Levee Breach Consequence Model
Validated by Case Study in Joso, Japan

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Abstract-- In September 2015, extreme rainfall from two tropical cyclones caused the Kinugawa River levee to overtop and breach in three locations near the city of Joso, Japan. Citizens, government agencies, and television news observed the breaches and resultant flood damages. The well-documented disaster provides a unique opportunity to validate levee breach progression, flooding, evacuation, and lifeloss estimations generated by the suite of models used by USACE and others to support levee safety risk assessments.

In this paper, we describe how data from social media augmented official sources to create a complete and accurate data set. Specifically, we scoured multiple online sources to describe the breach erosion progression at a level of detail rarely available outside of a controlled environment. We then describe the multi-step modeling process of: 1) setting up the HEC-RAS river hydraulics model, with the required boundary conditions and breach parameters; 2) calibrating the HEC-RAS model to observed breach flow velocities, flood depths, and inundation extents in the leveed area; and 3) using the HEC-RAS results and the available information on warnings and evacuation to validate the estimates of life loss from HEC-LifeSim.

I. Introduction

Flood risk for a given flood defense structure is a combination of the probability of failure of the structure and the consequences of that failure. Estimation of the consequences of flooding, specifically potential loss of life, caused by a failure requires consideration and estimation of the following factors:

- Flood severity: described by extents of inundation, depths, velocities, and arrival time.
- Exposed population: the portion of the population at risk (PAR) still in the area when the flood water arrives. This requires an understanding of the warning and evacuation effectiveness.
- Shelter type: accounting for potential safety provided by the location where exposed population are located (wooden home, concrete high-rise, vehicle, out in open, etc.). And,
- Fatality Rates: defining the likelihood that people subjected to the flooding will die given the flood characteristics and shelter type.

The full consideration of all these factors is a complex problem that requires detailed modelling of the physical processes (breach characteristics and flood routing), the warning and evacuation planning and processes, human decision-making, and performance of transportation systems (evacuation) and buildings under flood loading.

Levee failure events are rare with responsible personnel usually under emergency conditions, making real world data seldom available for model calibration or validation. A levee breach on the Kinugawa River in Japan in 2015 provided a rare opportunity. Several witnesses from different perspectives captured the event on video and in photos in real-time. Bringing together official government released data and unofficial data gleaned from social media allowed better calibration of the hydraulic modeling and a unique opportunity to validate the consequence modeling.

II. Background

A. Event

In September 2015, moisture from Typhoons 17 (Kilo) and 18 (Etau) converged over northern Honshu Island, Japan. Intense rain bands stalled between the cyclones over the central mountain range producing exceptional rainfall up to 660 mm over 5 days. On the Kinugawa River, four flood control dams spilled and sent record flows down the steep river. The river rose quickly (10 meters over 24 hours) and prompted warnings of possible flooding.

Early on 10 September a low point began to overtop in the municipality of Joso-shi and erode the natural high ground sending floodwater through rural neighborhoods and many hectares of rice fields. The river continued to rise and overtopped other low points in the left bank levee. Shortly before 13:00 hours, a 4 m tall levee breached directly adjacent to several homes, releasing a powerful flood wave capable of toppling homes and floating away cars. The breach flow combined with upstream flow from a minor breach and overbank flooding, and began to pool near the downtown area of Joso, trapping hundreds of people in their homes. The disaster resulted in two fatalities. National and local government agencies responded by performing thousands of rescues by air, water, and even carrying people to safety on their backs.

Figure 1 shows the extent of flooding in Joso-shi with the flood source locations and direction of flow. Joso-shi is a collection of several small towns and two small cities, Mitsukaido and Ishige, both on the east side of the Kinugawa; (a "shi" is similar administrative division to a county in the US).

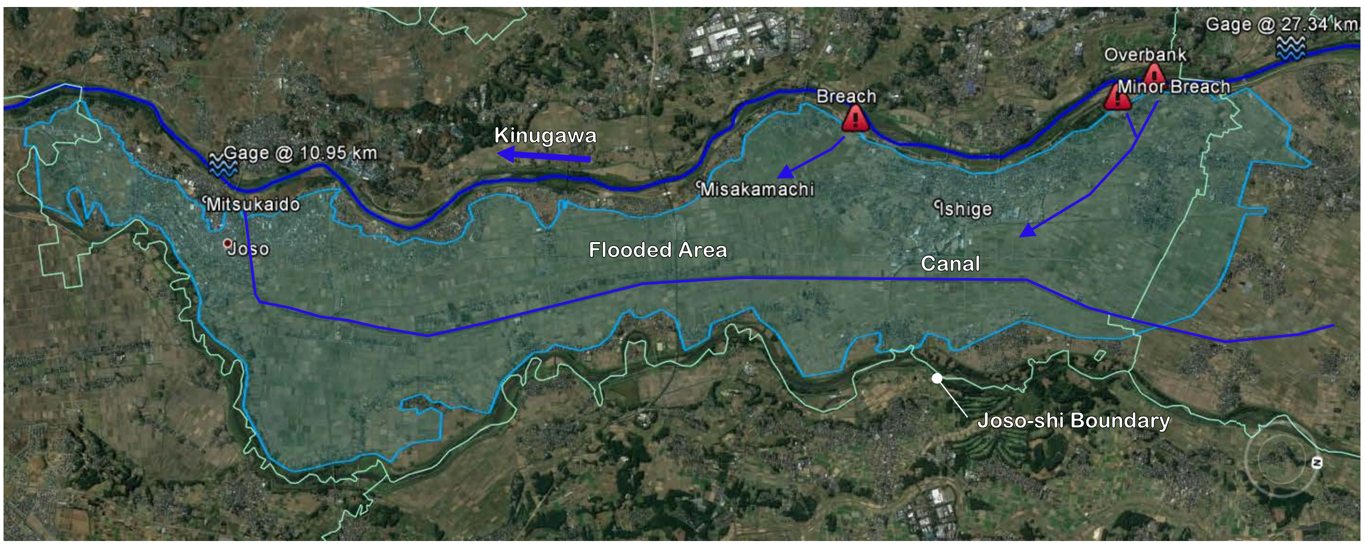

Figure 1: Flooded Area of Joso, adapted from Google Earth, [1]

B. Tools

The US Army Corps of Engineers, Hydrologic Engineering Center (USACE-HEC) develops software to model and understand flood risk. The study used two HEC products for modeling the event: HEC-RAS 5.0 for the river hydraulics and breach simulation and HEC-LifeSim 1.0 (beta) for the evacuation and consequences. HEC-RAS has the capability to model combined 1D and 2D unsteady-flow hydraulics including breach development [2]. It can output spatial results for velocity and depth for each timestep. The 2D model uses a finite volume methodology to solve the St. Venant equations using a flexible mesh. HEC-RAS Mapper facilitates creating and viewing geospatial data. HEC-RAS is widely used by hydraulic engineering professionals for studying all types of river hydraulics issues.

HEC-LifeSim is a geographic, agent-based, flood evacuation and consequence model [3, 4]. Taking a time series of depth and velocity grids from a hydraulic model, a structure inventory, population distribution, and a road network it simulates warning and evacuation of the population and estimates structural damage and fatalities for people in cars and buildings that exceed stability thresholds. The rate of fatalities is a function of the maximum exposed depth following research from Aboelata and Bowles [5, 6] and Jonkman [7]. HEC-LifeSim also uses a Monte Carlo analysis routine to sample input parameter uncertainty, outputting a range of possible answers.

C. Data Collection

The project collected data remotely through cooperation with the Japan Ministry of Land Infrastructure and Tourism (MLIT), from social media, newspaper websites, Google Earth and Street View. Photos and video together with government provided background data helped to re-create the flood extent, arrival time of flooding, flood depth, breach progression, evacuation, and rescue. Publically available data substantiated each piece of the modeling effort. The uniqueness of this dataset allows for calibration of both the river hydraulic and consequences modeling. The figure below highlights the coverage by either video or photo evidence, darker colors indicate multiple, overlapping sources.

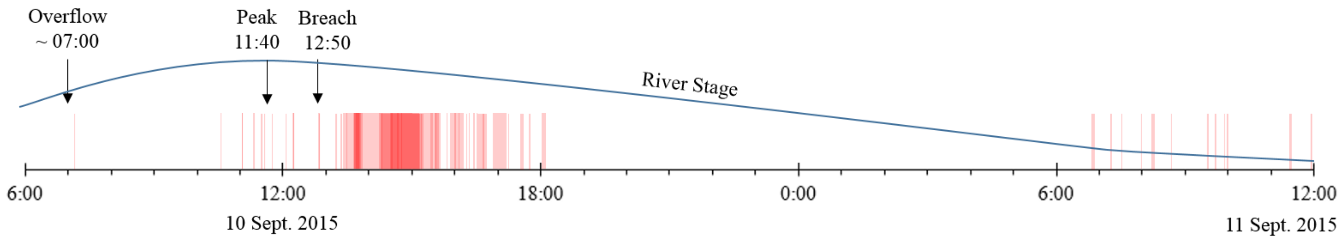

Figure 2: Timeline of photo and video coverage.

Figure 3 shows the extent of calibration data points for the hydraulics model. The points cluster near urban areas and include high water marks taken from Google Street View a couple days after the flood. Points include time and depth where they could be estimated and the limits of the flood at certain times.

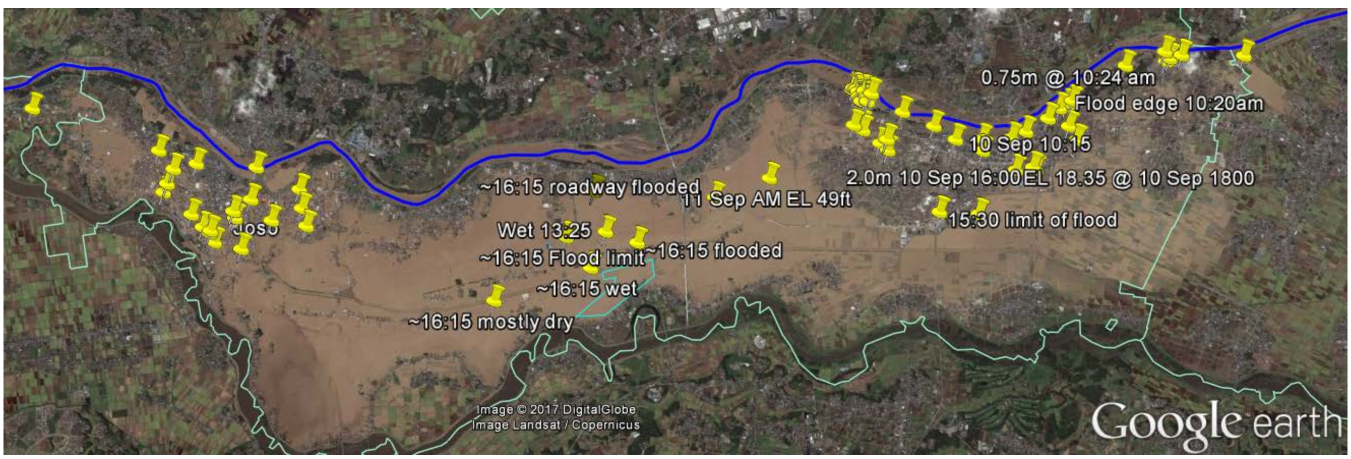

Figure 3: Calibration data points

The project also tracked observations of rescue and structural damage in real time. Figure 4 shows the situation about 30 minutes after the breach (~13:22). Red arrows show the path of structures moved off their foundations. White dots represent houses evacuated before the breach, yellow dots are for people evacuated by helicopter from the house, orange dots are for people rescued out of the water, and red dots are assumed fatalities. The two structures with red dots collapsed before any rescues were documented.

III. HYDRAULIC METHODOLOGY

A. Hydraulic Modeling

River hydraulic modeling started with pre-flood LIDAR terrain data for the Kinugawa and flooded area. Bathymetry was not available so there is no channel definition below the low water surface in the LIDAR. Neglecting the lower portion of the channel will not affect the river stages since the simulated flood hydrograph matches observed stages during the event. Boundary conditions included a downstream stage hydrograph in the 1D channel (Sta. 10.95 km, upstream from the Tone River confluence) and a normal flow boundary assumption for the southern 2D grid limit where a small portion of LIDAR was missing. No tributaries were in the modeled reach. Modeled levees use the lateral structure option to allow overtopping and breach. The large canal gate near downtown Joso allows flow to exit the flooded area once river levels begin to recede. A crucial missing component was the inflow hydrograph that the team had to derive from observed stage data at the Kamaniwa gage, at 27.34 km (upstream of the overtopping area). MLIT provided a modeled stage hydrograph at the breach location (21.0 km) to calibrate the inflow. They also reported that the design flow of 5,000 cms was exceeded, a helpful starting point. Using the shape of the stage hydrograph at the upstream gage, the team built a flow hydrograph by scaling the flow until the modeled stage matched the provided stage hydrograph at the breach site throughout the entire event.

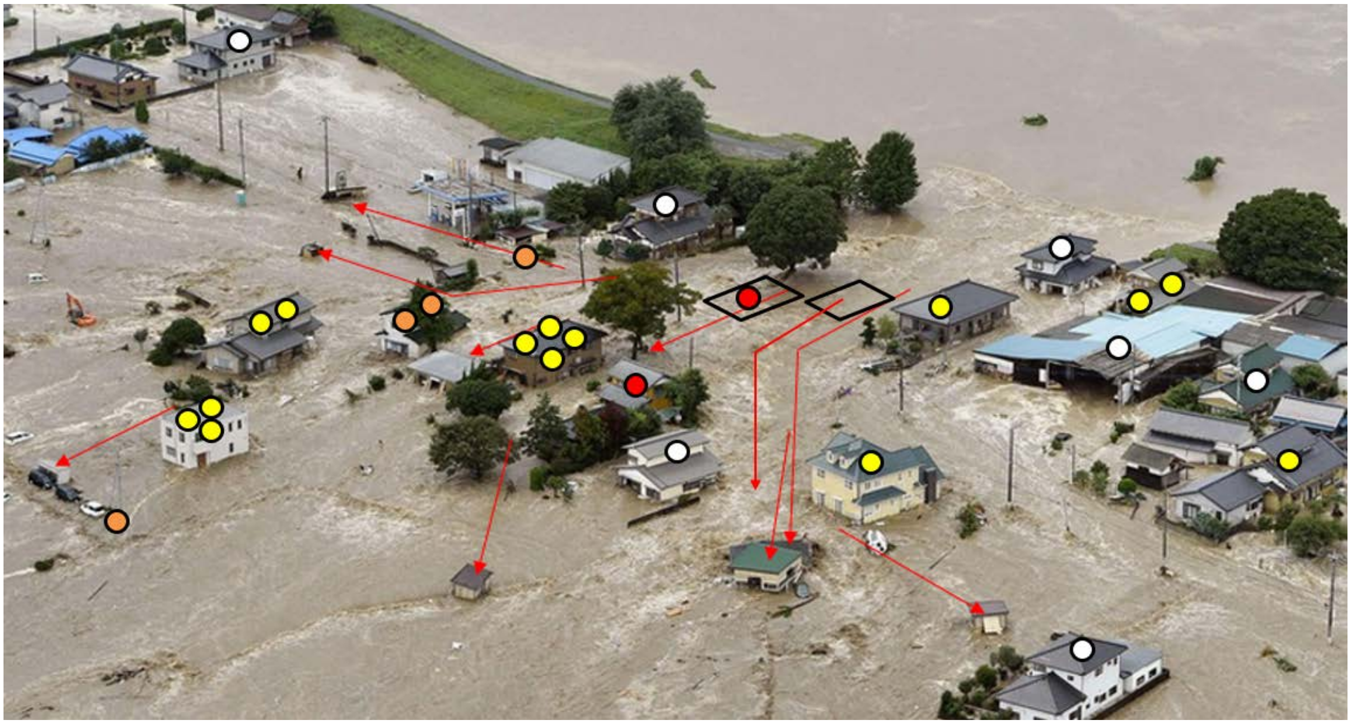

Figure 4: Main breach area 30 minutes after breach (adapted from [8])

Another key piece of this case history is the data on progression of the main breach. Many observations were made of the breach through the course of the event with their times noted and breach width estimated (Figures 5 and 6). Together these data points constitute a widening progression rarely documented outside of laboratory conditions. The team collected other information including depth and velocity estimates from photos, videos, and eyewitness descriptions allowing more accurate modeling of the main breach than previously possible. HEC-RAS utilized the breach widening rate in Figure 5 to prescribe the breach opening. In addition, MLIT provided surveyed cross sections of the breach site with elevations of the breach bottom, and side slopes. The upstream overtopping and minor breach had less info available, but enough to define the breach and get adequate flood volumes and timing.

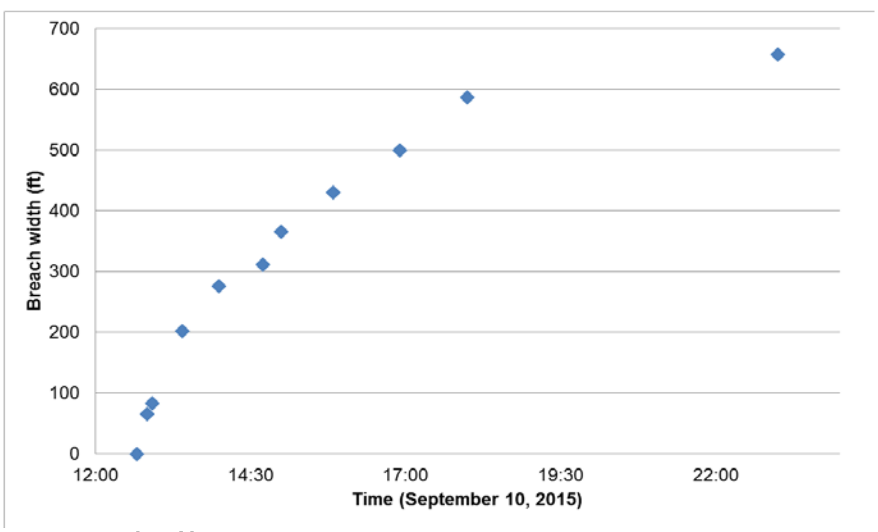

Figure 5: Breach width progression over time

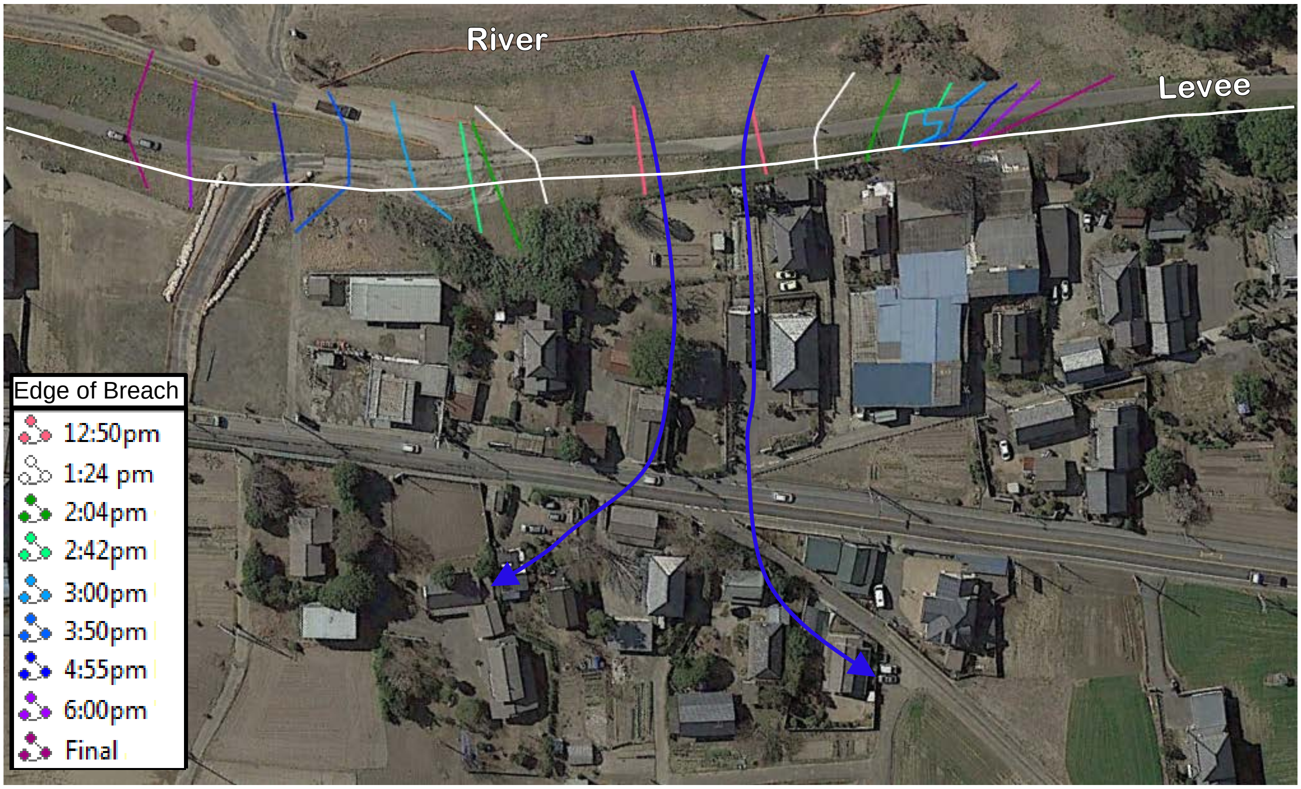

Figure 6: Breach progression observations, adapted [9]

B. Hydraulic Model Calibration

Calibration of the hydraulic model used data from a variety of sources. Several time-stamped aerial photos and Japan's Geospatial Information Authority (GSI) maps outlined the flood limits. Geo-located photos of high water marks provided over seventy-five maximum depth estimates. Time-specific depths came from photos, video, and eyewitness descriptions. Calibration focused on arrival time and maximum depth - the two criteria most important to evacuation and lifeloss modeling. Velocities were also spot checked where structures failed. One early problem with the river hydraulics model was that water was moving too fast through the floodplain trapping more people than expected. To match observed conditions the team added several road and railway embankments causing water to pool and overtop them sequentially before moving on. Figure 7 shows one such obstruction; a raised canal that temporarily stopped flow until it was overtopped. Final model results show a decent agreement in the arrival times and maximum depth both in the main breach zone and at the limits of the floodplain during and up to two days after the breach. After about a day, the city and others brought in dozens of pumping trucks and began to pump out ponded water. The peak stage (used for consequence estimates) had already passed and additional calibration of pumping would be very difficult due to lack of information, so the model simulation terminated at that point.


Figure 7: Shimotsuma canal, a typical flow limiting obstruction (Beya_Conger Panoramio via Google Earth).

Figure 8 shows the modeled flood extent overlain on an aerial image of the flooding near its peak on the morning of September 11. Agreement is good; indicating the right number of at-risk structures will be in the HEC-LifeSim model. In addition to the overall boundary, the model had well calibrate event depths and timing. Figure 9 is an example of the calibration near the southern limit of the model. Getting the right amount of water all the way to the southern limit at the right time is a good test for reasonable flood volume and stages. A ridge near downtown Joso pooled most of the water there and prevented it from moving south (left in the figure). Eventually it overtopped the short ridge and began to flood a parking lot of buses (picture C). As the lot flooded they pulled the busses to slightly higher ground in the middle (picture D). The two aerial photos were taken about two hours apart on the day after the breach. At the same time in the model the flood limits match very well in the parking lot and on land north and west of it (pictures A & B). The adjacent railyard is somewhat troubling, but it appears the terrain data picked up the rails or vegetation there and falsely attributed them to terrain.

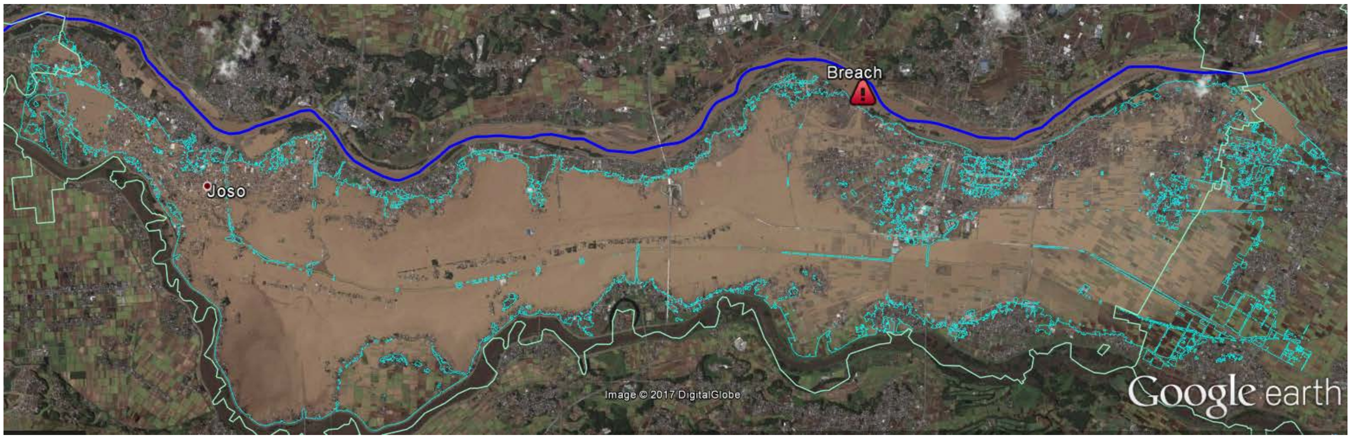

Figure 8: Calibration of flood extent [9]

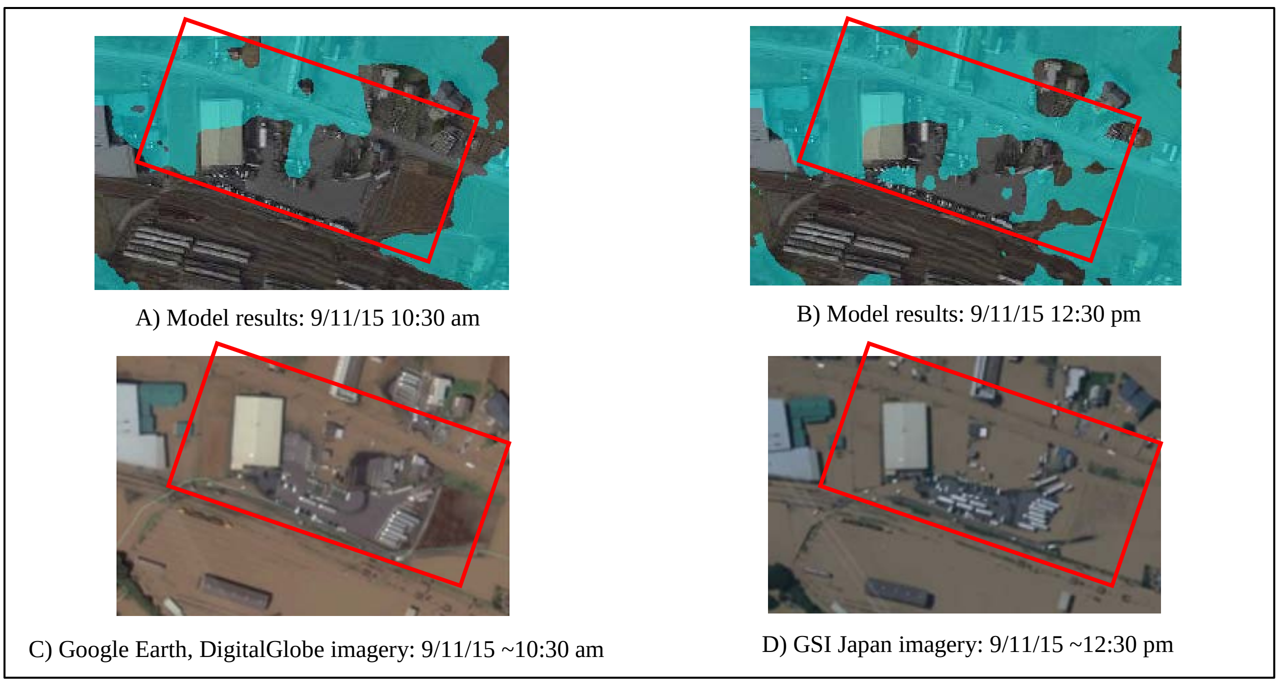

Figure 9: Calibration results near the southern limit of flooding

IV. CONSEQUENCES METHODOLOGY

A. Building the Consequences Model

HEC-LifeSim requires an inventory of all possibly affected structures as the starting point for population. A structure inventory was created by manually placing a point on each building observed in recent aerial imagery. The limits of the survey were the Kinugawa River on the west, the Kokaigawa River on the east, and a 100 m buffer beyond the observed flooding limit to the North and South. Each building has a damage category, occupancy type, foundation height, number of stories, and construction material. The structure locations were checked against OpenStreetMap while the other parameters were checked with Google Street View. Then the structures were populated based on their occupancy type for daytime and nighttime conditions.

The population estimate for Joso started with 2010 adjusted census data at the neighborhood level [10, 11]. It was indexed based on 2015 population growth rates at the shi level and applied uniformly across all census blocks within the shi. There was a small decrease in population from 2010 to 2015. The final population estimate was 28,052 in Joso-shi and 33,219 total including small parts of adjacent shi that were flooded. The model population is split into groups over and under age 65 based on the 2010 shi-level ratios (roughly 21-23% elderly). HEC-LifeSim uses age groups to compute differentiate evacuation and fatality rates. Once the population is calculated for each census block, it needs to be distributed amongst the appropriate structures.

Each structure in the structure inventory has a household unit (HHU) weight based on the values in Table I. The weights were derived in part from information in HAZUS-MH [12]. Each structure is populated with individuals based on its HHU weight. No fractional people are distributed. If the division is not even, any remainder is randomly distributed within the census block. For this event, the model used nighttime HHU weights to keep more people at home. The team assumed the heavy rain and early morning flood and evacuation warnings would keep most people at home for the day. A post event survey reported 96% of people were at home during the disaster [13], but the survey appears skewed toward elderly people, as discussed later. The team aimed to place people in livable spaces instead of sheds and garages with low foundation heights and little protection. In the southern part of the flooded area, more people may have left their homes per usual because they were not yet warned or flooded. Data show many people were at home and required rescue. Overall, the evidence leaned toward more people being at home rather than out.

The breach zones got special attention where deep and fast water can destroy buildings. These areas accounted for a significant portion of the lifeloss. Using video and other evidence of the rescue effort, the homes in the breach area were populated with the correct number of people at home. The structures were scrutinized more closely for foundation heights, construction materials, number of stories, etc. so that the proper depth and structural stability curve would be applied. In HEC-LifeSim, if a building collapses all the people inside are subject to the highest chance fatality rate (average of 91.45%) so it is important to define those buildings properly.

TABLE I

Population Assignment Weighting Factors

Structure Type	Occupancy Code	Description	Household units, Night	Household units, Day
Residential	Res1	Single family home	1	1
	Res2	Mobile home	1	1
	Res3a	Duplex	2	2
	Res3b	Multi-family (3-4)	3.5	3.5
	Res3c	Multi-family (5-9)	7	7
	Res3d	Multi-family (10-19)	14.5	14.5
	Res3e	Multi-family (20-49)	34.5	34.5
	Res3f	Multi-family (50+)	50	50
	Res4	Temporary Lodging (hotel/motel)	50	50
	Res5	Institutional Dormitory	50	50
	Res6	Nursing Home	50	50
Commercial	All codes		0.1	2
Educational	All codes		0.1	5
Industrial	All codes		1	5

The road import tool in HEC-LifeSim automatically builds a road network from OpenStreetMap data, used under Open Database License. Each road segment has a traffic capacity rating based on its size and design (e.g. highway vs. street). The team checked the network for one-way streets, unnecessary segments, and traffic capacity to prevent too many people trapped on roads while evacuating. Any bridges or elevated roads are vertically offset to prevent them from flooding. Destinations were set at each bridge out of the leveed area and roads leading north and south out of the flooded area (green diamonds in Figure 10).

B. Warning and Evacuation

In Japan as in the US, local municipalities give evacuation warnings while a national agency gives severe weather statements. Evacuation warnings come in the form of pre-evacuation information, evacuation recommendations, and evacuation orders. All three types of warnings were given at various times and places by local government officials based on their perception of the risk. The figure below shows several different zones that were given evacuation orders at various times on September 10, one that only received an evacuation recommendation (orange box) and some areas that were not warned (red boxes). For modeling purposes we assumed people outside of the warned zones may still have gotten a warning unintentionally or indirectly, but the warning dissemination will be slower. We also assumed the recommendation at 04:00 was not as good as an order. The HEC-LifeSim model used the zones and timing of each warning in Figure 10 as direct input.

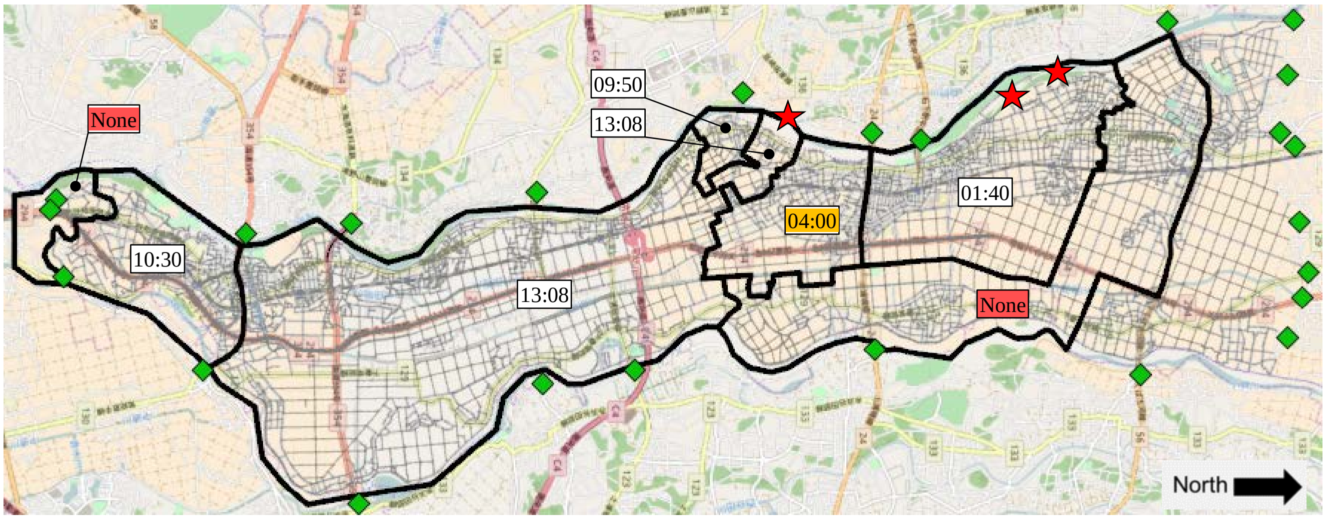

Figure 10: Time of evacuation orders with destinations and road network, adapted from [14]

The model uses curves to define the time and percent of protective action initiation (PAI), Figure 11. The PAI curve defines the time when evacuation begins. People evacuate by car following the road network from a structure to the nearest destination point. Flatter curves indicate populations are slower to evacuate after hearing a warning. Typically a maximum rate is set below 100% because some portion of the population will choose not to leave, or cannot leave. For this event, the max rate was set at 58.5% based on responses from the survey. This rate aligns with anecdotal evidence from Japan that evacuation rates are typically low, but there is no solid information about how many, how fast, or by what means people evacuated. The PAI curve is the most uncertain parameter in the consequence model due to the lack of information. There were reports of traffic congestion and thousands of people in shelters, but also thousands rescued by boat and helicopter, and people walking out through the flood. Rescue and sheltering are not accounted for in model evacuation.

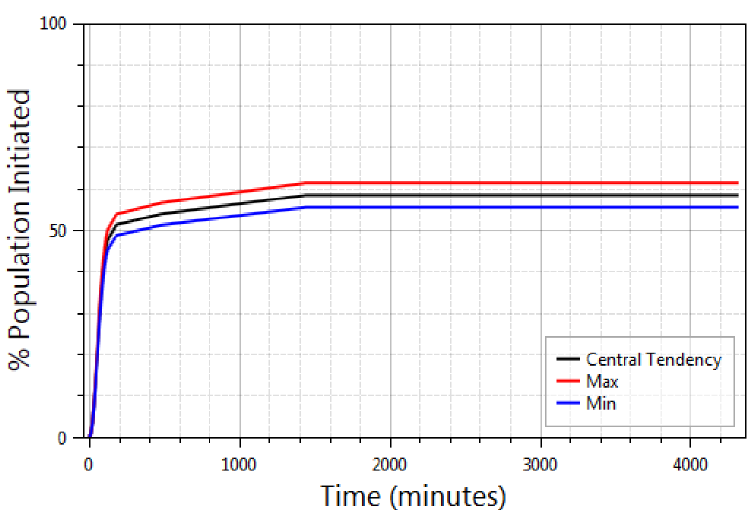

Figure 11: Example PAI curve for people receiving early warning

If water arrives at a structure before the occupants evacuate, they are trapped in their structure and subject to the maximum flooding at the structure. If an evacuating vehicle encounters water it will attempt to reroute until all options are flooded at which point the vehicle is subjected to the maximum hydraulic criteria on that road segment.

V. Results

A. Sensitivity Testing

Sensitivity of two parameters were considered in the consequence modeling. First the PAI curves, and then the structural stability criteria. Although the PAI curves had considerable uncertainty due to a lack of information, they did not seem to be very sensitive for the overall lifeloss. Doubling evacuation rate in the first 12 hours or using a higher maximum evacuation rate (96% instead of 59%) resulted in little change to the lifeloss (less than 1 person on average). This means people are being caught in their homes before they can evacuate.

Two stability criteria are available in HEC-LifeSim to calculate the collapse of buildings due to the force of water acting on the building (Table II). The first method was developed by USACE Portland District in 1985 and includes depth, velocity, and $d*v^2$ criteria, (developed in the range of 0-10.7 m of depth and 0-3 m/s velocity). Exceedance of any of the criteria in Table II is expected to result in structural collapse. The thresholds are adjusted for building material and number of stories above ground. The second set of criteria was developed by the Finnish Government project RESCDAM. It uses a velocity and d*v criteria. RESCDAM does not consider height of the structure, but does consider attachment to the foundation for wood framed structures. Using the unanchored for homes resulted in the best agreement. Similar to the USACE criteria, all stronger building types are lumped together in masonry/concrete.

TABLE II
Structural Stability Collapse Thresholds [15, 16]

Building Type	Source	1-Story	2-Story	3- Story
C – Masonry or Concrete	USACE	v > 1.9 m/s -&- $d*v^2 > 13.8\ m^3/s^2$	v > 2.3 m/s -&- $d*v^2 > 38\ m^3/s^2$	v > 2.3 m/s -&- $d*v^2 > 57\ m^3/s^2$
D – Wood Stud Framed	USACE	d > 3.1 m -or- $d*v^2 > 8.1\ m^3/s^2$	d > 4.6 m -or- $d*v^2 > 8.1\ m^3/s^2$	d > 6.1 m -or- $d*v^2 > 8.1\ m^3/s^2$
D – Steel Stud Framed	USACE	v > 1.6 m/s -&- $d*v^2 > 10.2\ m^3/s^2$	v > 1.6 m/s -&- $d*v^2 > 20\ m^3/s^2$	v > 1.6 m/s -&- $d*v^2 > 29\ m^3/s^2$
Wood Framed (unanchored)	RESCDAM	$v*d >= 3\ m^2/s$	Same as 1-story	Same as 1-story
Wood framed (anchored)	RESCDAM	$v*d >= 7\ m^2/s$	Same as 1-story	Same as 1-story
Masonry, concrete & brick	RESCDAM	v >= 2 m/s -&- $v*d >= 7\ m^2/s$	Same as 1-story	Same as 1-story

Using aerial photos from before and after the event, 174 buildings near the breach zones were categorized as “total failure”, “partial collapse”, and “flood damage only”. Luckily, the extent of very damaging flows was localized near the breach and overtopping area so there was little risk of any other buildings exposed to similar conditions. The exception is wooden, 1-story buildings subjected to the USACE criteria of Depth > 3.05 m which occurred in a few places. The results from the sensitivity tests as shown in Table III. Both methods seemed to perform well for wood-framed structures that accounted for nearly all of the tracked buildings. Both methods underestimated damages on the same 7 structures. The reason appears to be a local hydraulic model error. During the breach a few strong buildings and some trees redirected flows creating preferential courses and initiating erosion. The hydraulic model didn’t take this into account and had a more uniform, distribution of flow from the breach site. The redirected flow was aimed at some buildings that you wouldn’t expect to see damaged. The other problem was with outbuildings and garages in the model. They either floated off their foundations or collapsed. The USACE method also overestimated damages to three masonry and/or structural steel buildings in the middle of the breach zone. These structures withstood the damaging flow better than calculated indicating that criteria may be too low. RESCDAM predicted their minimal damage correctly.

TABLE III
Structures in the Breach Zones

	USACE stability	RESCDAM Stability
Matched damage	164	167
Overestimated damage	3	0
Underestimated damage	7	7

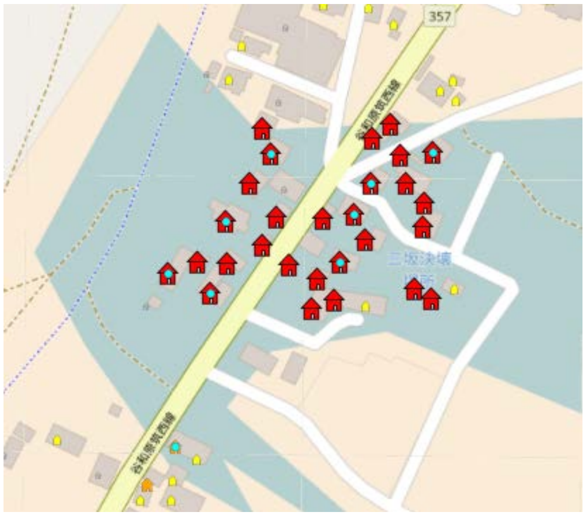

Figure 12: Destroyed structures near the breach as modeled in HEC-LifeSim (homes have blue dots)

B. Validation and Discussion

Table IV below presents the modeling results, the post-event survey results, and the best estimate of the actual event based on compilation of many sources as described above. The two stability methods resulted in different lifeloss mostly due to differences in building collapse, but also may differ by a couple just due to randomness of the Monte Carlo simulation.

TABLE IV
Consequence Modeling Results (with % of total)

Result	Actual Event Estimates	Survey Results (n = 516)	Modeled (RESCDAM)	Modeled (USACE)
Total Structural Loss	10-11 homes, 23-44 other	N/A	7 homes, 19 other	7 homes, 25 other
Flood Damage	5256 homes (?%)	44%	6110 homes (63%)	
Population	31400	N/A	33219	
Population at Risk	22000 (70%)	68%	21163 (64%)	
Population Warned	30399 (97%)	74%	21021-21108 (63%-64%)	
Population Evacuated	22100 (70%)	59%	10427-11466 (31%-35%)	
Population Sheltered	5519 (18%)	27%	N/A	
Population Rescued	4268 (14%) 1339 by helicopter	11%	N/A	
Population Exposed	9000 (29%)	N/A	10146 (30%)	
Life Loss	2	N/A	20-37	28-45

The population estimate and PAR seem to have reasonable agreement. The values for warned population seem to differ significantly, but the actual percentage of population warned is unknown. The reported number comes from MLIT tracking the number of people included in the warned areas, including some not at risk of flooding, but not if they actually got the warning. Therefore 97% is an upper limit of those who received a warning.

The number of people indicating they were warned in the survey responses had some discrepancy, but gives a better estimate. In the survey 52% indicated they heard an evacuation order, but when asked how they got evacuation instructions only 26% indicated they did not hear anything (meaning 74% did). One can infer that about 52% of respondents heard the instructions directly and the rest of the 74% heard it second-hand or from an unofficial source. The team assumed survey results represent the total population, because they include many people who did not have flooding at their homes [13]. Unfortunately, the survey does not represent the population well demographically. The age distribution of respondents was skewed much older than the 2010 census population (see Figure 13 below). Older people are more likely to be home during the day and may utilize different sources of information than younger people.

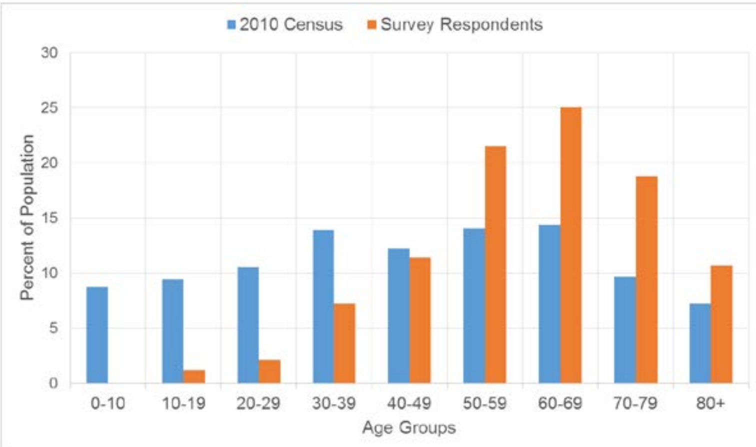

Figure 13: Age of Joso Population and Survey Respondents [10, 13]

One problem in the modeled results is regarding the evacuated population. The model shows about 64% received a warning but only 31-35% of the total population evacuated, significantly lower than estimated for the event. Adding the rescued population of 4,300 to the evacuated does not make up the difference (46%). The low rate seemed to be in line with anecdotal evidence of low evacuation rates in Japan, but not in agreement with the survey or MLIT evacuation figures [17]. Actual evacuations appear to have beaten expectations despite some difficulty with warnings. It seems many people also moved based on flood messaging and information before evacuation orders were issued.

The survey highlighted two groups of evacuees that were about equal, people who evacuated to shelters and to other safe places. For an alternate estimate of evacuated population, doubling the official sheltered population count of 5,519 you get about 11,000 evacuees, which fits well with the simulation. Since many homes are two or more stories (>90% according to the survey), this error did not have a large impact on the model results because people could easily move out of the floodwater. The modeled evacuation rates could be adjusted to fit data, but there was no information available to base a change on.

The actual life loss was two men, aged ~55 and 71 both found in interior rice paddies. No sources of information gave their exact location or circumstances of death. For this study, the team assumed the two men were in two houses near the breach as shown previously in Figure 4. Three homes collapsed there before rescue helicopters arrived in the area. In one of the houses, a window was open on the second floor but no one was visible in the house. Nearly all the houses in the breach zone were occupied at the time of breach and had yet to receive evacuation orders so it is likely the three houses were occupied.

The modeled lifeloss is overestimated by an order of magnitude. Figure 14 below shows the breakdown of modeled lifeloss. Of the 20-45 modeled fatalities, 0-9 are on roads and the rest are in structures. The highest modeled concentration of life loss occurs in the breach zone, most of whom were actually rescued before their structures collapsed. The other significant category is outside of the breach zone where all of the fatalities are elderly people in 1-story homes with deep flooding. HEC-LifeSim assumes those people cannot escape to an attic or roof so they are subject to more flooding than a younger person. These are people the model should have evacuated, but did not.

Looking at HEC-LifeSim results, there are 1,254 people who were warned but could not evacuate before water trapped them at home. Changing the PAI curves for more early evacuation didn't help much to get them out in time, so they were probably too close to the source to escape in time.

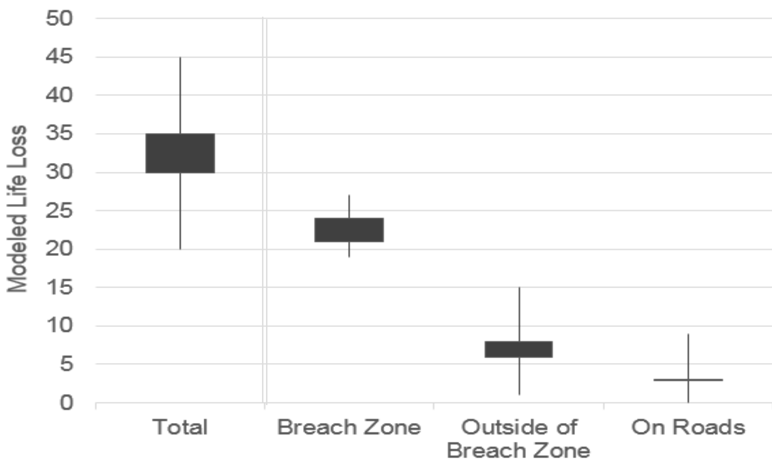

Figure 14: Modeled conditions of life loss with uncertainty bands

C. Conclusion

Data assimilation from multiple sources, including social media, provided a more accurate data set for hydraulic and consequence modeling. The hydraulic modeling performed very well leading to accurate timing and flood depths through most of the flooded area. There was sensitivity to interior road embankments and canals that ponded and directed flow patterns. This could have been rectified with a more generalized roughness calibration, but where the problem was obviously a missing embankment, the direct solution was preferred. The breach was reconstructed with little problem because so many factors were known based on observation. Model improvements in the breach zone could be made where vegetation and buildings directed flow non-uniformly from the breach site. This led to inaccuracies in the hydraulics. In practice, these factors are almost impossible to know before a breach. However, in an event reconstruction more time could be spent adding in buildings and trees that obstruct and redirect flow to improve hydraulic model accuracy.

Building stability criteria from two sources both gave reasonable results with RESCDAM performing slightly better for masonry/steel buildings.

The consequence model, HEC-LifeSim, also performed well considering it could not account for rescue. The evacuated population was likely higher than expected pre-event. If the model results are an indicator, heroic efforts reduced the lifeloss significantly from structures that eventually collapsed and cars that overturned. It also seems that a strong community fabric exists in Joso, one concerned with evacuating the elderly and less mobile people. Where modeling showed several fatalities to this vulnerable group, none occurred in Joso outside the breach zone.

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