When Floods Hit the Road:

The cascading consequences of future flooding in the San Francisco Bay Area

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GOAL

How do we quantify the far-reaching, indirect consequences of sea level rise and storm induced flooding?

Estimating Direct Losses: Costs of Building/Content Damage

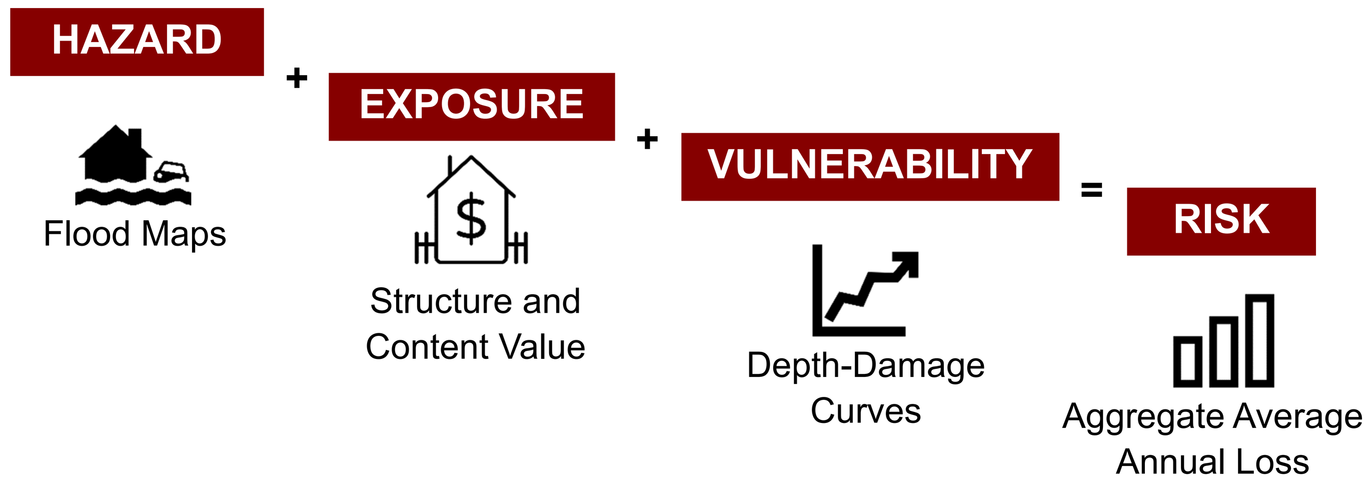


Figure 1: Average annual loss (AAL) for cities along San Francisco Bay computed using a traditional risk framework.

Estimating Indirect Losses: Costs of Commute Disruption

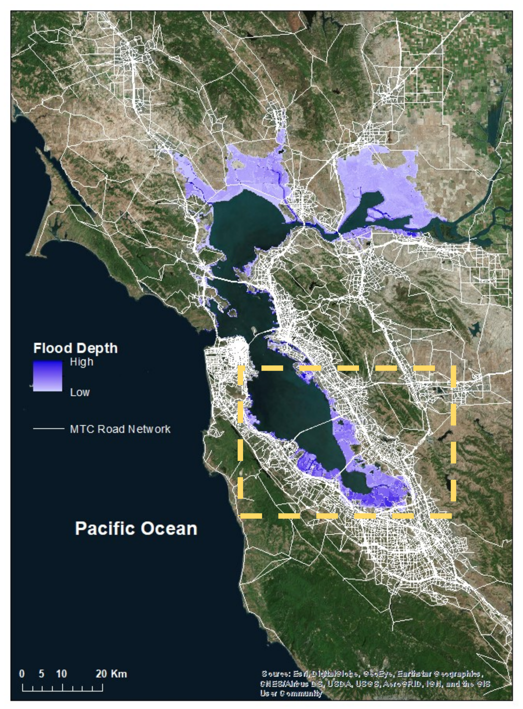


Figure 2: The San Francisco Bay Area with an example flood map and a simplified road network.

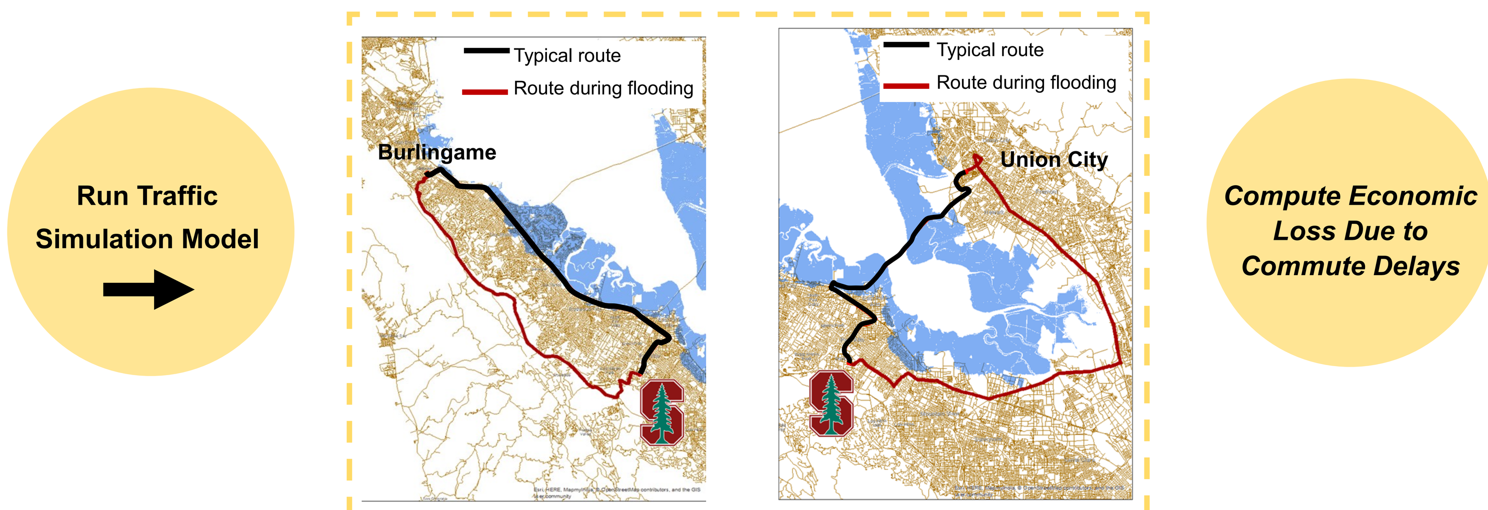
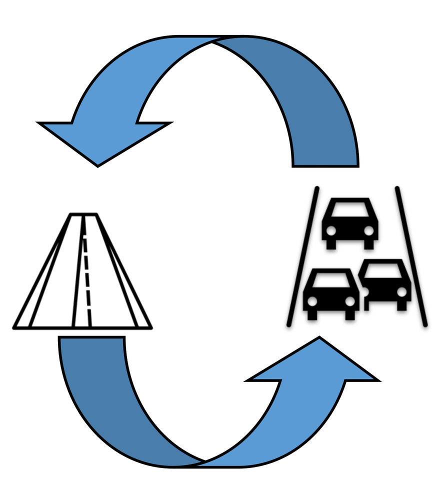


Figure 3: Variation in home to work travel route based on an example flooding scenario. Commuters in Burlingame (left) and Union City (right) "choose" a travel route to Stanford based on the shortest time to destination.

METHODS

Using a combination of ArcGIS and Python tools, flooding is mapped to a simplified road network (MTC, 2017) and a new free flow travel time (FFT, i.e., the road travel time in the absence of traffic) is computed for each road link. The impact of flood inundation is modeled by increasing the FFT over each road link using the Pregnolato et al., 2017 empirical function for the maximum possible velocity at which a car can safely travel across an inundated road. When the depth of flooding is over three inches, the road link is assumed to be inaccessible and is not included in the traffic simulation, increasing the amount of commuters on alternate roads.

Figure 4: King tide flooding in Mill Valley, CA; Photo credit Robert Sanford.



Commute simulation is modeled using a classic Traffic Assignment approach (e.g., Wang et al., 2012), where commuters are assigned a travel route from home to work (LEHD, 2015) based on the route which takes the shortest time. All commuters are arranged into groupings, to simulate commuters leaving their households at slightly different times. After each commuter is assigned a route in the initial group, the travel time on each road link is updated based on traffic volume. This process is repeated in succession for all groups of commuters.

Total economic losses are computed by using hourly wage by income group to estimate commuters' financial losses from being late or unable to get to work. For commuters who are unable to complete their commute to their workplace, we consider a day's worth of wages lost.

Acknowledgements

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ROAD NETWORK MODIFICATIONS

While the simplified road network (MTC, 2017) has been used previously to model commute disruption due to earthquake hazards (Miller, 2014) the following had to be considered to be used in a flooding context:

Position of Roads: The position of the simplified road network did not always align with the actual location of roadways, creating inaccuracies in traffic simulations during flooding events. For example, some areas on HWY 101, which runs alongside the San Francisco Bay, ran across marshland when in reality it would curve around it (Figure 5). In ArcGIS, the road network was snapped to OpenStreetMap roads based on spatial proximity. Roads were then automatically (and when necessary, manually) aligned to preserve the curved nature of roads around the bay.

Figure 6: HWY 37 over the Napa River is depicted during flooding from a 12" rise in sea level. The bridge would be improperly assumed to be closed due to flooding without elevation corrections.

Elevation of Roads: While most roads in the bay area are low lying and susceptible to flooding events, bridges and elevated roadways over rivers form an important part of the daily commute. In most DEMs, bare earth processing removes these features from the landscape (Figure 6). We use a roadway elevation dataset (OPM&P, 2016) and subtract the elevation from a high resolution DEM (USGS, 2013) to append realistic elevations to the simplified road network.

Figure 5: Example of corrections to the position of roads. HWY 101 is depicted here during flooding from a 12" rise in sea level. The simplified MTC network would be flooded, while the corrected roadway would not, based on position.

RESULTS

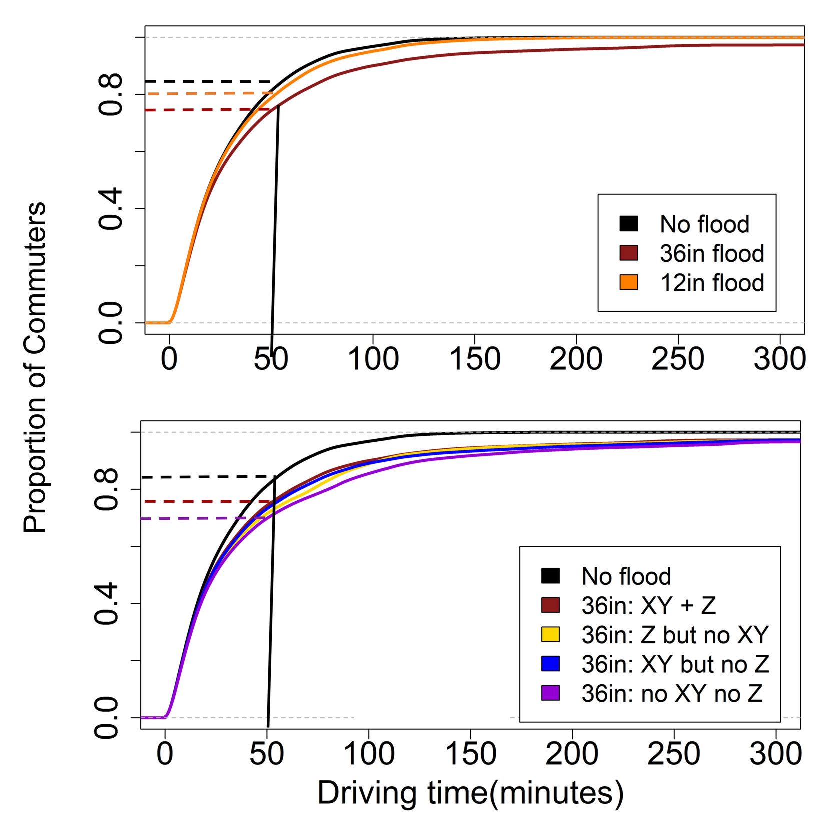

Figure 7: Commute disruption under two different example flooding scenarios (top panel) and for road network modifications to the position (X,Y coordinates) and elevation (Z coordinate) of the simplified network (bottom panel).

Sea Level Rise/Extreme Storm Scenarios: Under no flooding, almost all commuters in the bay area reach their destination within 2 hours (Figure 7, top panel). Under 12" of flooding only slightly disrupts traffic and the majority of commuters are still able to reach their destination. However, the loss to employees due to commute disruption is ~\$80 million.

Scenario	Proportion of Commuters Reaching Their Destination Within 50 Minutes
No flood	85%
12" flood	80%
36" flood	75%
36" flood no elevation/ position corrections	70%

Under 36" of flooding, ~4% of commuters cannot reach their destination within a timely manner. The average commute time considering no traffic of 30 minutes increases by 25% and the loss to employees is greater than \$200 million.

Road Network Modifications: In the absence of horizontal (X,Y) and vertical (Z) adjustments, the impacts of flooding are overestimated, delaying commutes by 5-10% (Figure 7, bottom panel). Elevation adjustments to the roadway are slightly more important than horizontal adjustments.

Figure 8: Nuisance flooding on the Embarcadero, San Francisco. Photo credit, Jessica Christian, SF Examiner.

KEY CHALLENGES AND OPPORTUNITIES FOR IMPROVEMENT

Flood Map Accuracy and Validation

- Since DEMs have uncertainty, can social media help to fill in the role of flood event validation during low level (e.g., nuisance) flooding events?
- Are there imagery databases that are high enough spatial/temporal coverage to depict disruptive (rather than catastrophic) flood events?
- Does the department of transportation have a certain threshold they use to put in permanent flooding and water conditions signs (Figure 10)?

Figure 10: An example road sign for flooding and high water conditions. Photo credit, Bill Koplitz.

Flood Exposure and Indirect Loss

- Can we augment our understanding of flood-induced damage with flood/auto insurance data?
- How do we continue to quantify indirect losses like the loss of business due to lack of access, potential increases in mortality rates due to increases in traffic incidences, or the disproportionate burden low level flooding may put on vulnerable communities?

Social Response to Flooding

- How can we better understand human behavior in response to flood events?

Figure 9: Example Twitter Bot that tweets live traffic data from the California Highway Patrol.