Science Advances
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Supplementary Materials for

High-tide flooding disrupts local economic activity

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Published 15 February 2019, *Sci. Adv.* **5**, eaau2736 (2019)
DOI: 10.1126/sciadv.aau2736

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Supplementary Material

Drivers of high-tide flooding in the Chesapeake Bay
Global mean sea level over the 20th century increased at a rate of 1.2–1.5 mm yr^{-1}, which is attributed primarily to thermal expansion of the ocean and addition of mass to the ocean (*1*). However, within the Chesapeake Bay, sea level rise has outpaced the global mean. The enhanced rate of sea level rise within the Bay is attributed to subsidence associated with the retreat of ice sheets during the last glacial period and the weakening of the Gulf Stream as a result of climate change (*23*, *24*, *32–35*).

However, the shorter-term processes that influence high-tide flooding are often different and superimposed upon the sea level rise trend. Coastal flooding frequency and intensity changes along the U.S. East Coast have been linked to longer-term, intra-seasonal and decadal variability (e.g. variability of the North Atlantic Oscillation and Gulf Stream), along with intra-annual variability of atmospheric patterns and storms (*36*).

Summary of interviews
In August 2017, semi-structured interviews were used to evaluate business and government experiences with recurrent coastal flooding. M.H. and S.B. administered the in-person interviews in Annapolis, MD, with the interview protocol reviewed and approved by Stanford's IRB for human subject research (Protocol #42138). Prospective interviewees were purposively selected based on proximity to known flooding areas from news coverage and government correspondence and were contacted via email, phone, and canvassing. Interview length ranged from 10 to 90 minutes. Ten interviews were conducted: three local government officials and seven business representatives spanning food service (3), retail (3), and tourism (1).

Business respondents were asked the following questions:

Is flooding an issue at this location?
Does this flooding disrupt your business? If so, in what ways and how often?
Are you aware of anything the city is doing to address these issues?

Government respondents were asked the following questions:

Is flooding an issue in your area? If so, where?
How does the city address these issues? Please describe step by step.
Does flooding affect businesses in these areas? If so, in what ways and how often?

All interviewees were prompted with additional questions in longer interviews, if clarification was required, and at the discretion of the interviewers. These other questions included the location of flooding, step-by-step logistics of how they respond to flood event, and their perceptions of the events.

Interviews were transcribed and coded in Dedoose based on the type of impact that the respondents identified. Codes that emerged included: impacts to customer access and foot traffic, impacts to employee access, and impacts to business operations. Instances when respondents indicated that there was no impact were also identified.

Perceived impacts from high-tide flooding ranged widely between and within groups. Some respondents cited negative business impacts and reduced foot traffic while others identified positive business impacts. Respondents reported a similarly wide range of flood frequencies from a couple times per year to two to three times per week. Finally, respondents diverged on their preferred course of action; desired solutions included more infrastructure investments, increased government outreach, and managed retreat. Respondents held divergent views on what causes flooding in Annapolis, as well as its impacts. Illustrative quotes for each theme are shown below.

Table S1. Summary of interviews. Selected quotes illustrate the range of responses received during semi-structured interviews with representatives of local government and City Dock businesses. Responses reflect diverse perceptions of flood frequency and its impacts.

Emergent Themes	Illustrative Quotes
Customer access and foot traffic	"If it's flood down here at all, even if it's just half the parking lot, they'll just go up there [Main Street] and forget us and not bother." (retail) "I'm not sure what impact flooding has on foot traffic" (tourism) "50-50 on if foot traffic is higher or lower on flood days" (retail) "[referencing flooded parking lot] It's a really significant impact for the businesses in that area." (government) "So if it's flooded over the top, folks have trouble getting in here but as long as there's one lane, no real effect." (food service) "Word gets out that there is flooding and I think it may affect business a little bit that way. People don't come downtown." (food service)
Flood frequency and cause	"Normally, you can expect it like two to three times a week." (retail) "Well I would have said it floods about once a month … but I just read a report recently that said it floods more often - like 40 times a year." (retail) "I'd say 15-20 times a year." (food service) "95% of flooding is tidal, coming up through the storm drains, the other 5% is rainfall or storm surge, like hurricanes." (government) "When it floods, flooding happens what would you say -- all the time? Whenever it rains." (retail) "When we typically get a day of rain, because the Chesapeake Bay is an estuary or the estuaries flow into here or whatever, it floods Annapolis." (retail)
Response to flooding	"We just deal with it [flooding]. Cross our fingers and hope that sea levels aren't rising too much." (food service) "I'll let people know like check Facebook and make sure if we're going to be open or not. And I put it up there saying closing because of flooding on the block. But they can't get here anyway. If they close the street off, they'll come down here and have to turn around. So they'll find out one way or another." (food service) "You know what I think should happen? They should just take all these businesses away and let the water do what the waters supposed to do. … There's nothing to fix if you ask me, we are the problem." (retail)
Business operations	"We'll have to reroute traffic, and that adds for a little bit more logistics." (tourism) "If I know there is a tide coming, then I'll alert my main supplier." (food service) "You know, usually UPS and those kinds of people can get here by going through the

	water and going to the side here, so it doesn't affect that part of our business." (retail)

Documentation of flooding

Although we gathered as much photographic evidence of flooding as possible, there are days with water levels above the 1.73 ft threshold for which we do not have photographic evidence of flooding. We expect to miss floods in our photographic documentation, given that some floods may occur in the middle of the night and others last for very short periods of time. In our two-year time span, there are 78 days with a maximum water level equal to or greater than 1.73 ft. Of those, we document flooding on 19 days and we "miss" 59 days (261 hours) of flooding; that is, there are 59 days with water levels above 1.73 ft for which we do not have photographic evidence of a flood.

Flood documentation is driven by the duration, timing, and severity of the floods. Figure S1 shows how our hours with and without documentation break down by time of day and by water level. Many of the hours without documentation are very early in the morning, or at low flood levels.

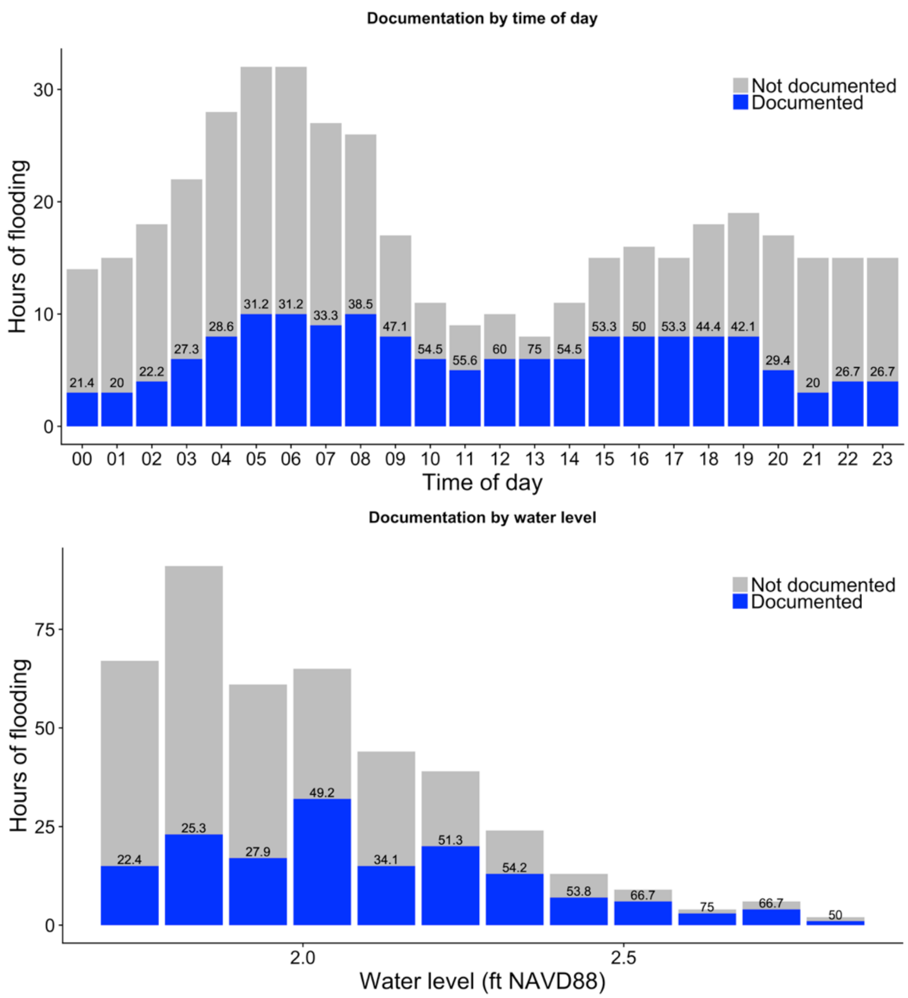

Fig. S1. Documentation of flooding by time of day and by water level. An hour is considered documented if there is photographic evidence of flooding on that day. Numbers above the blue bars are the percentage of hours documented.

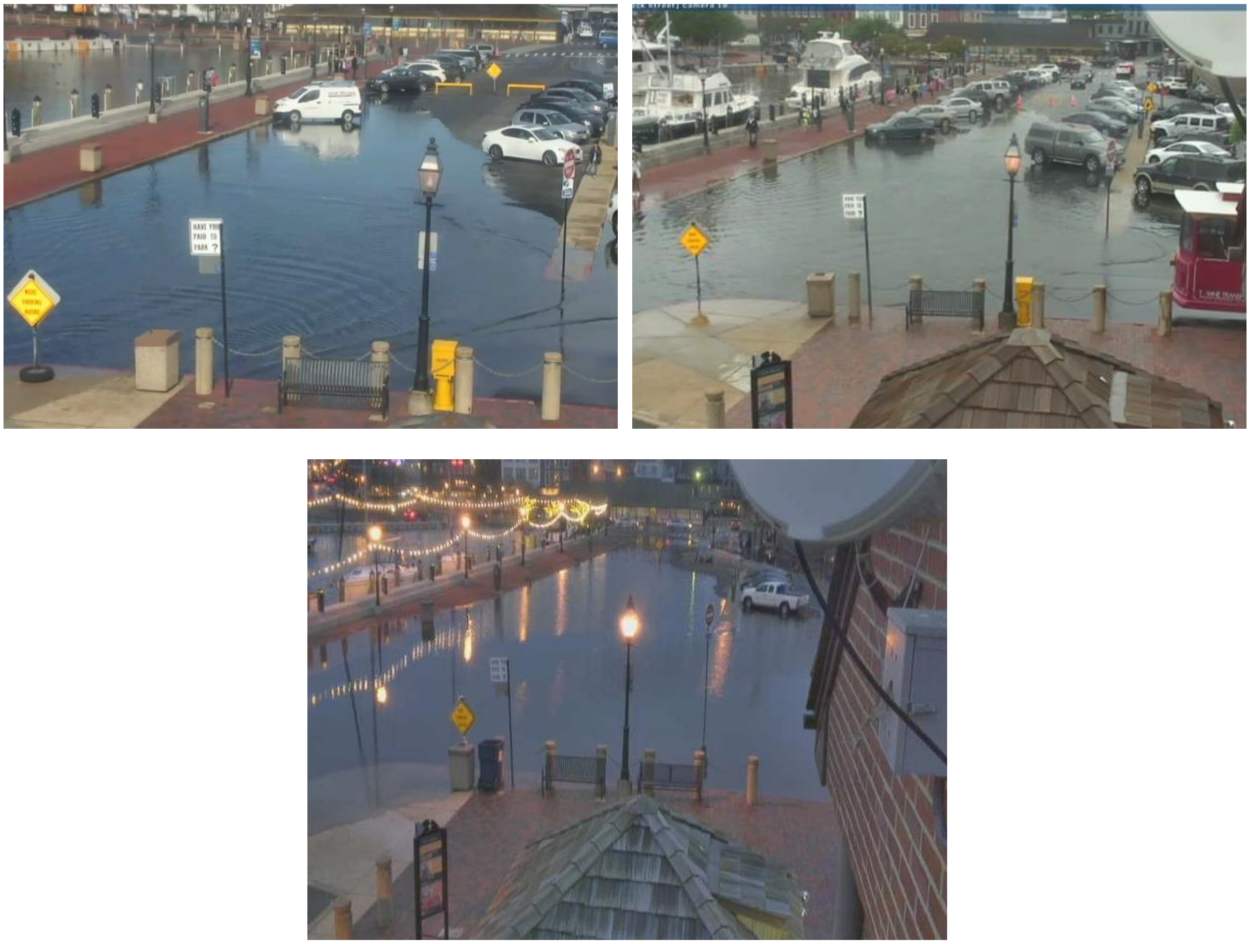

Fig. S2. Documentation of flooding on City Dock. These photos of flooding on City Dock illustrate minor (top left), moderate (top right), and major (bottom) flood levels. Photos are taken looking northwest toward the main entrance to City Dock. All photos courtesy of the City of Annapolis Police Department.

Robustness and validity

To evaluate the sensitivity of our results to model specification, we provide detailed regression results and the results from additional model specifications below. Table S2 shows the primary four models, in addition to one model specified with week (rather than month) fixed effects. The significant negative effects of flooding persist across all specifications. Table S3 shows the results when flooding is specified as a binary variable, or water level is used as a continuous variable with a cubic relationship with visits. The cubic fit is plotted in fig. S3. Figure S3 also shows the residuals from a regression of visits solely on time of day, day of week, and month fixed effects. The remaining negative deviation at high water levels shows how sharply flooding affects visit rates – in other words, there are far fewer visits at high water levels than can be explained by time of day, day of week, and month alone. Figure S3 also demonstrates that the cubic fit is not fully capturing the non-linearity at high water levels, making the non-parametric binned specification more suitable. Overall, the negative impact of water levels above our defined threshold holds across specifications.

The validity of the estimated decreases in visits due to flooding depends on the assumption that, conditioned on the time of day, day of week, and month of year, there are no other factors that are correlated with both flood frequency and customer visits. This assumption seems plausible because while there are certain months of the year that tend to experience higher water levels, the variation is not systematic from week to week. In addition, water levels are strongly affected by wind direction and speed, which fluctuate frequently. The estimates may also be biased if our definitions of flooding are wrong, such that there are floods when the water level is below 1.73 ft, or there are no floods when it is above it. Our selected threshold of 1.73 ft is derived from photographic evidence and aligns closely with Annapolis' nuisance flood threshold. Additionally, in fig. S3, we expect the threshold to approximate the water level at which the residuals begin to drop. The residuals do begin to fall in the neighborhood of 1.73 ft, though the precise threshold is not clear.

Table S2. Regression results for model specifications. The main models in the two left-hand columns include all lag variables (Equation 2), and the main models in the third and fourth columns do not include the lag variables (Equation 1). The fifth column uses hour, day of week, and week fixed effects, rather than hour, day of week, and month fixed effects. Robust standard errors are shown for Poisson regressions, and standard errors are shown for negative binomial regressions.

	Poisson	Neg. bin.	Poisson	Neg. bin.	Neg. bin.
minor	-0.483^{***}	-0.469^{***}	-0.467^{***}	-0.456^{***}	-0.386^{***}
	(0.054)	(0.054)	(0.054)	(0.054)	(0.053)
moderate	-1.009^{***}	-1.062^{***}	-0.992^{***}	-1.046^{***}	-0.940^{***}
	(0.098)	(0.075)	(0.098)	(0.075)	(0.073)
major	-2.178^{***}	-2.195^{***}	-2.162^{***}	-2.181^{***}	-2.087^{***}
	(0.285)	(0.195)	(0.285)	(0.195)	(0.188)
prcp	-1.896^{***}	-1.400^{***}	-1.931^{***}	-1.408^{***}	-1.371^{***}
	(0.461)	(0.153)	(0.471)	(0.153)	(0.144)
lag1	-0.329^{***}	-0.295^{***}			-0.249^{***}
	(0.102)	(0.090)			(0.084)
lag2	-0.405^{***}	-0.382^{***}			-0.318^{***}
	(0.109)	(0.078)			(0.073)
lag3	-0.211^{**}	-0.227^{***}			-0.188^{***}
	(0.099)	(0.072)			(0.068)
lag4	-0.231^{***}	-0.238^{***}			-0.193^{***}
	(0.073)	(0.069)			(0.064)
lag5	-0.154^{**}	-0.137^{**}			-0.111^{*}
	(0.066)	(0.070)			(0.065)
lag6	-0.116^{**}	-0.111^{*}			-0.096
	(0.055)	(0.066)			(0.062)
dayafterflood	0.002	-0.004			0.011
	(0.016)	(0.019)			(0.020)
Constant	3.905^{***}	3.909^{***}	3.894^{***}	3.897^{***}	3.945^{***}
	(0.030)	(0.030)	(0.030)	(0.030)	(0.075)
Hour FEs	Yes	Yes	Yes	Yes	Yes
Day of week FEs	Yes	Yes	Yes	Yes	Yes
Month FEs	Yes	Yes	Yes	Yes	No
Week FEs	No	No	No	No	Yes
Observations	4,584	4,584	4,584	4,584	4,584

Note: *p<0.1; **p<0.05; ***p<0.01

Table S3. Regression results for alternative specifications. The models in columns 1 and 2 use a binary flood variable, and the model in column 3 uses a continuous water level as the independent variable, fitted as a cubic polynomial. The binary flood specification marks hours as 1 if the water level is above 1.73 ft and 0 otherwise. The continuous water level specification does not include any flood variables; instead, visits are regressed on hourly water level, water level squared, and water level cubed. The continuous water level specification is shown graphically in fig. S3. Robust standard errors are reported for the Poisson regression, and standard errors are shown for the negative binomial regressions.

	Poisson	Neg. bin.	Neg. bin.
Flood (binary)	-0.722^{***}	-0.732^{***}	
	(0.059)	(0.043)	
Water level			0.087^{***}
			(0.014)
Water level^2			-0.093^{***}
			(0.009)
Water level^3			-0.055^{***}
			(0.006)
prcp	-1.877^{***}	-1.370^{***}	-1.339^{***}
	(0.459)	(0.153)	(0.154)
lag1	-0.328^{***}	-0.294^{***}	
	(0.101)	(0.090)	
lag2	-0.405^{***}	-0.381^{***}	
	(0.109)	(0.079)	
lag3	-0.211^{**}	-0.227^{***}	
	(0.099)	(0.073)	
lag4	-0.231^{***}	-0.237^{***}	
	(0.072)	(0.069)	
lag5	-0.154^{**}	-0.136^{*}	
	(0.066)	(0.070)	
lag6	-0.116^{**}	-0.110^{*}	
	(0.055)	(0.066)	
dayafterflood	0.002	-0.003	
	(0.016)	(0.019)	
Constant	3.902^{***}	3.906^{***}	3.943^{***}
	(0.030)	(0.031)	(0.031)
Hour FEs	Yes	Yes	Yes
Day of week FEs	Yes	Yes	Yes
Month FEs	Yes	Yes	Yes
Observations	4,584	4,584	4,584

Note: *p<0.1; **p<0.05; ***p<0.01

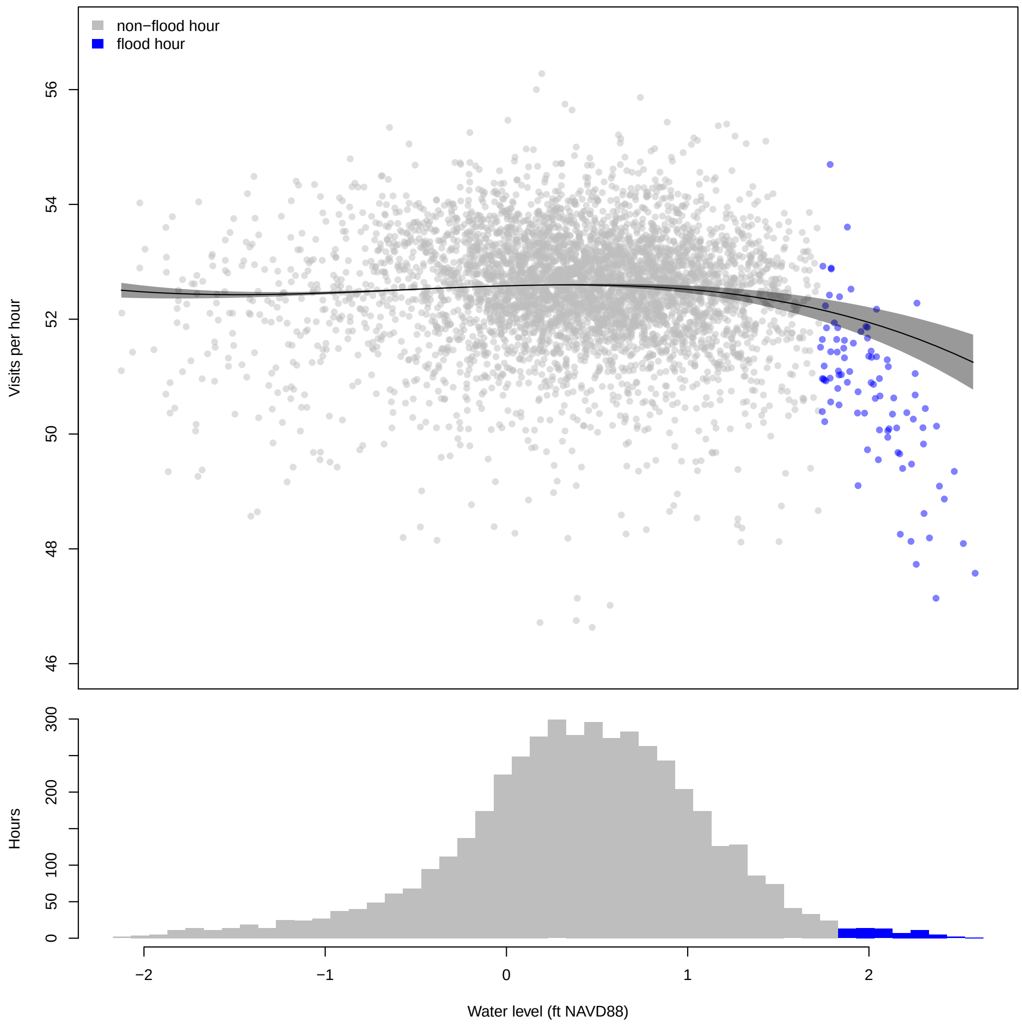

Fig. S3. Visits as a continuous function of water level. Each point in the top panel represents an hour in the data. The y-axis is the residual from a regression of visits on time, day of week, and month controls, added to the mean number of visits per hour. The line is a cubic fit with water level as a continuous variable (see column 3 of table S3 for fit details), with bootstrapped 95% confidence intervals in gray. The histogram in the bottom panel indicates the number of observations at each water level. The blue bars indicate hours above the estimated flood threshold.

Spatial substitution: visits to other parking lots

Parking transaction data from the most proximate alternative to the City Dock lot, Market Space, were attained for the calendar years 2016 and 2017. Using the exact same primary models as for City Dock visits (as shown in Figure 4), the results indicate that the Market Space lot does not experience an increase in visits while the Dock Street lot is flooded, nor are visits affected in the immediate hours after a flood. Visits do decline during rain hours, as expected. However, these analyses may be constrained by the Market Space parking lot often being near capacity. There are 39 spots within this parking lot, and the mean number of visits is 30 per hour, providing relatively little room for visitors displaced from City Dock. Overall, this evidence implies that would-be parkers at City Dock are not simply parking at Market Space instead. They may substitute to different neighborhoods altogether, or a different lot.

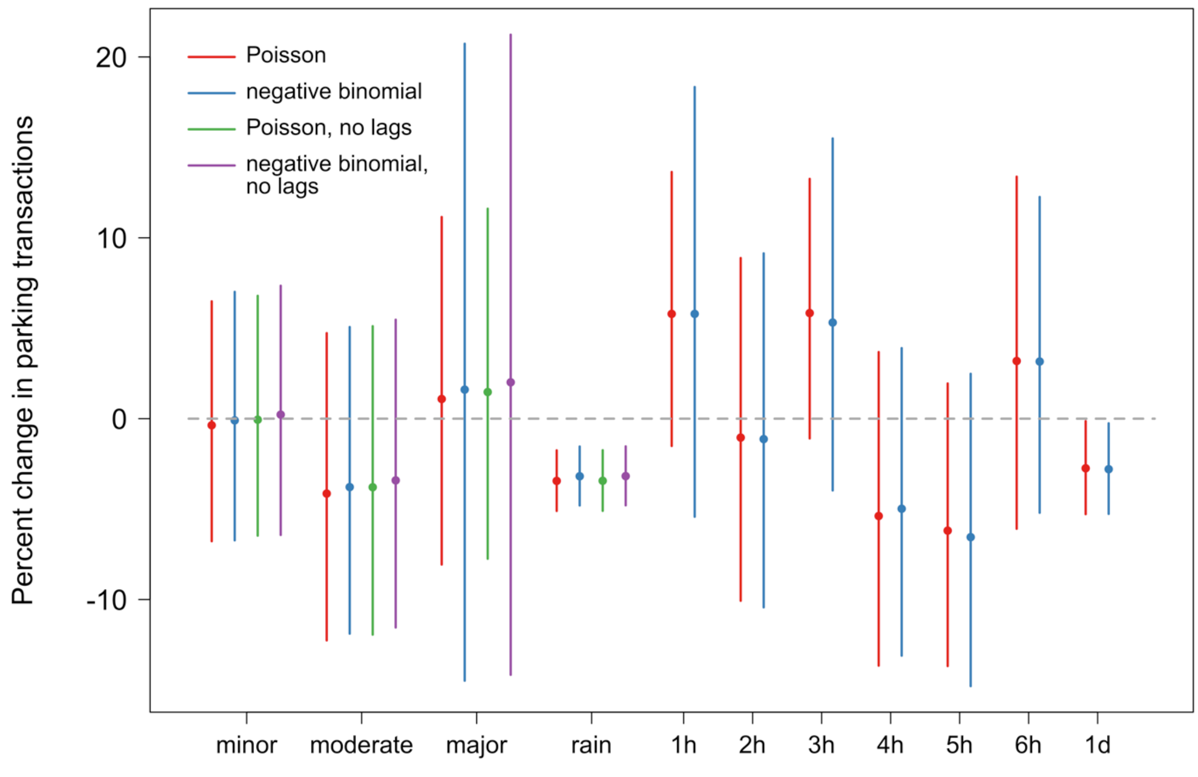

Fig. S4. Model results showing estimated changes in visits to the Market Space parking lot during minor, moderate, or major flood hours; during rain hours; and during post-flood time periods (1 to 6 hours postflood and the day after a flood). Errors bars show 95% confidence intervals, using standard errors for the negative binomial models and robust standard errors for the Poisson models. Effect of rainfall is represented as the effect of 0.085 inches per hour, which is the average rainfall per hour for non-zero rain hours.

Estimating historical visits using hourly water level measurements

In the main analysis, 2017 hourly water levels are adjusted uniformly based on the difference between annual mean sea levels. Rather than uniformly incrementing or decrementing 2017 water levels, historical visits can be estimated using observed hourly water levels (for years with no gaps in the tide gauge record). That is, floods are assigned based on the observed water level in each hour, and the counterfactual number of visits is estimated on that basis. This analysis keeps visits constant; that is, visits from 2017 are combined with hourly water levels from past years. The results shown below reflect the up-and-down nature of the plots in Figures 5A and 5B. Although mean sea level is rising steadily over time, 2010 had a higher mean sea level and more flood hours than many of the subsequent years. The effect on visits will also be moderated by how many of the flood hours occur during business hours, which varies from year to year.

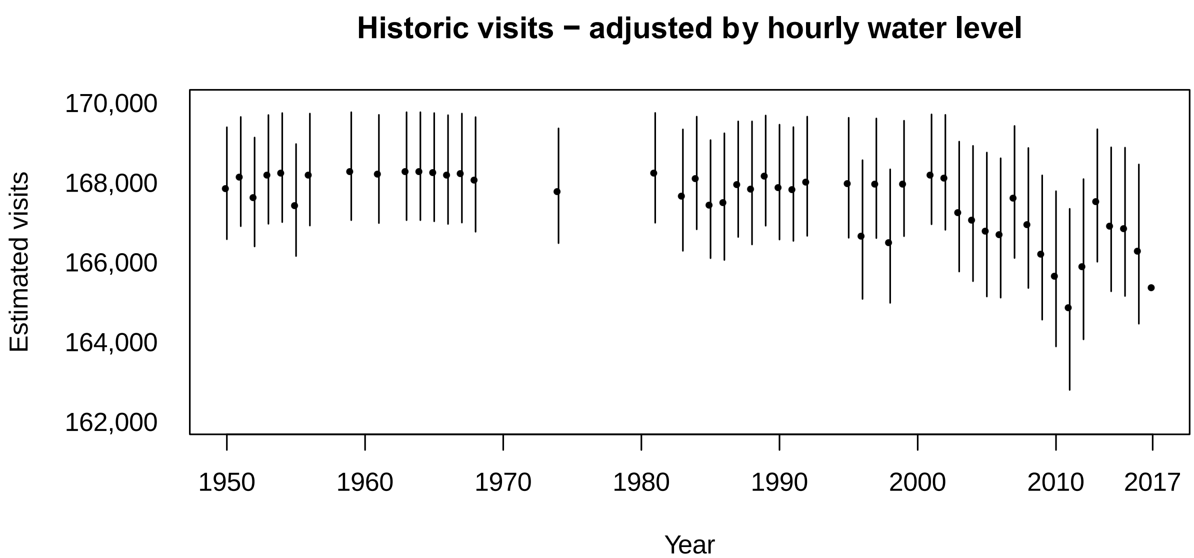

Fig. S5. Estimated visits in past years using hourly water level measurements. Historical visits are estimated using hourly tide gauge records from past years, rather than uniformly incrementing or decrementing 2017 sea levels. Years without complete tide gauge records are missing.