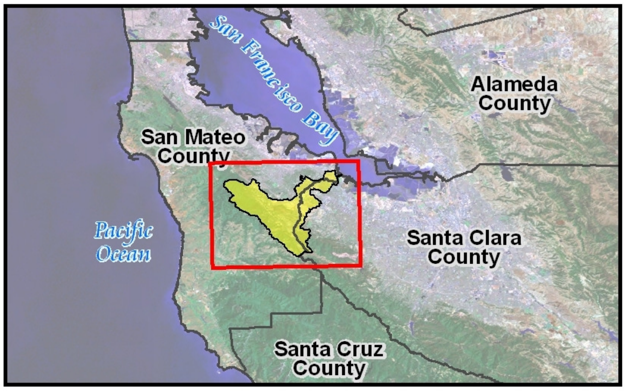
Table 4. Simulated flooding characteristics.

Parameter	Floodplain area	500-yr	250-yr	100-yr	50-yr	25-yr
Total inflow volume (acre-ft)	North 1	835	545	273	92	11
	North 2	856	741	562	376	219
	South	3,216	2,307	1,258	485	144
	Total	4,907	3,593	2,093	953	374
Floodplain storage (acre-ft)	North 1	835	545	273	92	11
	North 2	765	673	562	376	219
	South	2,333	1,990	1,258	485	144
	Total	3,933	3,208	2,093	953	374
Max inundated area (acres)	North 1	709	509	345	154	44
	North 2	231	220	208	173	133
	South	1,134	1,073	917	602	350
	Total	2,074	1,802	1,410	929	527

Table 5. Results of model sensitivity runs for South floodplain for 100-year flood.

Model parameters			Simulation results	
Grid cell size (ft)	Manning's roughness coefficient	Area Reduction Factor	Maximum inundated area (acres)	Area change** (%)
Main model				
30	0.04	Yes	917	--
Sensitivity test models				
30	0.02*	Yes	878	-4.3
30	0.06*	Yes	941	+2.6
50*	0.04	Yes	898	-2.1
20*	0.04	Yes	932	+1.6

* Changed parameter; ** Relative to main model results.



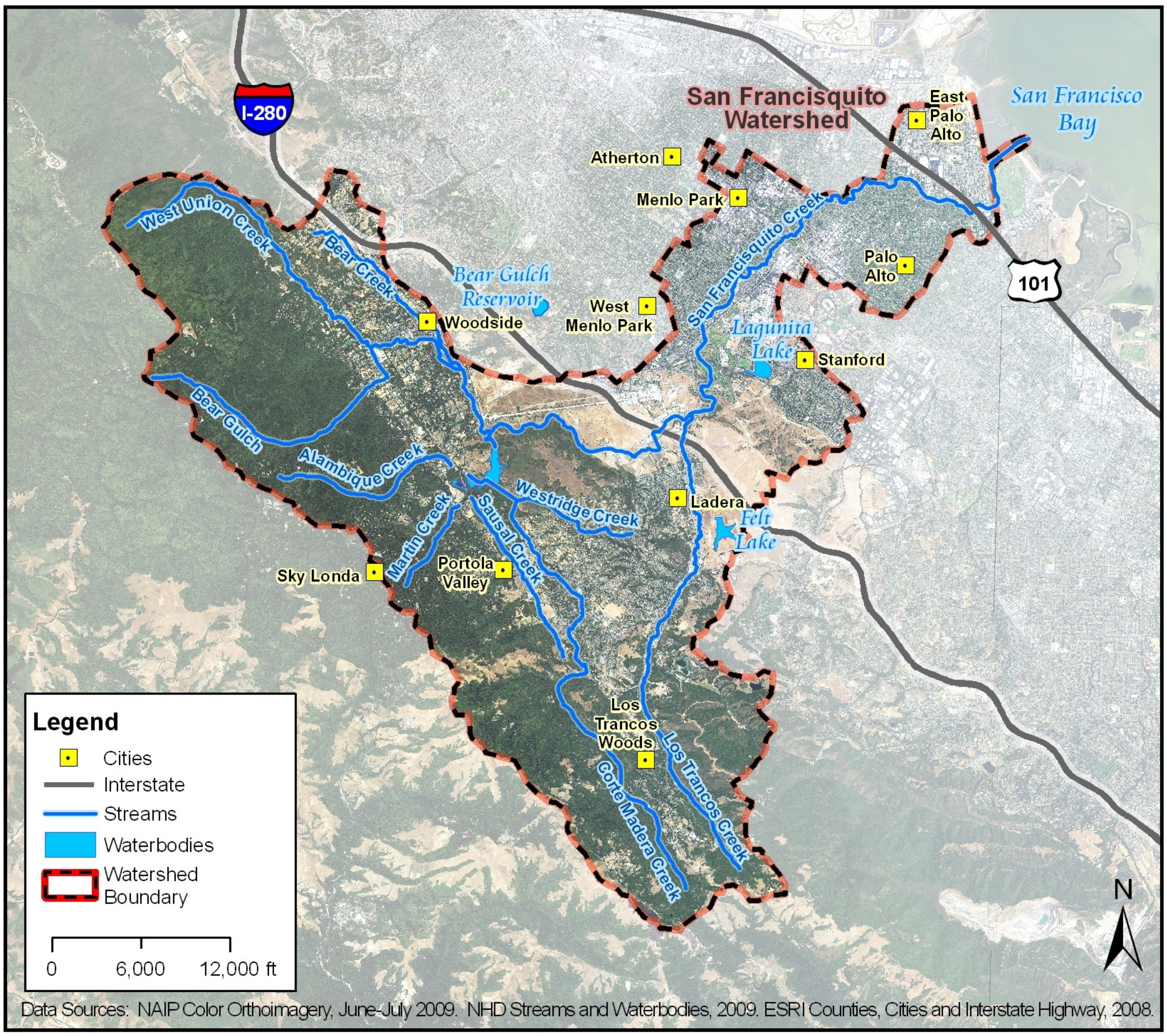


Figure 1. Watershed boundary.

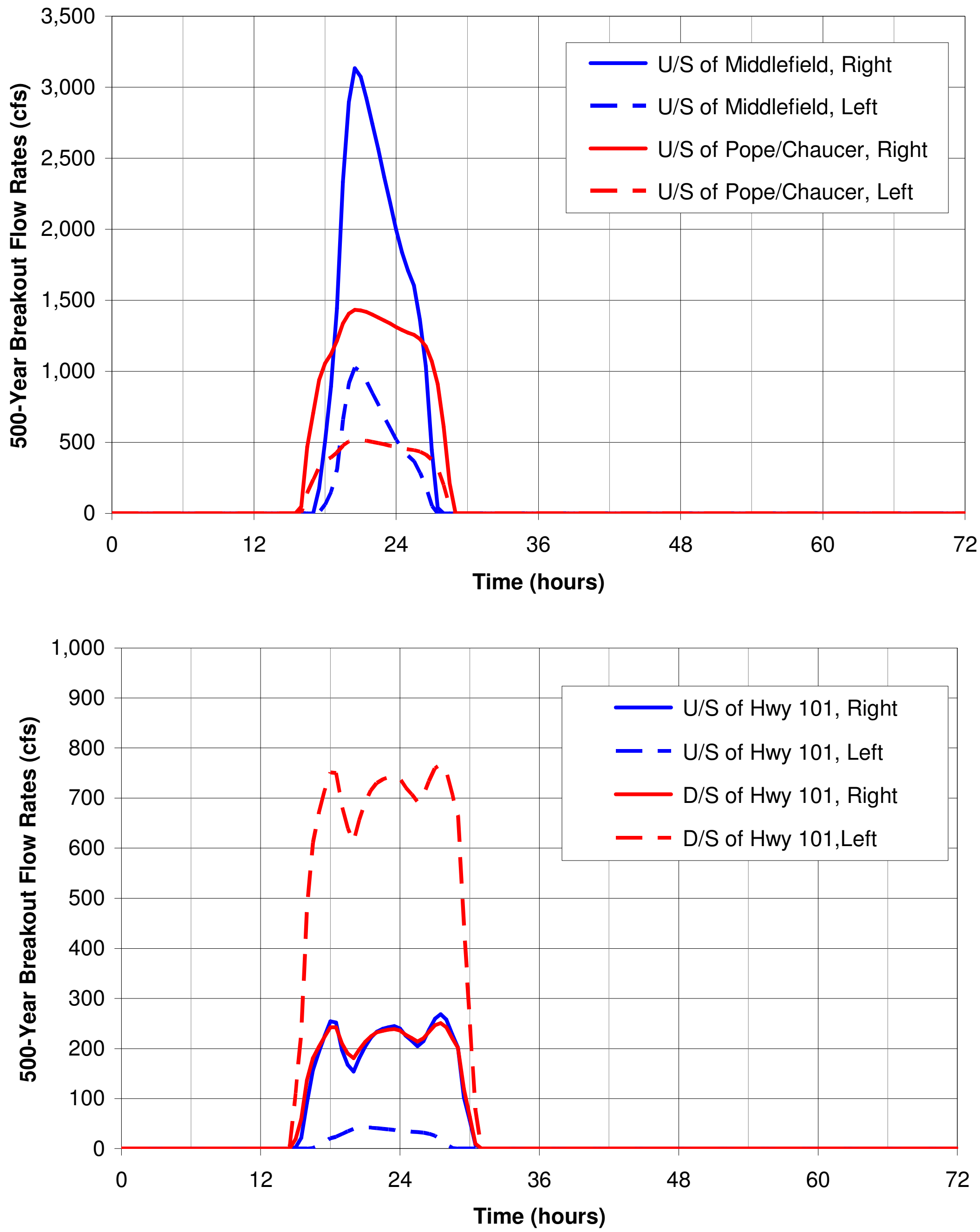


Figure 2. 500-year flood breakout hydrographs (provided by NCI).

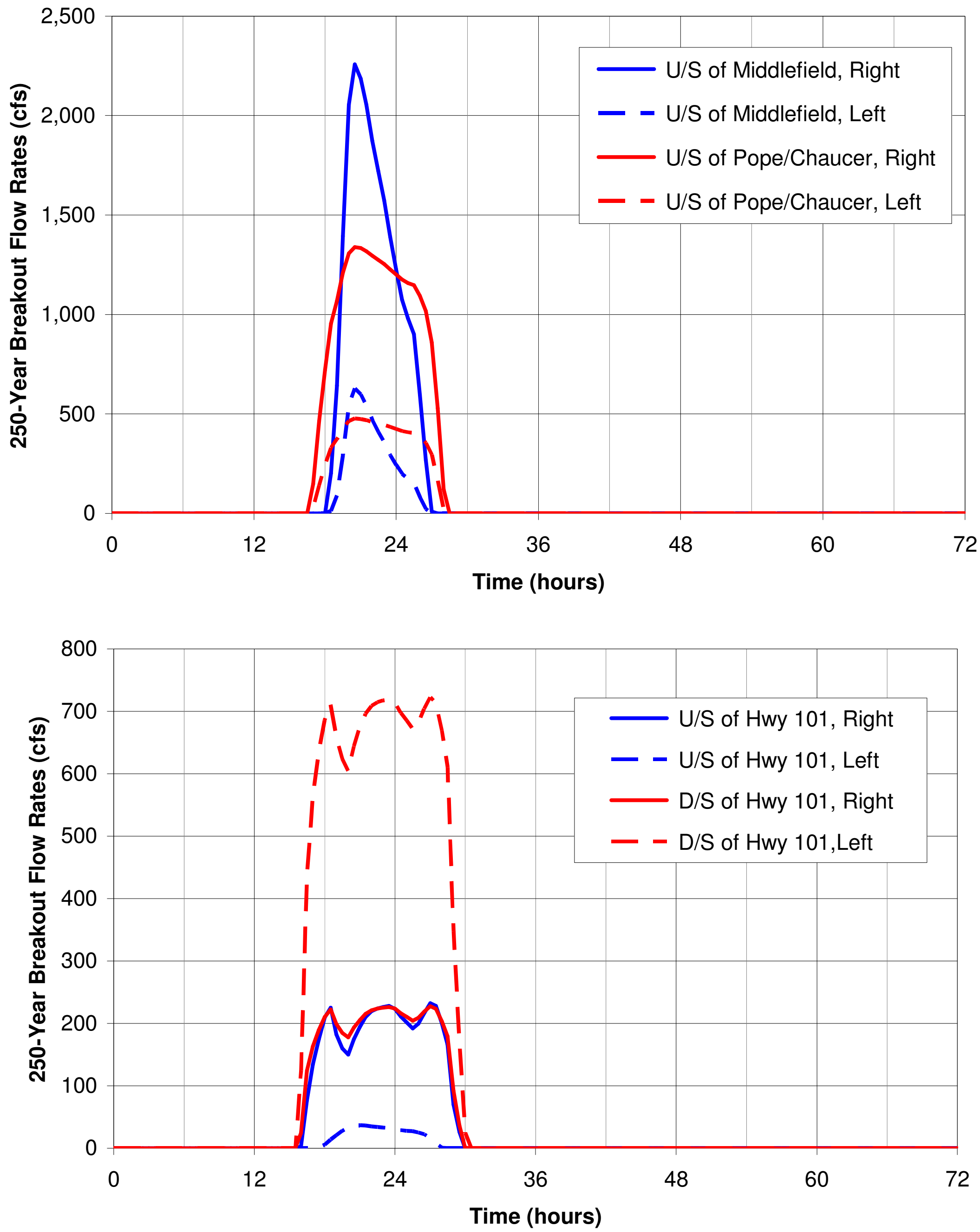


Figure 3. 250-year flood breakout hydrographs (provided by NCI).

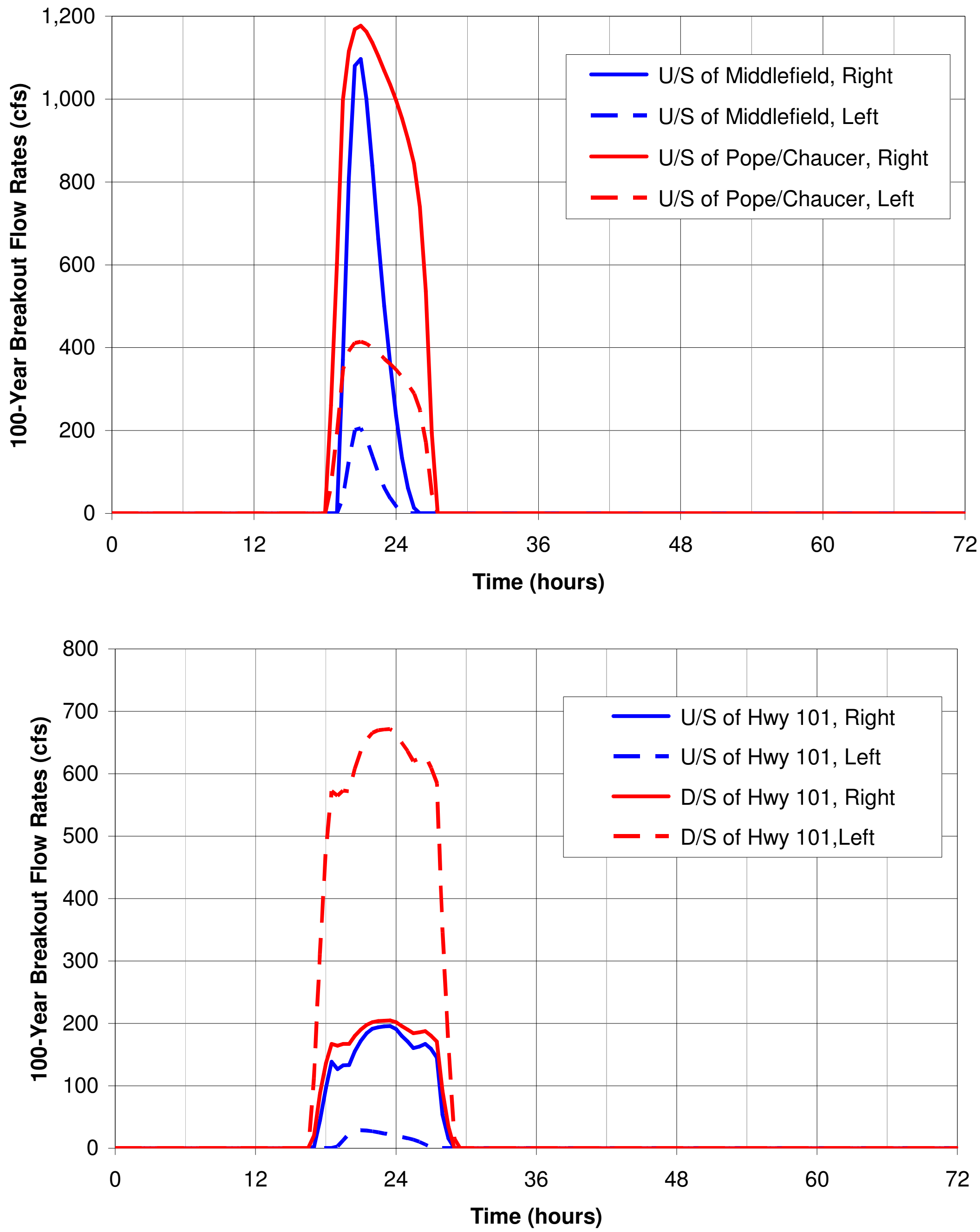


Figure 4. 100-year flood breakout hydrographs (provided by NCI).

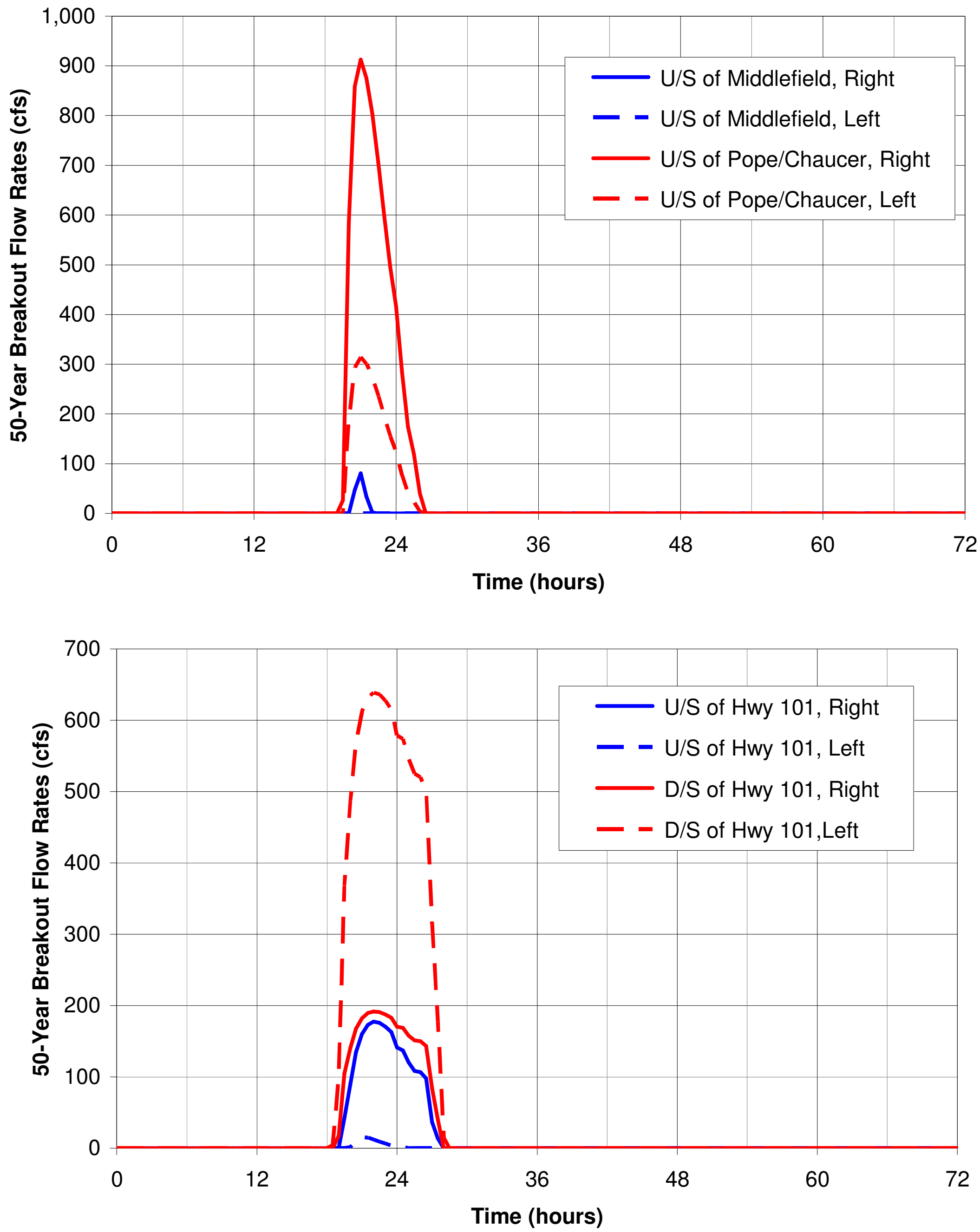


Figure 5. 50-year flood breakout hydrographs (provided by NCI).

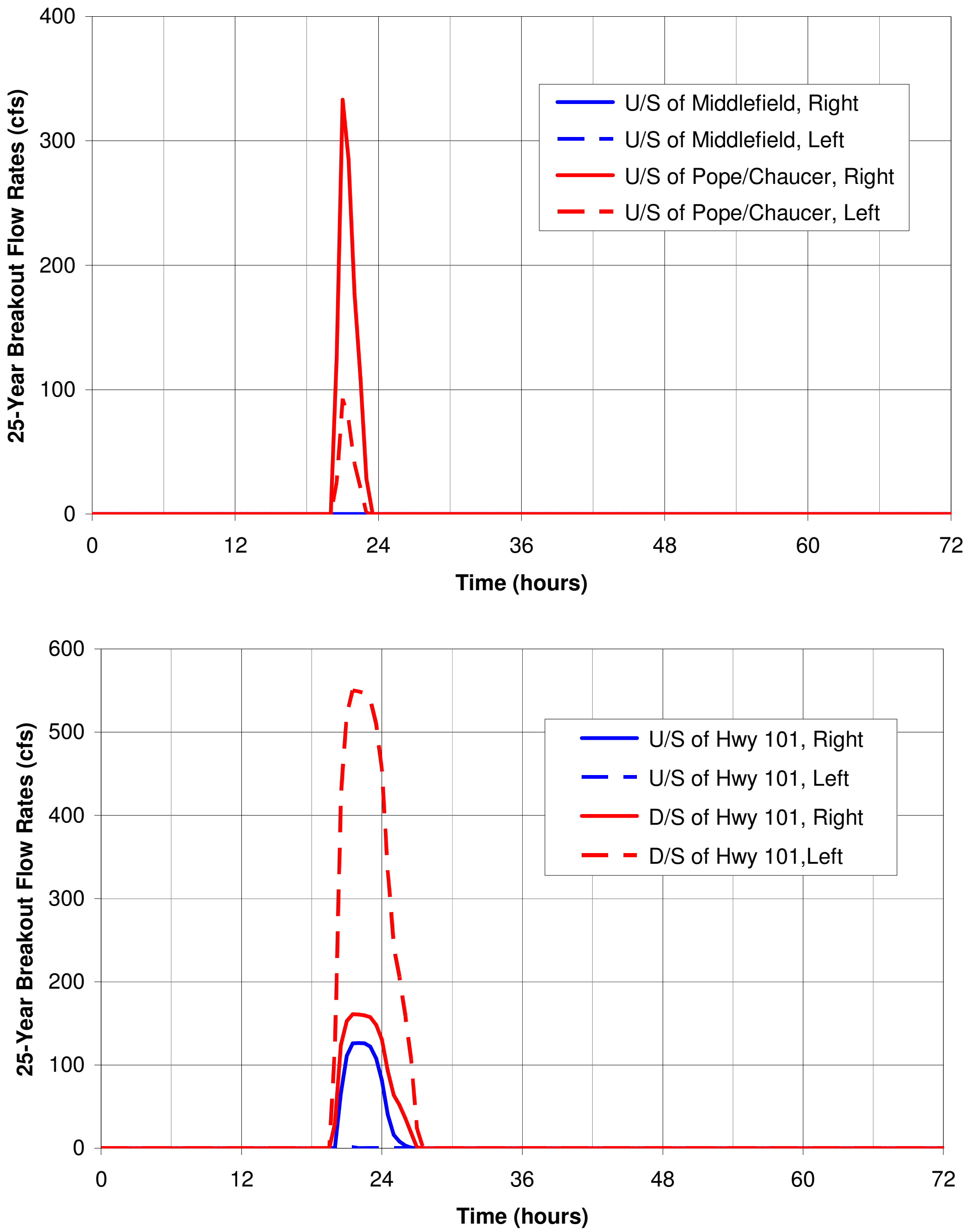


Figure 6. 25-year flood breakout hydrographs (provided by NCI).

Figure 7. FLO-2D model domains.

APPENDIX

FLOOD INUNDATION MAPS