A Rapid Response Survey to Characterize the Impacts of the 2017 High Water Event on Lake Ontario

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Research Impact Statement: A real-time survey of flood impacts on Lake Ontario during the 2017 high water event provides valuable information to better understand and model flood risk.

ABSTRACT: In the spring and summer of 2017, communities along the Lake Ontario shoreline suffered from the worst flood event on record. In late May, daily water levels reached their highest point in over 100 years, and flooding continued throughout much of the summer as lake levels slowly declined, with inundation and erosion significantly impacting shoreline homes and businesses. In this work, we present results from a rapid response online survey of property owners along the New York Lake Ontario shoreline to quantify the perceived flood impacts of the 2017 extended high water event. The survey focused on the degree and spatial distribution of inundation and erosion; the duration and drivers of inundation; the associated damages to different property features, with an emphasis on shoreline protection; and the degree of disruption to business and other activities and services. Photographic documentation of inundation extent and property damage was also provided by survey respondents. We demonstrate the potential utility of this dataset by characterizing key features of inundation and erosion impacts across the shoreline, and by using classification and regression trees to explore the predictability of inundation and erosion based on property characteristics. This work is part of a larger effort to develop models of inundation and erosion that can support flood impact assessments across the shoreline and help communities better prepare for future extended high water events.

(**KEYWORDS:** flooding; survey; Lake Ontario; water levels)

INTRODUCTION

The shoreline of the Great Lakes presents a unique physical setting for flood risk. High water levels and associated flood events result from the combination of a variety of processes that drive lake level variability across multiple time scales (Norton and Meadows, 2014). In addition to a strong seasonal cycle in lake levels (Lenters, 2001), long-term shifts in water supplies (e.g., precipitation, evaporation, runoff) drive static water level fluctuations on inter-annual to decadal timescales (Gronewold and Stow, 2014), while instantaneous water levels vary sub-hourly in response to wind-driven storm surge and seiches (Trebitz, 2006). Floods linked to extended periods of high static water levels tend to occur during the late spring and summer and are of long duration, while storm-related flooding linked to surge and wave activity are often shorter and occur most often during the spring and autumn when storm activity is greatest (Angel, 1995). These event types can also overlap, with extended high water levels enhancing flood impacts from storm-related activity (Meadows et al., 1997). Flood impacts can vary depending on whether properties are located in an embayment or directly on the lakeshore, and are driven not only by inundation but also by erosion linked to lake hydrodynamics (Rovey and Borucki, 1994). To date, data on flooding impacts specifically linked to periods of extended high static water levels are sparse, making it difficult to understand the unique impacts of these long-duration events.

A major flood impacted the shoreline of Lake Ontario in the late spring and summer of 2017, driven primary by an extended period of high static water levels. Flood levels, defined by static levels above 75.5 m, were reached in late April, and by late May, water levels peaked at 75.88 m, the highest in the 100-year record (Carter and Steinschneider, 2018). Levels remained elevated for several months afterward, causing widespread property damage linked to inundation and erosion.

The 2017 high water event, though unprecedented in its severity, was not without historical analogue. Flood events linked to extended periods of high static water levels along the shoreline of Lake Ontario are episodic, occurring approximately every 20 years (1929, the mid 1940s and early 1950s (1943, 1947, 1951, 1952), the mid 1970s (1973, 1974, 1976) and in 1993). In response to these events and other storm-induced floods, various provincial (Shoreline Management Review Committee, 1986), federal (Canada-Ontario Great Lakes Shore Damage Survey, 1975), and international (International Joint Commission 1976, 1983, 1993) agencies across the U.S. and Canada have conducted multiple studies over the past several decades to examine the types of damages caused during extreme lake levels and the actions taken to both prevent and mitigate these damages. However, these earlier reports generally did not distinguish between damages caused by high static levels and instantaneous peak levels linked to storm activity. Only a handful of studies have made such distinctions, and were conducted around the time of the last major high water event on Lake Ontario in 1993. Kreutzwiser and Gabriel (1992) and Shrubsole et al. (1993) compiled a review of past literature, government reports, and newspaper articles to summarize 131 coastal flooding events in Ontario along the Great Lakes from 1859-1987, including the temporal and spatial distribution of flooding and the nature and magnitude of damages. They found a general rise in damages over time, and a tendency for floods to occur more often under high static water level conditions, although storm activity alone also played an important role in flood occurrences. Angel (1995) confirmed this finding for the U.S. shoreline, using *Storm Data* published monthly by NOAA to show that property damage due to passing extra-tropical cyclones was substantially higher during times of high static lake levels. The effects of static water levels on flood and erosion damage also vary by lake. For instance, Gabriel et al. (1997) determined threshold water levels at which Canadian shoreline interests began experiencing major damages and compared these levels to prevailing static and storm-induced water levels across the Great Lakes using mean and instantaneous water level data. They found that flood damages were more related to instantaneous water levels on Lake Erie, but were more closely correlated to fluctuations in static levels on Lakes Ontario, Huron, and St. Clair.

The location of lakeshore property relative to the waterline is another critical factor for flood impacts (Kreutzwiser, 1987). On Lake Ontario, the proximity of property to the lakeshore has been influenced by the history of lake level management. After a series of floods in the 1940s and 1950s, the International Joint Commission (IJC) sought to reduce flood risk and support other coastal stakeholder interests by regulating lake level fluctuations. To do so, they constructed the Moses Saunders Dam on the St. Lawrence River between Massena, New York and Cornwall, Ontario, and also dredged the St. Lawrence Seaway to manage and increase the capacity of outflows from the lake. The 1956 Order of Approval to regulate Lake Ontario levels stated that levels should be managed within a range of 74.15 m to 75.37 m (i.e., a 4-foot range), although it acknowledged that this range could be violated due to natural fluctuations in water supplies to the lake. Yet the proximity of shoreline property to the waterline and the design of shoreline protection structures (e.g., seawalls, revetments) were often determined based on the stated 4-foot elevation range, exposing property to elevated flood risk when water levels are above average.

To further compound this risk, the IJC recently began managing Lake Ontario water levels and downstream releases under a newly instituted lake level plan, termed Plan 2014. The plan was implemented in January 2017 prior to the most recent flood. Plan 2014 was designed to better support coastal ecosystems by reintroducing some of the variability in lake levels that had been reduced under the older management plan. The IJC projected that flood damages would be modestly higher based on the new plan, particularly for shoreline protection infrastructure, although they recognized the uncertainties in the estimated impacts and the need for additional research and data collection to better inform these estimates (IJC, 2014). In particular, there is a paucity of information available on damages from past flood events caused specifically by extended periods of high static water levels: available information is composed primarily of sparse photographic evidence and FEMA insurance claims that record damage, but cannot establish causality (inundation, wave attack, wave splash/spray), duration, or nature of the damage (near-shore property, outbuildings, primary home) and how these attributes vary across the shoreline.

In response to this knowledge gap, this study presents results from a rapid response online survey of property owners along the New York shoreline of Lake Ontario to assess the impacts of the persistent high static water level conditions during 2017. The survey was administered from late May through August and collected information from property owners living on the lake coast and embayments, particularly those living in several targeted municipalities where outreach efforts were concentrated. The information collected includes the degree, timing, and spatial distribution of inundation and erosion; the duration and drivers of inundation; the associated damages to different property features, with an emphasis on shoreline protection; and the degree of disruption to business and other activities and services. Photographs of inundation extent and property damage were also requested. These data provide the first real-time overview of the impacts of an extreme event to shoreline interests under Plan 2014, and can be used to inform the ongoing evaluation of the new lake level management plan. We demonstrate the potential utility of this dataset by characterizing key features of inundation and erosion impacts across the shoreline, and by using classification and regression trees to explore whether the degree of inundation and erosion are predictable based on unique property characteristics. This effort will help assess whether property characteristics can be used to improve quantitative models of inundation and erosion, such as those used in the development of Plan 2014 (IJC, 2014). Importantly, the real-time nature of these data makes them uniquely suited to validate such flood risk models at the parcel level, since data collected several months or years after a flood has passed often cannot accurately characterize exactly where (which specific parcels and property features) and when (specific dates) flood impacts occurred. This information is needed if flood risk models are to be used for detailed, community-based planning for flood risk reduction and management along Lake Ontario. We conclude the study with a discussion of data limitations and future research efforts that can make use of this novel dataset.

METHODS

Web-based Survey

As the unusual nature of the water levels of 2017 was becoming clear, we were able to quickly mobilize a web-based survey data collection strategy to explore the real-time impacts of high water levels during 2017 on Lake Ontario shoreline property owners. Survey implementation primarily targeted property owners in 14 municipalities in Monroe, Wayne, Oswego and Jefferson Counties (see Table 1, Figure 1). These municipalities were chosen because 1) they had some of the largest populations of property owners living along the lakeshore, 2) they have historically been susceptible to impacts from high water levels, and 3) we had established relationships with municipal leaders to help promote the research.

[INSERT TABLE 1 HERE]

[INSERT FIGURE 1 HERE]

Distribution of the survey proceeded quickly over the course of the late spring and summer of 2017 to capture real-time impacts. Accepted as best practice (e.g., Dillman, 2011), multiple contacts were made with potential respondents. The survey was first made available using the Qualtrics Survey Software on May 25, 2017 and responses were collected up until August 31st. We used monthly water level forecasts provided by the USACE to try and ensure that the start date closely coincided with the occurrence of peak water levels, so that all survey respondents experienced these levels before reporting on impacts. To help avoid potential non-response bias, and to increase representativeness of responses overall, responses were encouraged even if property owners had not experienced flood damage. We also ensured confidentiality for respondents through guarantees that the address of their parcel would not be shared publicly and that all results would be reported at aggregate (i.e., town, county) scales. Although random sampling from a known population is generally accepted (e.g., Fowler, 2013) as the best mechanism to promote representativeness of results, we had to take a different approach. The need for rapid collection of responses in real time, especially in disaster contexts, allows loosening the assumptions of random sampling (see Beebe 1995 for a useful review). We emphasized maximizing response density among shoreline property owners in the targeted municipalities, rather than random sampling across a wider geography. The survey was distributed to residents in targeted municipalities through two primary approaches. First, municipal officials from communities identified in Table 1 were asked through email and at inter-municipal meetings to circulate the survey to their constituents using e-mail lists of property owners in their communities; fliers at municipal offices and emergency response trailers; and a link to the survey on municipal websites. Secondly, the survey was advertised directly to property owners over a variety of media outlets, including a posting on the New York Sea Grant website; traditional and social media (newspaper, TV, radio, Facebook, Twitter); and agenda time at town hall meetings. We were unable to implement our strategy in precisely the same way across municipalities, as some strategies were unavailable in some places (e.g., some municipalities did not hold public meetings or have email listings for property owners). In addition, while implementation primarily targeted coastal property owners in the municipalities in Table 1, shoreline residents outside of the targeted municipalities and non-coastal property owners also saw advertisements for the survey, e.g., on social media and radio and television broadcasts. These constraints make it impossible to calculate a traditional response rate. Using GIS software, we identified and retained responses from other Lake Ontario shoreline properties in New York outside the municipalities in Table 1, as they were considered potentially informative, but removed responses from all non-coastal property owners, as they were considered outside the scope of our analysis.

The full survey instrument can be found in the Supporting Material. We summarize its main features here. Basic information that was requested in the survey includes: property address/location of damage, confirmation that the property was located on the shoreline, and whether the respondent was the owner of the property. Specific questions were then posed for three categories of impacts, including inundation, erosion, and shore protection damage:

- Inundation was defined as occurring when property is submerged by water, even if only momentarily or from wave activity. Questions were asked regarding the type of property feature that was inundated (e.g., dock, lawn, landscaping, outbuildings, utility infrastructure, foundation, first floor), and then for each feature, the date that inundation began, duration of inundation, whether inundation was caused by static water levels in isolation or with additional wave activity, and the degree of damage.
- Erosion was defined as occurring when land collapses or slides into the water because it has been weakened by high water levels and waves. Questions were asked regarding the type of shoreline on the property (e.g., beach, bluff), amount of erosion that occurred, and the degree of damage to different property features caused by erosion.
- The most common hard shoreline protection structures for private property along the shoreline include revetments and seawalls or bulkheads (Keillor, 2003). Revetments are shore-parallel structures with a sloping face that protect a bank or bluff from erosion, while seawalls and bulkheads are vertical, shore-parallel structures that protect land and property from rising water levels and wave activity. However, our initial conversations with property owners indicated they were often unsure which of these structure types best described their shoreline protection. Therefore, hard shoreline protection structures were defined simply as vertical or

sloping walls used to protect property against flooding and erosion. We also defined “living” or nature-based shorelines by the use of living/natural materials to stabilize the shoreline. Living shorelines have been promoted as alternative erosion control strategies that avoid the environmental impacts of hard shoreline protection structures (Keillor, 2003). Questions were asked regarding the presence, type, material, and age of hard shoreline protection structures, the degree of damage or failure of these structures, whether the property had a living shoreline, and the damage to that living shoreline.

We developed a 4-point scale to measure property owners’ perceived degree of impacts in the categories above: no impact, small impact, moderate impact, and substantial impact. We chose this scale instead of an economic estimate of monetary damages because 1) it would have been a burden for respondents to gather proof of expenses, likely reducing participation and increasing survey fatigue, 2) doing so may have increased concerns about confidentiality and use of the data, 3) if receipts were not required, respondents may have elected to inflate damage estimates in the hopes of using the survey results to support requests for compensation, and 4) because survey distribution was administered during the peak of flooding, monetary damages would not yet be complete, nor would estimates be available until after the flood waters receded.

Information was also collected regarding disruptions caused by inundation (e.g., loss of street or property access and use, increased travel time, property cleanup), other costs related to fighting floods (e.g., sandbags, paid labor), impacts to local businesses (e.g., lost revenue, loss of rental income, business closure), whether the property in question was covered by flood insurance, and a summary score (1-10 scale) of the overall perceived impact of the flood event, with 10 being the largest perceived impact. Again, all questions related to costs were measured on the 4-point scale described above. For all responses related to this 4-point scale and all other inquiries regarding flood impacts, it is important to recognize that these scores provide a measure of respondent perceived impacts, rather than technical measurements of damage (i.e., foundation damage, mold, soil loss, etc.). We did not conduct these sorts of measurements in our study.

Finally, the survey requested that the respondent provide photographs of flood impacts, including the location of the waterline on the property and images of property damage linked to inundation and erosion. These images were requested to provide critical ground-truth information that could support the development of quantitative flood risk prediction tools for the Lake Ontario shoreline, including data that could be used to validate predictions of inundation based on a digital elevation model (DEM) and water level and wave data. Such tools formed the basis of the flood damage estimates used to assess the impacts of new lake level management strategies (IJC, 2014) and to support local flood risk planning, but concerns over the precision of the DEM, water level data for certain areas of the coast, and estimates of wave height and direction motivate the need to validate these models. The images collected in this survey provide such an opportunity for model testing, but will be engaged in a subsequent study (discussed later).

In total 896 surveys were returned, although 16% (144) were excluded because the reported property was not located on the New York shoreline of Lake Ontario. In addition, 89 responses were duplicate responses for the same property. For the vast majority of these locations, only one of these duplicate responses was linked to a fully completed survey, and this often coincided with the first of the duplicate responses. The other responses were generally associated with additional photos or augmented written descriptions of damage. Therefore, the responses for each of the duplicates were reviewed and the most complete response selected. An additional 173 responses were removed because they failed to answer a large number of questions, often with over 90% of the data fields missing. The request for photos of the waterline appeared near the beginning of the survey instrument, so this missing data may be linked to the respondent's reluctance to take and upload photos. The removal of these responses resulted in 490 total usable responses, which is approximately 7% of all Lake Ontario shoreline land parcels in New York. These response parcels are well distributed along the entire shoreline of Lake Ontario, with the greatest number of responses in Monroe and Wayne Counties, and to a lesser extent Oswego and Jefferson Counties (see Figure 1).

In this work, we use the final 490 responses to address the following questions:

- How did inundation and erosion impacts vary across the New York shoreline?
- How long were different property features inundated, and was inundation more often causes by high static water levels or wave activity?
- How much property damage was linked to inundation and erosion, and how did this vary across property features, including hardened shoreline protection and living shorelines?
- Were these damaged well covered by flood insurance?

These questions are addressed using frequency diagrams and Chi-Square tests of independence to determine whether particular impacts (e.g., inundation occurrence, land loss to erosion, property damage) exhibited significant differences across categories of interest (e.g., county, duration of impact, property feature). They are motivated by the need to better understand where flood impacts were most severe and what aspects of the flooding led to the most hardship for shoreline interests. This information will help determine where future efforts would most improve the quantification of flood risk along the shoreline, both in terms of characterizing the hazard and determining the exposure of shoreline communities.

Classification and Regression Tree Analysis

We are also interested in the association between parcel-level characteristics and the occurrence and damage associated with inundation and erosion during the high static water levels of 2017. Here, we define two categorical dependent variables: the occurrence of foundation inundation and the severity of land losses due to erosion. The former variable is binary, and we define the second variable as binary by combining the four levels of erosion (none, small amount, moderate amount, and substantial amount) into two categories: none/small and moderate/substantial. We consolidated the erosion data to simplify the analysis and because 1) it is difficult to distinguish between similar erosion impacts when building a model on nominal data, and 2) an ordinal regression on the original erosion categories would be sensitive to nonlinear and non-additive relationships in the data. The classification of the binary variables for inundation and erosion is based on a series of predictors collected in the survey, including shoreline type, the presence and age of shoreline protection infrastructure, and the presence of a living shoreline. We also generated two supplemental data fields, including the distance from the front of the home to the waterline and the minimum elevation of the home. These variables have clear importance to the occurrence of inundation and erosion and were therefore included to avoid omitted variable bias when estimating the importance of other property characteristics for inundation and erosion risk. Distances were calculated in Google Earth based on the addresses provided in the survey response and the waterline captured in the Google Earth base imagery taken in August 2016, which was very close to the lake-wide period-of-record (1918-2016) average water level (74.77 m). Elevations were calculated using GIS software by first creating a polygon around the foundations of each home as depicted in the satellite and high-resolution aerial imagery base map in ArcGIS, and then calculating the minimum elevation within this polygon from a 1/9 arc-second DEM developed by NOAA in 2014 (https://www.ngdc.noaa.gov/metaview/page?xml=NOAA/NESDIS/NGDC/MGG/DEM/iso/xml/5197.xml&view=getDataView&header=none). Elevations are measured in meters above the low water datum (LWD) for Lake Ontario, given as 74.16 m.

The predictability of inundation and erosion classes based on the predictors described above was explored using classification and regression tree (CART) analysis (Breiman et al., 1984). CART is a binary tree-growing algorithm that is used to predict the class of a dependent variable based on empirical rules using a series of predictors. The tree is constructed by recursively splitting subsets of data into two smaller subsets ("child nodes") based on values of the predictors. Model fitting requires the selection of predictor variables that determine the splits at different levels in the tree, the threshold values of the predictors that define these splits, and the determination of when a node should be considered terminal. At each node in the tree, the predictor and threshold value that best splits the dependent variable data into two "purer" groups is selected based on the Gini index (Breiman et al., 1984), which is a measure of impurity that quantifies the degree of homogeneity of the data within a node. The splitting process is continued for each parent node until a minimum number of observations are no longer available in a child node to attempt a split, thus defining that node as terminal. This minimum threshold is a parameter of the model selected by the analyst, and is set to 10 observations in this study.

The resulting tree structure defined by the procedure above is complex and likely provides an over fitted model to the data. Therefore, a second pruning step is included to reduce the size of the tree based on a cross-validation procedure. For a particular degree of tree complexity (i.e., number of terminal nodes), a unique tree can be defined that minimizes prediction error for classes of the dependent variable. To determine the optimal degree of tree complexity, the data are split into K different groups, and the model is fit on all but the k^{th} group, which is reserved for out-of-sample prediction. For a particular value of tree complexity, a skill score based on classification prediction error is then estimated for the k^{th} group. This score is re-estimated for each of the K groups and aggregated to produce a single measure of cross-validated prediction skill associated with that degree of tree complexity. This cross-validated measure of prediction skill can then be compared across different values of tree complexity to select the optimal degree of complexity for out-of-sample prediction. In this work, the fitting procedure is conducted in the *R* statistical programming environment using the *rpart* package (Therneau and Atkinson, 2017).

The *rpart* package employs listwise deletion for any observations that are missing values for the dependent variable. For observations missing data for some but not all of the predictors, a data imputation procedure is employed to populate missing data fields. First, the Gini index is calculated only for observations without missing predictors to determine the splitting variables and split points to be used in the tree. Then, for observations with a missing predictor value, the missing datum is estimated using the independent variables that are available based on another classification tree. The class of the dependent variable can then be predicted based on this imputed predictor value.

RESULTS

Characterization of 2017 flood impacts

We begin by summarizing some of the key findings from the survey, including the nature and spatial distribution of flood impacts. The timing and number of survey responses over the sampling period are presented in Figure 2. Hourly water levels on Lake Ontario, as measured at Rochester NY, peaked on May 19th prior to the beginning of the sampling period, ensuring that all respondents experienced peak levels before reporting on flood impacts. Response rates clustered in time as outreach efforts were extended to different municipalities along the shoreline, and generally declined over the sampling period, despite a peak in mid-July that was associated with outreach efforts in the Rochester metropolitan area. After normalizing the data by the number of responses per day, no significant linear trends at the 0.05 level were found in key impact variables, including the inundation of near-shore property (e.g., lawn, landscaping, dock) or primary homes, the duration of inundation, degree of erosion, and the summary assessment (1-10 scale) of flood impacts. Responses by date were linked to mean daily water levels, with both variables declining over the sampling period. However, the rate of responses was uncorrelated to storm surge events (Kendall tau test, $p=0.61$), defined for each day as the difference between the maximum and mean hourly water level, suggesting that response rates did not increase significantly following high instantaneous peak water levels. Lagged correlations between the two variables were also insignificant. Finally, we note that there was a moderate increase in responses in August, when static water levels were at their lowest point over the sampling period.

[INSERT FIGURE 2 HERE]

The summary measure of overall impacts of the 2017 flood reported by respondents on a scale from 1 (smallest impact) to 10 (largest impact) shows that impacts were perceived as substantial: over 20% of all respondents selected the highest level of impact (10), and 61% reported impact levels between 7-10. However, the cause of the high level of overall impact can vary across respondents, depending on the degree of inundation, erosion, damage to shoreline protection, and other impacts they experienced. These sources of variation are examined in detail below.

Inundation Impacts

Figure 3 shows the occurrence of inundation across the entire lakeshore and by county for different property features, including near-shore features (e.g., lawn, landscaping, dock, beach-access stairs or ramp), secondary structures (e.g., utility infrastructure, outbuildings), and both the foundation and first floor of the primary home. In this figure and all figures to follow, the number of responses (n) is presented, and excludes missing responses and responses that indicated that the question did not apply to their property. Almost all respondents experienced some inundation of their near-shore property, and a large majority also had secondary structures inundated. Importantly, half of the respondents also reported inundation of their foundation, with almost 10% experiencing first floor inundation, suggesting a high degree of damage to property. The largest clusters of high-impact inundation (i.e., foundation, first floor) normalized by response rate (i.e., as a percentage of total responses for each property feature) are located near the metropolitan Rochester area (Monroe County), around Sodus Bay (Wayne County) and Fair Haven (Cayuga County), and a portion of the southeastern shore south of Henderson Bay (Oswego County). Notably, less inundation occurred in Niagara County and the western portion of Orleans County, as well as around Henderson Bay (Jefferson County). These differences between counties are significant at the 0.01 level (chi-square = 37.89, 18 df, p= 0.004), and generally suggest higher inundation impacts correlate with increased development in low-lying areas near embayments.

[INSERT FIGURE 3 HERE]

The nature of the inundation was unique to the very high static water levels experienced during the summer of 2017. For instance, the duration of inundation was quite long, with a majority of property features experiencing over 2 months of inundation, and at least 75% of all features experiencing at least 1 month of inundation (Figure S1). The duration of inundation for property features that are generally located at higher elevations (first floor of home) tends to be shorter than those features at lower elevations (near-shore property), although these differences are not statistically significant (chi-square = 15.04, 15 df, p = 0.45). The perceived cause of inundation also varied by property feature (Figure S2). For near-shore property, inundation appears evenly attributed to static levels and waves, but static levels alone play a larger role for secondary structures (58% of inundation occurrences), home foundations (68% of occurrences), and particularly first floor inundation (81% of occurrences). These differences by property features are highly significant (chi-square = 32.09, 6 df, p < 0.001). Further analysis reveals that all but 2 homes with first floor inundation linked to static levels alone are located within an embayment, while all but 1 home with first floor inundation linked to wave activity are located directly on the lake shore.

Figure 4 shows the degree of damage to each property feature due to inundation. For most features, damages are near evenly distributed across the different levels of damage, with a slight tendency towards higher damages, although most respondents reported more substantial damages for near-shore property. These differences were highly significant (chi-square = 61.38, 12 df, $p < 0.001$). In addition, many respondents were unsure of the degree of damage to structures on their property, as the flood waters likely had not receded at the time of reporting.

[INSERT FIGURE 4 HERE]

Erosion Impacts

Erosion linked to high static water levels posed another major problem to residents along the Lake Ontario shoreline. Figure 5 shows the perceived degree of land loss due to erosion across the entire lakeshore and by county, and Figure S3 shows the associated, perceived damages to different property features. These reported categories provide a lower limit on the actual erosion loss and damage, as land would only continue to erode after the time of reporting. Aggregating across the shoreline, reported erosion loss was spread somewhat equally across the different categories of erosion, albeit with a weak tendency towards larger losses. There is also some spatial coherence in the degree of land loss, with clusters of low erosion in Wayne County and larger amounts of erosion along the southwestern shoreline (Orleans and Niagara Counties), although these differences are not statistically significant at the 0.05 level (chi-square = 31.98, 24 df, $p = 0.13$). Erosion losses caused the largest damages to near-shore property, with 39% of respondents reporting substantial damages. However, a majority of respondents indicated that their primary homes avoided erosion-linked damage altogether. Still, 17% of respondents reported moderate or substantial erosion-related damage to their primary homes, while 15% were unsure at the time of reporting. Similar percentages were reported for secondary structures. The differences in damage across property features are highly significant (chi-square = 197.23, 8 df, $p < 0.001$).

[INSERT FIGURE 5 HERE]

Shoreline Protection Structure Impacts

Approximately 3 out of 4 respondents indicated that they had some form of hardened shoreline protection structure on their property. Survey results (not shown) indicate that about half of these structures were built between 1970 and 1995, with the rest evenly distributed between pre-1970 and post-1995 construction. Most of these structures were built from cement, although many were built from steel, rock, or a combination of these materials. While 18% of respondents were unsure of the damage to these structures at the time of reporting, over 60% of respondents reported either moderate or substantial damages to their protection structures, with less than 10% stating that no damage had occurred.

Of the 490 total respondents, 183 reported having a living shoreline as a means to stabilize the shoreline on their property. Of those respondents, 65% reported moderate to substantial damage to their living shoreline (50% reported substantial damage). We note that these levels of damage are notably higher than the level of erosion losses reported across all respondents (see Figure S3). This difference is discussed further in the CART analysis.

Importantly, 83% of respondents did not have any form of flood insurance. Based on a chi-square test of independence, flood insurance status and the occurrence of inundation of the foundation of the home were not independent, with property owners more likely to have insurance if the foundations of their homes were inundated. This makes sense, as property owners who own lower-elevation properties are at higher risk and may be more likely to purchase insurance. Similarly, if property owners had either a seawall or a living shoreline, they were statistically more likely to have insurance. However, the occurrence of land loss to erosion and erosion damage categories for different property features were independent of flood insurance status.

CART predictions of inundation and erosion

The results above suggest that residents along the Lake Ontario shoreline suffered substantial damages from both inundation and erosion during the 2017 event. Can such impacts be predicted based on the characteristics of individual properties? Figure 6a shows the CART tree for predictions of foundation inundation. After fitting the model via cross-validation, only the elevation of the property was selected as a significant predictor. Inundation is predicted for those homes with a minimum elevation below 2.5 m above the Lake Ontario LWD, and the model produces correct predictions for approximately 7 out of every 10 homes under cross-validation (70% accuracy). This elevation threshold aligns well with the maximum water level during 2017, which reached 1.7 m above the LWD. Given that the average monthly mean wave height in the summer is approximately 0.4 m and the average monthly maximum wave height is 1.4 m, normal wave conditions coupled with the maximum static water level in 2017 would inundate most homes with elevation less than 2.5 m above LWD.

[INSERT FIGURE 6 HERE]

Figure 6b shows the results of the CART model for the amount of land loss to erosion. Here, three predictors are selected under cross-validation: 1) whether the home has a living shoreline, 2) elevation of the home, and 3) seawall age. The presence of a living shoreline is the primary predictor of the model, and the model indicates that moderate to severe erosion occurs when a living shoreline is present. Therefore, it appears that there is some characteristic associated with living shorelines along Lake Ontario properties that make them more prone to erosion losses. In addition to the presence of a living shoreline, the model also selected elevation as a significant predictor, with less erosion predicted for properties below 2.5 m above LWD. This may be linked to the exposure of land to eroding forces, as properties at lower elevation are less likely to have high bluffs or banks that are susceptible to wave activity and erosive processes. It is worthwhile to note, however, that properties on beach and bluff shorelines show no significant difference in reported land loss due to erosion. Finally, the model suggests that properties with newer seawalls experience somewhat less erosion, suggesting that newer hardened shoreline protection provides improved erosion control. The CART model for erosion provides slightly less predictive ability compared to that of inundation, with a prediction accuracy of 65% under cross-validation.

DISCUSSION AND CONCLUSION

This work presented the results of a rapid response online survey distributed to shoreline property owners of Lake Ontario to assess the real time impacts of the 2017 high water event. The survey instrument focused primarily on three categories of impact - inundation, erosion, and damage to shoreline protection infrastructure. Results showed that almost all near-shore property and about 10% of homes were inundated along the shoreline, with substantial damages resulting from long-duration inundation (often greater than 2 months) that was caused primarily by high static water levels and in the absence of wave activity. Given the larger percentage of homes linked to static water versus wave inundation, these results suggest that homes located in an embayment appear to be at a higher risk of major inundation compared to those on the main lake shoreline. This is consistent with the type of shoreline commonly found in these two areas, with homes more likely to be located along low-lying beaches in embayments and higher-elevation bluffs and banks on the lake shoreline. Accordingly, counties with significant development along low-lying shorelines (Monroe, Cayuga, Wayne, and Oswego) experienced greater inundation impacts than counties with a higher percentage of homes along high bluffs (Orleans, Niagara).

The range of land loss to erosion was near evenly distributed across the shoreline, although there was a tendency towards more loss in Orleans and Niagara Counties. Erosion primarily caused damage to near-shore property, although a nontrivial amount of damage was also caused to secondary structures and individual homes. Damages to shoreline protection infrastructure were substantial, including to living shorelines used to control inundation and erosion. The lack of flood insurance among homeowners also likely increased the burden and stress of the event, particularly for those suffering from erosion impacts since they were less likely to have insurance than respondents suffering primarily from inundation. This result is significant since insurance provided through the National Flood Insurance Program covers the collapse or subsidence of land along the shore of a lake as a result of erosion caused by waves or currents of water exceeding normal levels. Therefore, the lack of flood insurance among residents who experienced considerable erosion losses has large implications for their financial losses due to the 2017 event.

A CART analysis was used to determine whether key impact variables, including the occurrence of foundation inundation and the degree of land loss to erosion, were predicted by property characteristics. Unsurprisingly, inundation was best predicted by the elevation of the home. For erosion, the presence of a living shoreline on the property was the primary predictor selected by the model. Somewhat surprisingly, living shorelines were associated with larger, rather than smaller, erosion losses. This result is somewhat counterintuitive, as living shorelines are used to stabilize the shoreline. One possibility is that those properties that are more at risk to erosion are those more likely to have developed living shorelines. Alternatively, omitted variables that are actually driving erosion losses could be collinear with the presence of a living shoreline. There is also the possibility that the development of living shorelines on properties along Lake Ontario might not be to the standards required to reduce erosion, thus causing those properties with hardened shorelines to better protect against erosion (properties that reported having hardened shoreline protection reported less erosion than those without). These results suggest that more research is needed to understand the mitigative effects of existing living shorelines along Lake Ontario on erosion.

The survey results presented in this work provide a first comprehensive, real-time picture of the extent of damage caused by the 2017 high water event on Lake Ontario. Though limited in scope to the New York shoreline, this information can be used by the IJC and other interested entities to inform the ongoing evaluation of regulatory policy for Lake Ontario water levels. In the past, the impacts of lake level management have been reviewed to determine if modifications to regulatory policy could provide additional benefits to both US and Canadian socio-economic interests and the environment (e.g., the Lake Ontario-St. Lawrence River Study (2000-2006) and International Upper Great Lakes Study (2007-2012)). To aid in this review effort, the IJC established the Great Lakes-St. Lawrence River Adaptive Management (GLAM) Committee, which undertakes the monitoring, modeling and assessment needed to support ongoing evaluation of the regulation of water levels and flows. The survey results presented here provide the GLAM Committee with the first overview of how the revised regulation of water levels and flows under Plan 2014 affected socio-economic interests (shoreline property owners, in particular) across an extended length of shoreline during the first extreme event experienced under the new plan. As more is learned about such impacts of Plan 2014 under extreme conditions, this information will help determine whether changes to regulations should be considered. The GLAM Committee has recognized the value of these survey data for this purpose, and has recently redistributed a modified version of the survey to the entire lakeshore, including Canadian shoreline provinces, to complement the data reported on in this work and extend its coverage across the international border.

Although the survey instrument used in this study provides a detailed assessment of the impacts of the 2017 high water event and their spatial distribution across the shoreline, the dataset does have some limitations. First, we acknowledge inconsistencies in the survey sampling approach based on our need to mobilize quickly to capture real time damages, and differences in implementation capacity across municipalities. As such, randomized sampling was impossible within this timeframe. Nonetheless, we achieved strong coverage across a good range of geography. Future research could utilize a geo-referenced database of property owners to allow random sampling (or stratified sampling based on key site characteristics to permit systematic comparisons).

Second, as we have alluded to above, the information collected in the survey does not provide formal estimates of monetary damage. Although such estimates would be useful —e.g., for constructing more tailored flood damage curves — we were concerned that any economic estimates we obtained would be incomplete and biased: most respondents were not able to assess the damage to certain property features at the time of reporting because the flood event was still ongoing. This indicates that an additional survey effort, such as that being conducted by the GLAM Committee, will be valuable to better assess damages to properties now that floodwaters have receded, and to acquire formal estimates of monetary damage. These data could also be paired with tax information to determine if newer, higher-value homes, which have been replacing older homes at closer proximity to the shoreline over the last several decades, received greater rates of damage. In addition, it would also be useful for subsequent survey efforts to inquire about the reasons for the low rate of insured homes along the shoreline (e.g., lack of awareness of available insurance products, cost, underestimation of risk).

Finally, there is the potential for participation bias in the results, despite our efforts to minimize these effects. The positive relationship seen between water level and response rates could be interpreted as a participation bias towards higher impacts, with more respondents choosing to participate in the survey in May and June when water levels were higher. However, our outreach efforts were also the most intense early in the sampling period, making it difficult to assess the association between response rate and water level variations. The lack of correlation between storm surge and response rate indicates that high instantaneous water levels did not strongly impact the rate of responses. The increase in August responses further supports this argument, although it is also possible that the additional responses may have been motivated by the exposure of damage with lowering levels. Overall, the results generally suggest that the response rate and reported impacts were unrelated to variability in water levels over time. Still, it is possible that property owners were more likely to respond to the survey if they were experiencing substantial impacts from the flood event, regardless of the timing of their response. Therefore, it may be prudent to interpret the impacts reported in this work as a likely *upper-end estimate* of impacts actually experienced by residents along the shoreline. However, this may be balanced somewhat by the fact that respondents had to estimate flood impacts prior to the end of the high water event. For instance, the duration of inundation and extent of erosion are likely underrepresented, because respondents who completed the survey at the beginning of the sampling period likely continued to experience inundation and erosion after survey completion.

The rare, real-time nature of the information collected in this survey affords a unique ability to validate quantitative flood risk tools used to estimate the damages from high water events. For instance, models like the *Flood and Erosion Prediction System (FEPS)* and *Flood Tool* formed the basis for flood risk estimates that were used to assess different water level management plans for Lake Ontario (IJC, 2014). These models generate alternative lake level hydrographs and extreme event scenarios of surge and wave activity using a simulation model of Plan 2014 and flood frequency analyses. Structural and building content damages related to first floor inundation are evaluated at the parcel level based on FEMA stage-damage curves, while damage from wave activity is estimated based on relationships with wave power. Damages can be assessed for a user-specified set of parcels, and can be mapped using GIS tools and online mapping software. If provided to local communities, these models could support local flood risk planning at the municipal and county level. However, predictions of flood impacts from these tools suffer from several uncertainties at the parcel level (IJC, 2014). For instance, elevation data available for the shoreline are based on LIDAR data that have error in their vertical (RMSE: 20 cm) and horizontal (RMSE: 75 cm) measurements, which can lead to large discrepancies in flood damage predictions because at high water levels, relatively small differences in water levels can lead to large differences in damage predictions. In addition, the spatial distribution of storm surge can vary substantially with wind speeds, but there are only a handful of gages that record hourly water levels along the shoreline. Similarly, data on wave height and direction is limited along the shoreline. Therefore, it is difficult to assess whether the actual flooding impacts experienced at particular parcels on the shoreline are well captured by flood risk tools used to estimate damages (personal communication, Mike Shantz, Environment Canada). In ongoing work, we are using the real-time data collected in this study, including dated reports and photos of inundation for different property features on individual land parcels, with routines in the models mentioned above to validate whether exisiting water level and wave data are sufficient to predict flooding at the resolution of indivdual parcels. In particular, we plan to focus on the uncertainty between predicted and observed flood impacts, which can then be integrated into flood risk tools to help ensure that they provide a conservative estimate of flood damages linked to different water level and wave conditions. These efforts are being coupled with semi-structured interviews and focus groups to better understand how local stakeholders perceive and plan for flood risk, so that the developed tools can be designed to provide tailored decision support to lakeshore communities.

DATA AVAILABILITY

The data from this survey are publicly available and can be accessed at http://seagrant.sunysb.edu/articles/t/coastal-community-development-program-resources-projects-high-water-impact-surveys.

SUPPORTING MATERIAL

Additional supporting information may be found online under the Supporting Information tab for this article: Additional figures showing features of flood impacts related to inundation and erosion, and a pdf version of the web-based survey instrument used in this work.

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Tables

Table 1. Municipalities that were the primary target of outreach efforts for survey implementation.

County	Municipality
Monroe	Parma
Monroe	Greece
Monroe	Rochester
Monroe	Irondequoit
Monroe	Webster
Monroe	Penfield
Wayne	Sodus
Wayne	Sodus Point
Wayne	Huron
Wayne	Wolcott
Oswego	Mexico
Oswego	Pulaski
Oswego	Sandy Creek
Jefferson	Ellisburg

Figure Captions

Figure 1. Map of survey response parcels across the Lake Ontario New York shoreline. Counts of responses by county are also shown.

Figure 2. Hourly water levels on Lake Ontario at Rochester NY and number of responses received by day over the sampling period.

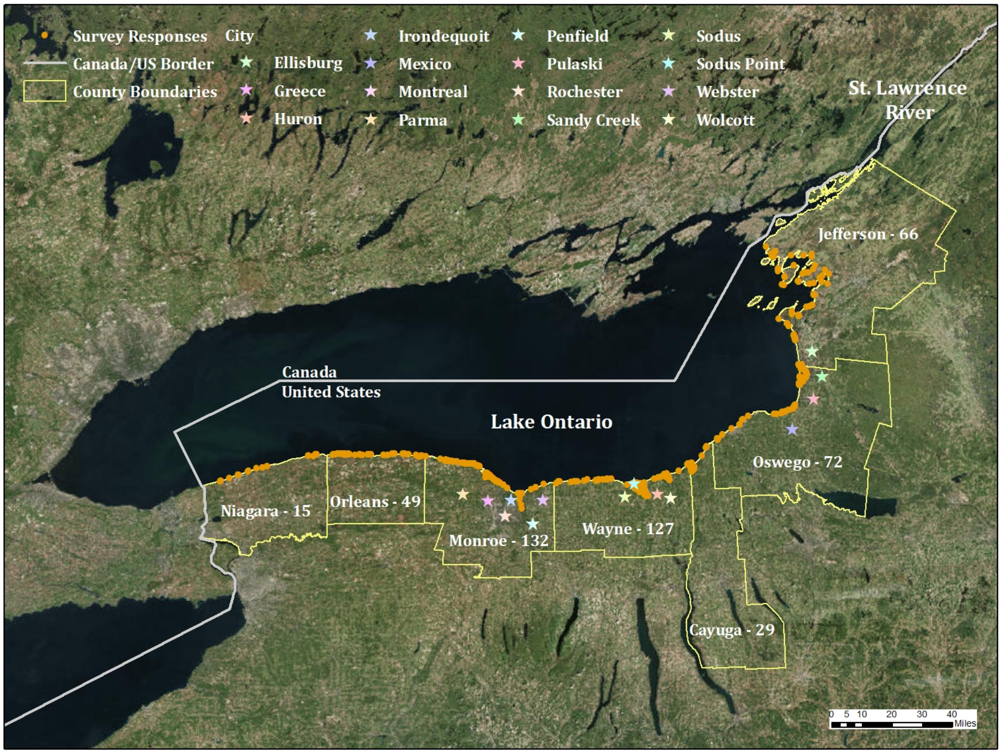
Figure 3. Occurrence of inundation for different property features for the entire lakeshore ("All") and by county, reported as a percent of total responses for each feature. The number of responses for each response is shown below each bar. Note that the total number of responses for each property type differs, and so percentages can vary across property types with the same number of responses. Differences between counties are statistically significant (chi-square = 37.89, 18 df, $p = 0.004$).

Figure 4. Damage to property features caused by inundation, reported as a percentage of total responses that reported inundation for that feature. Differences by property features are highly significant (chi-square = 61.38, 12 df, $p < 0.001$).

Figure 5. Perceived land loss due to erosion for the entire lakeshore ("All") and by county, reported as a percent of total responses for each location. The number of responses for each response is shown below each bar. Differences between counties are not statistically significant at the 0.05 level (chi-square = 31.98, 24 df, $p = 0.13$).

Figure 6. CART decision tree for the a) occurrence of foundation inundation and b) degree of land loss from erosion. Numbers within each box show the observed counts of properties under the given tree conditions that a) were and were not inundated or b) experienced no/small and moderate/severe erosion.

Figures



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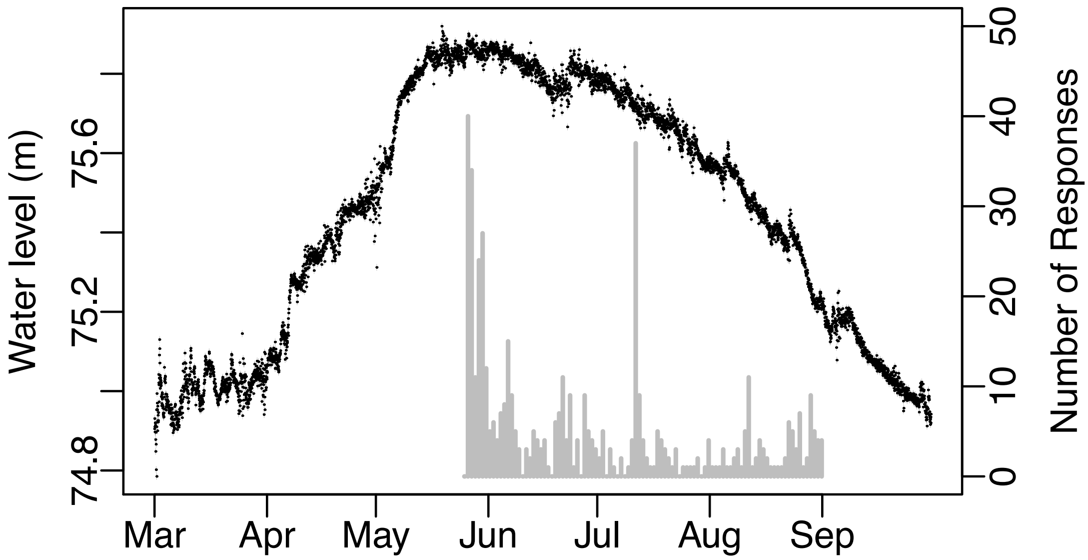

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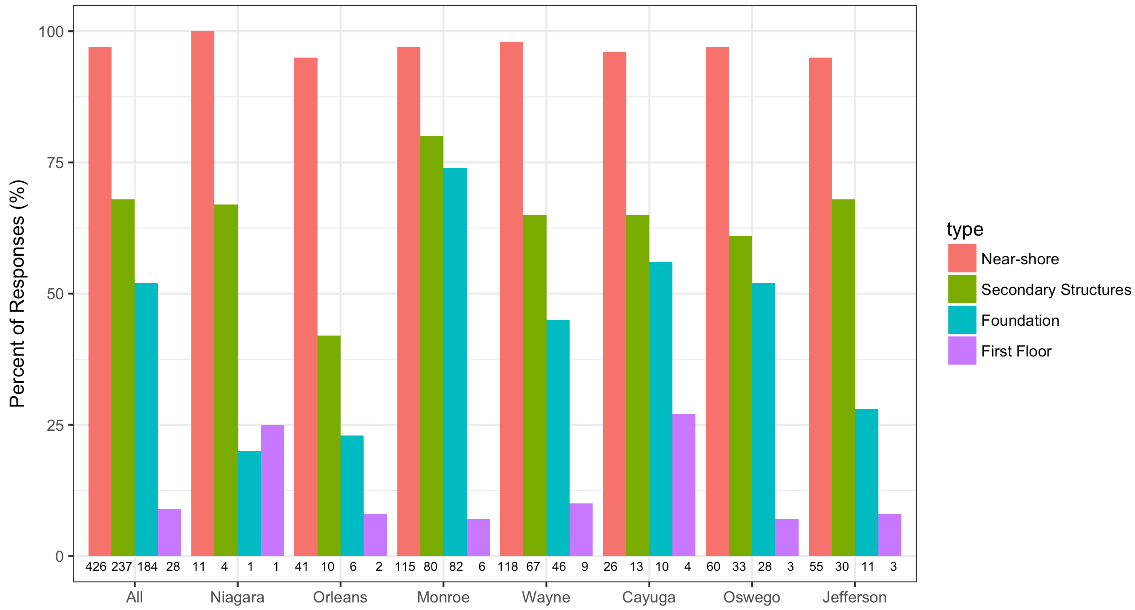

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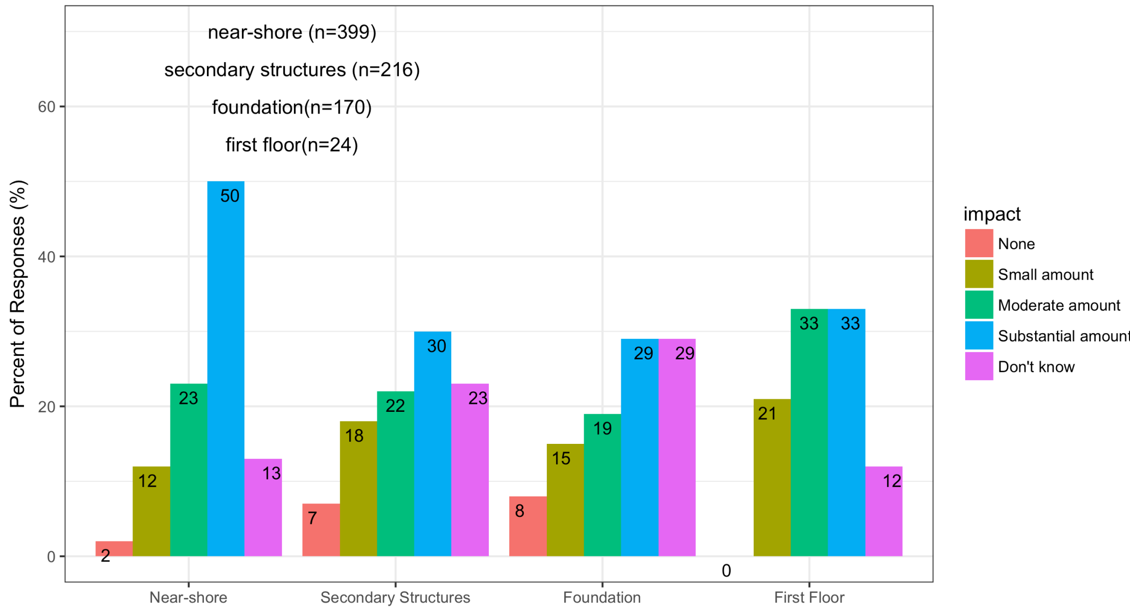

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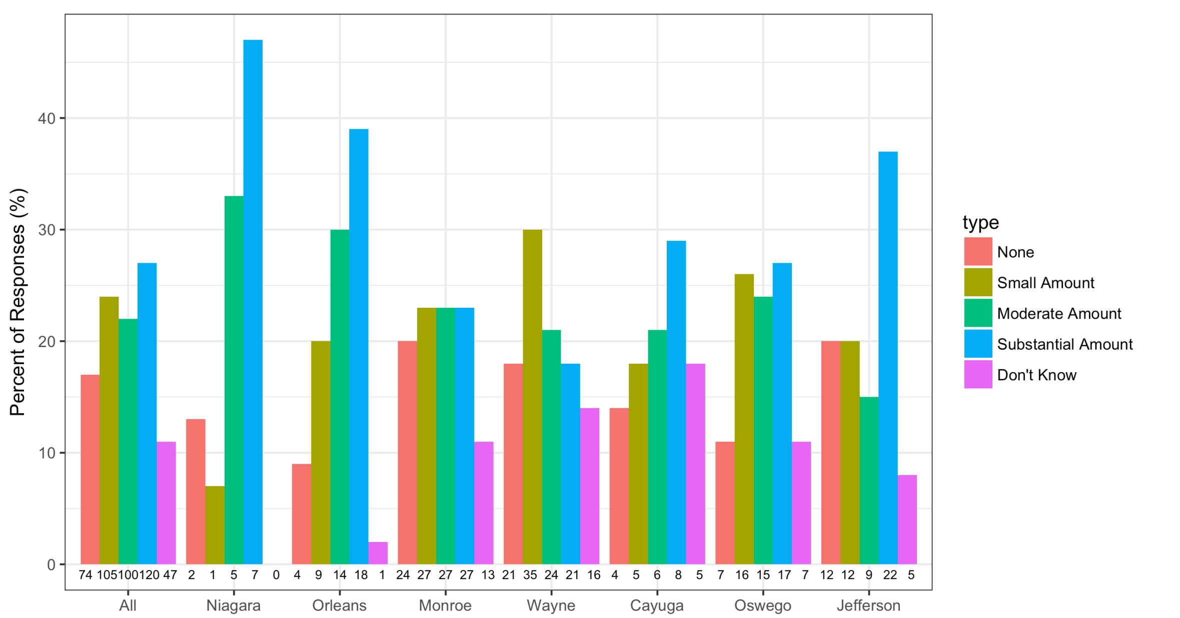

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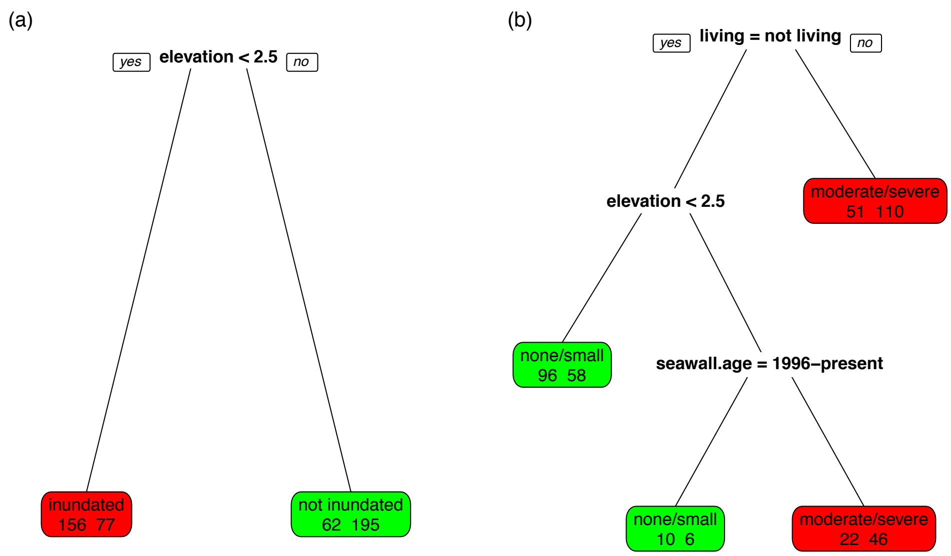

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