Depth#damage curves for rail rapid transit infrastructure

Massachusetts Institute of Technology

CIWEM Chartered Institution of Water and Environmental Management Journal of Flood Risk Management WILEY

Depth-damage curves for rail rapid transit infrastructure

Michael V. Martello[1] | **Andrew J. Whittle[1]** | **Hannah R. Lyons-Galante[2]**

[1]Department of Civil & Environmental Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA

[2]Department of Environmental Affairs, Massachusetts Bay Transportation Authority, Boston, Massachusetts, USA

Correspondence
Michael V. Martello, Department of Civil & Environmental Engineering, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139, USA.
Email: martello@mit.edu

Abstract

Estimates of flood-related damages and costs often rely on asset-specific depth-damage curves that characterize the fragility of a given asset. To date, there are very few depth-damage curves that are potentially applicable to rail rapid transit infrastructure, and no studies attempt to construct these relationships specifically these asset classes. Given the lack of empirical performance data or asset-specific reliability tests, we solicited expert engineering judgment to characterize the fragility of transit assets to saltwater flood exposure. We validate the resulting synthetic depth-damage relationships via a benchmarking approach and demonstrate consistency with previously published depth-damage curves for similar asset classes. The solicitation framework presented can easily be extended to other infrastructure assets and systems, potentially serving as a key step toward a more rigorous quantification of the potential risks posed to infrastructure by natural hazards and climate change.

KEYWORDS
coastal flooding, depth-damage, fragility, infrastructure, rail, risk assessment, transit

1 | INTRODUCTION

Current climate projections and expected sea level rise (SLR) suggest the frequency and severity of extreme weather and coastal flood events will increase throughout the 21st century (Buchanan et al., 2016; Kopp et al., 2014). This expected increase in coastal flooding poses particular challenges for highly developed and heavily urbanized coastal cities, where valuable waterfront development, low-income communities, and critical infrastructure will become increasingly vulnerable and prone to flood damage. In particular, current and future coastal flood risk represent a significant threat to rail rapid transit infrastructure (Martello et al., 2021) as demonstrated firsthand by the significant and extensive damage caused by Hurricane Sandy, 2012 (Aerts et al., 2013). Despite an emerging understanding of this threat and assessments of

the damage sustained during Hurricane Sandy,[1] the relationship between flood depth and damage to transit infrastructure assets remains very poorly characterized (Habermann & Hedel, 2018; Rosenzweig et al., 2011).

Recent research projects global average annual flood losses in major coastal cities could increase 860% from 2005 levels to an estimated $52 billion in annualized damages by 2050 (Hallegatte et al., 2013). Yet, these estimates likely underrepresent the expected direct damage to infrastructure systems, as they do not attempt to quantify damages to infrastructure systems and instead rely on a proportional multiplier of insured losses (based on limited case study data) to approximate infrastructure damage costs (Hallegatte et al., 2011). Other studies, particularly those focused on regional estimates of flood-related losses and risk (e.g., Kirshen et al., 2018; Oddo et al., 2020; Rasmussen et al., 2020) neglect flood damage

and losses to infrastructure entirely. This lack of characterization can be primarily attributed to the relative complexity of infrastructure systems compared to other physical assets (particularly residential and commercial structures), as well as a prevailing lack of relevant information characterizing the sensitivity of infrastructure assets, particularly for rail rapid transit systems (Rosenzweig et al., 2011).

As transit agencies increasingly focus resources and efforts to improve climate change resilience (Miao et al., 2018; NASEM, 2017, NASEM, 2021), an improved understanding of the sensitivity of assets and subsystems will be increasingly important, particularly when conducting economic analyses and quantifying the risk reduction benefits of climate change adaptation projects. Adequate estimates of asset sensitivity to flood exposure will also be increasingly important as transit agencies begin to plan climate change adaptation projects, issue green bonds to finance such projects (TRB & NASEM, 2021), and obtain insurance policies (e.g., catastrophe bond issuance or purchase of parametric insurance; Evans, 2020). Such actions will require accurate and unbiased estimates of projected flood-related damage costs if they are to be priced and structured in alignment with present and projected future levels of risk (Franco et al., 2020; Keenan, 2019).

In this paper, we aim to address this gap in the literature and practice by constructing a set of synthetic (i.e., expert judgment derived) depth-damage curves for rail rapid transit facilities and assets. Aggregating the expert judgment of transit professionals, researchers, insurance underwriters, and consulting engineers, we obtain best estimates of flood damage (as a percentage of replacement cost) for various depths of saltwater flooding across a set of rapid transit facilities and linear assets. We further benchmark these survey results against previously published depth-damage curves for related assets, demonstrating a general agreement with less specific depth-damage curves currently employed in practice.

2 | DEPTH DAMAGE RELATIONSHIPS

Flood depth is typically used as a primary indicator of damage severity in standard flood damage cost estimation practices (de Moel, 2012; Gerl et al., 2016; Kok et al., 2004; Wagenaar et al., 2016). This relationship is characterized via a depth-damage function, which characterizes the relationship between flood depth and the associated magnitude of damage (relative to replacement cost) for a given asset class (Budiyono et al., 2015; Kok et al., 2004; de Moel, 2012; USACE, 2015; Wagenaar

et al., 2016). Depth-damage functions are among the most important factors influencing flood damage estimates and flood risk, though they are often weakly based in factual knowledge (USACE, 1992a). Depth-damage curves in the literature are often presented or employed with little justification other than the authority of the original source (most often a government institution). This lack of provenance partially contributes to the present consensus that depth-damage curves are among the most uncertain aspects of flood damage models (e.g., de Moel, 2012; Kok et al., 2004; Prahl et al., 2016; Saint-Geours et al., 2015). Where the construction of depth-damage curves is mentioned, they are typically either empirically derived via correlation of available data (USACE, 1992b; Pistrika et al., 2014; Lehman & Hasanza-deh Nafari, 2016) or synthetically-constructed via solicitation of expert judgment (Gerl et al., 2016; USACE, 2006, 2015).

Aside from a lack of provenance, there is also a recognition that other attributes can inform damage magnitude aside from flood depth. Wave action, flood duration, water salinity, sediment load, water quality, flood timing, asset age, and construction typology can also influence flood damage magnitude, though such factors typically do not directly inform present flood damage estimation practices (Dottori et al., 2016; Franco et al., 2020; USACE, 1992a, 2015; Pistrika et al., 2014). Despite these inherent limitations, depth-damage curves remain the most prevalent, transparent, and direct approach of estimating the magnitude of damage (relative to replacement cost) to assets affected by a flood event.

3 | TRANSIT SPECIFIC DEPTH-DAMAGE DATA

Unlike residential or commercial buildings, for which instances of damage are well-documented for insurance claims processing (Dombrowski et al., 2020) and less frequently for construction of depth-damage relationships (USACE, 2015) flood damage to transit systems is comparatively poorly documented. This is further compounded by a comparative lack of flood events that have significantly affected transit systems. While this is in some sense fortunate, insofar as there have only been a handful of noteworthy flooding events damaging transit systems prior to 2009 (Compton, 2009) and even fewer since then[2] (most notably Hurricane Sandy in 2012; Aerts et al., 2013), this lack of empirical data makes the construction of depth-damage relationships via statistical methods (e.g., Lehman & Hasanzadeh Nafari, 2016; Pistrika et al., 2014) impractical, if not impossible.

While limited data pertaining to the direct damage sustained by the New York City Transit (NYCT) system from Hurricane Sandy is publicly available, it is insufficient to draw any meaningful conclusions regarding sensitivity of assets to floodwater depth. A study conducted by Aerts et al. (2013) likely contains the most comprehensive collection of publicly available damage information for Hurricane Sandy; however, a detailed record of flood depths is not listed alongside damages, making the data provided insufficient for computing depth-damage correlations. Similarly, a study conducted by HNTB (2014) investigating the extent of flooding and damage to Amtrak tunnels after Hurricane Sandy potentially contains enough information to estimate depth-damage relationships. However, such an estimate would require a significant level of subjective judgment to disentangle suggested upgrades and prior state of good repair backlogs from any damages directly attributable to flooding. Due to these shortcomings, the publicly available record of damages to NYCT and Amtrak assets from Hurricane Sandy is insufficient to glean any meaningful information to construct empirical depth-damage estimates for transit assets.

4 | EXPERT JUDGMENT SOLICITATION METHODOLOGY

Without an appreciable quantity of relevant data, expert judgment is the most viable method for constructing depth-damage functions. Depth-damage functions constructed in this manner, often referred to as synthetic depth-damage curves, are quite common in the literature, comprising nearly half of all cataloged damage curves in a recent extensive literature review (Gerl et al., 2016). The process of collecting damage estimates via the judgment of qualified experts, can be formally characterized as a structured expert judgment solicitation process. Regardless of the area of expertise, all structured expert judgment processes require an aggregation technique to combine expert assessments (Aspinall & Cooke, 2013; Cooke, 1991; Hanea et al., 2021). These aggregation techniques can be subdivided into either behavioral or mathematical techniques (Hanea et al., 2018). Behavioral aggregation techniques require experts to form a consensus and collectively converge on an answer (Hanea et al., 2021). Mathematical techniques instead combine individual answers via either equal weighting or performance-based weighting schemes based on expert performance on a set of calibration questions (Cooke, 1991).

There are very few studies available detailing the construction of synthetic depth-damage curves, and fewer still that explain underlying expert judgment aggregation techniques in detail. Of the literature surveyed by the authors, only a single report (USACE, 2015) provided insight into aggregation techniques for synthetic depth-damage curve construction. The study allowed for a limited degree of behavioral aggregation, iteratively displaying responses to all experts, allowing for some degree of information sharing, discussion, and reevaluation. Notwithstanding this iteration process, the study relied on mathematical aggregation of responses using equal weights, ultimately following an approach similar to the IDEA protocol outlined by Hanea et al. (2018).

Rather than apply an identical approach, which would require synchronous interaction of experts, we instead solicited expert judgment via survey, relying only on mathematical aggregation of responses. Practical limitations on the availability of potential expert respondents ultimately constrained solicitation to an asynchronous format, as participants were not compensated and spanned multiple cities, organizations, and time zones.

4.1 | Mathematical aggregation approach

Given the prevailing lack of data on rapid transit asset flood damage, there was insufficient information available to generate calibration questions with non-trivial answers. In such circumstances, recent literature instead suggests equal weighting of expert respondents in lieu of assignment of performance weights (Hemming et al., 2021). Further, equally weighted aggregations of expert opinion are likely to score higher on measures of statistical accuracy than performance weighted aggregations (Clemen, 2008; Hemming et al., 2021). In particular, equally-weighted aggregations typically achieve better predictive accuracy for *out-of-sample* data (i.e., performed better on questions not used in calibration of performance weights; Clemen, 2008). In addition, performance-weighted assessments may not be well suited for situations of deep uncertainty, where a variance of credible underlying assumptions can lead to diverging sets of projections, from which it is only possible to discern correct assumptions in hindsight (Morgan, 2014). For these reasons, we chose to mathematically aggregate answers by giving equal weighting to each respondent, rather than implementing a performance-weighted aggregation.

5 | SURVEY OVERVIEW

Informed by several discussions with Massachusetts Bay Transportation Authority (MBTA) personnel, we

TABLE 1 Summary of transit facilities and linear assets included in the flood damage estimation survey

Facilities	Linear assets
Underground station	Rail
At-grade station	Track switches
Ventilation room	Signal system
pump room	Tunnel structure
Rail maintenance facility	Third rail
	Catenary
	Power conduit
	Tunnel lighting

designed a transit asset flood damage estimation survey to solicit expert engineering judgment to obtain damage estimates for specific rail rapid transit assets subject to varying levels of saltwater flooding. Damage estimates were provided as a percentage relative to complete replacement, wherein values can range from 0% (i.e., no damage) to 100% (i.e., fully damaged and requiring complete replacement). We first asked survey respondents to provide damage estimates associated with saltwater flooding at four depths of standing water (0.5, 3, 7, and 15 ft) for several types of facilities. Facilities were limited to the basic facility types and mechanical support rooms listed in Table 1. We then presented survey respondents with a typical tunnel cross-section (Figure 1) flooded at four depths of standing water and asked to provide damage estimates for a set of linear assets also listed in Table 1. Here, we considered rail (inclusive of ties and ballast), track switches (electronic and mechanical components placed at-grade responsible for enabling trains to transfer tracks), signal systems (electronic components responsible for detecting and directing trains), third rail (which provides DC power to heavy rail cars), catenary (provides DC power to light rail cars), power conduit (providing DC and AC current; height of placement can vary within and across transit systems), tunnel lighting, and tunnel structure.

Rather than solicit a maximum, minimum, and best estimate (i.e., median) for each asset type (as done by USACE, 2015) we instead asked respondents only for a best estimate of flood damage. When validated against a set of (empirical) surveyed damage data, the maximum and minimum depth-damage curves produced by the USACE (2015) study were of mixed quality. While the majority of the best-estimate (median) depth-damage curves presented by USACE (2015) well-approximated the empirical survey data trend, the maximum and minimum curves poorly bounded the survey data, suggesting an overconfidence bias among USACE experts. While expert solicitation of a three-point estimate

characterizing a range of values is generally preferred over provision of single point estimates (Ayyub, 2001; TRB & NASEM, 2007), the results from USACE (2015) suggest the predictive power of upper and lower bound estimates for depth-damage curves is quite low when compared to empirical data. Given this low predictive power and the significant additional effort required of participating experts to provide such ranges for each asset type, we instead separately solicited their judgment on general damage uncertainty and variability by soliciting generalized upper and lower bound estimates of damage. We also solicited respondents' estimates of the relative severity of saltwater as compared to freshwater flooding.

6 | RESULTS

A total of $n = 31$ experts responded to the survey. Seventy-one percent ($n = 22$) of respondents were transit agency professionals, 15% ($n = 5$) engineering consultants, 10% ($n = 3$) academic researchers, and 3% ($n = 1$) insurance professionals. Fifty-eight percent of respondents ($n = 18$) identified the MBTA as their primary system of expertise, 32% ($n = 10$) were most familiar with the New York City Metropolitan Transit Authority (MTA), and 10% ($n = 3$) were more familiar with other transit systems (Hong Kong MTR, Metrolink, and Amsterdam Metro). Figure 2 summarizes the breakdown of survey respondents. Responses were collected in two rounds during late spring (Round 1) and summer (Round 2) of 2021. A meeting with prospective first round respondents was also conducted with MBTA personnel on April 21, 2021 where feedback and suggestions on survey structure were collected.

6.1 | Facilities

Expected depth-damage curves and associated standard deviations of responses for transit facilities are shown in Figures 3 and 4, respectively. The shape of the depth-damage curves across all facility types are very similar, with nearly identical depth-damage curves for maintenance facilities and underground stations. The standard deviation of responses is more variable across facility type, with maintenance facility responses showing the closest agreement among respondents (i.e., lowest standard deviation). Respondents noted that in addition to depth, the duration of flooding also influences the damage estimates, consistent with prior findings (e.g., Dottori et al., 2016; USACE, 2015). Respondents further suggested this is of particular importance for electrical equipment located throughout facilities, as the degree of

FIGURE 1 Typical tunnel cross section presented to survey respondents, highlighting the linear assets of interest within the study
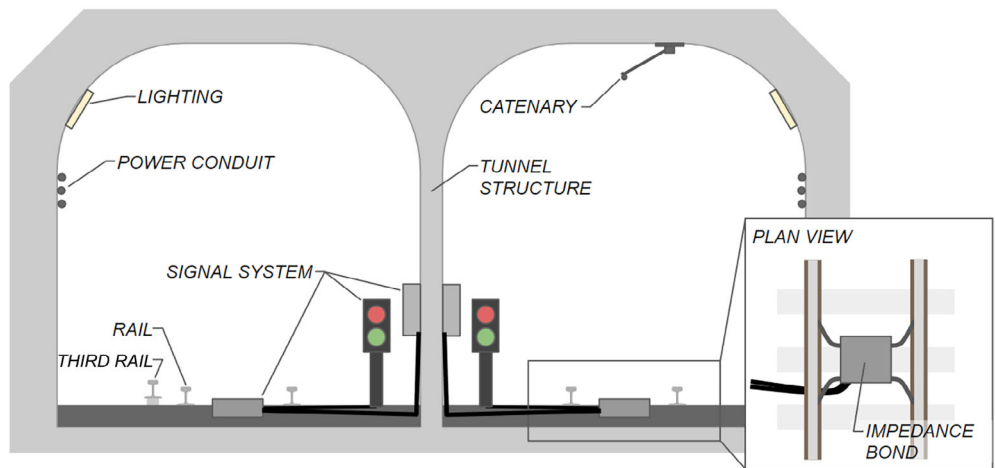

FIGURE 2 Survey respondents' (a) industry backgrounds and (b) primary agency of familiarity
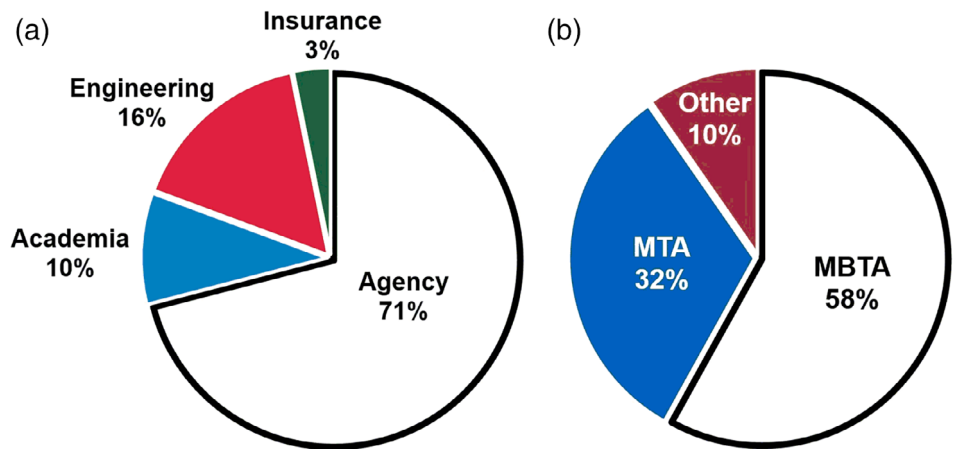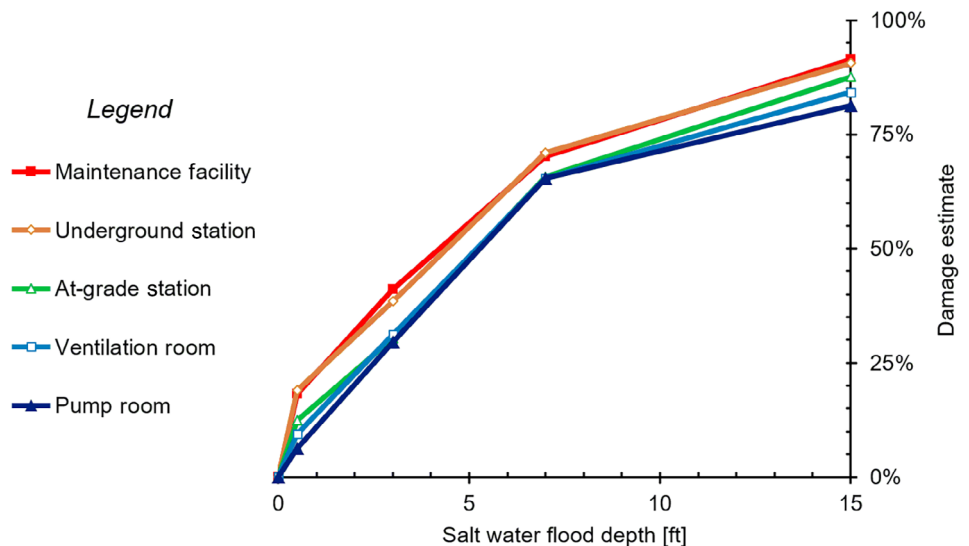

FIGURE 3 Depth damage curves for transit facilities constructed by equal weighting of survey responses

corrosion is expected to be greater when equipment is exposed for longer periods. For more severe flooding, respondents expect electrical infrastructure within the facilities (e.g., fare collection, fire alarm, communications, and power systems) would be damaged beyond repair and require complete replacement.

Respondents also noted that the layout of facilities, particularly the placement of equipment in ventilation and pump rooms would inform damage estimates. In the case of pump rooms, respondents noted that submergence of centrifugal pumps (typically mounted a few feet off the ground) for any length of time would likely render
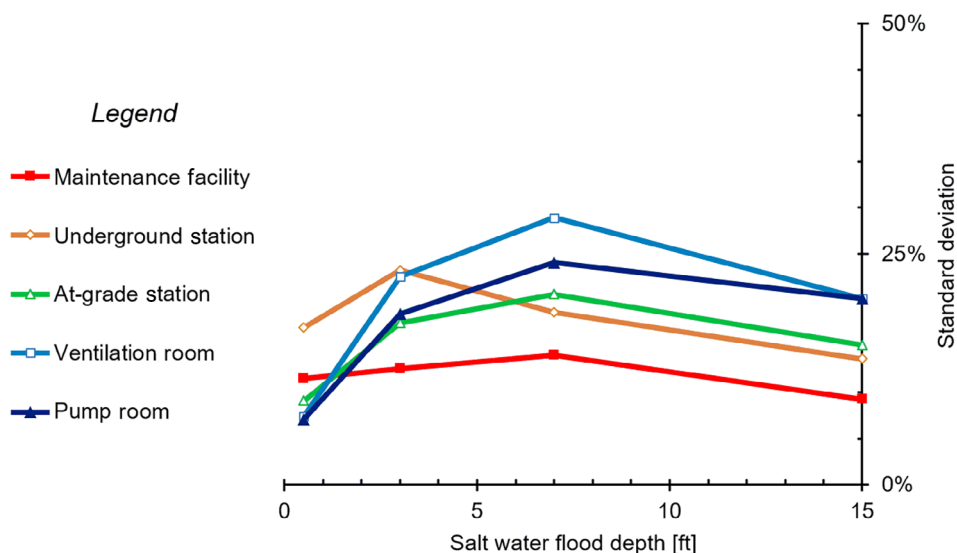
FIGURE 4 Standard deviation of survey responses for transit facilities

them inoperable and require replacement. For ventilation rooms, respondents note that while ventilation fans are typically wall or ceiling mounted, motor starters and sensitive electrical control equipment are typically situated only sit a few inches off the ground and could be significantly damaged if exposed to a few feet of standing water. Respondents also noted that flow velocity and wave action, particularly for at-grade stations, would also inform the extent and severity of damages, consistent with prior literature (Dottori et al., 2016; USACE, 2015).

In the case of rail maintenance facilities, respondents note that any level of standing water would result in damage of all equipment that is installed below grade, collecting in all pit areas. These areas contain critical equipment, such as wheel truing machines, which are integral to transit service, vehicle maintenance, and regular operations. MBTA respondents noted that significant damage to these facilities would eliminate the ability to run service on the affected lines. These comments are consistent with conclusions of prior studies conducted on the resilience of the MBTA Blue Line (MBTA, 2018; MBTA, 2019). While not formally included in the survey, respondents also mentioned that any vehicles or rolling stock exposed to and damaged by saltwater would likely be written off as a total loss, as the MBTA would be unable to guarantee the safe operation of revenue vehicles after saltwater inundation. In such instances, rolling stock would require replacement, though respondents note they could potentially be salvaged for parts.

6.2 | Linear assets

Depth-damage curves and associated standard deviations of responses for linear assets are shown in Figures 5 and 6, respectively. The depth-damage curves shown for signals and track switches are identical for less severe (i.e., >3 ft) flooding, with signals expected to be more sensitive to more severe flooding. The depth-damage curves for rail and third rail were found to be quite similar at all flood depths, suggesting similar sensitivity to saltwater flooding. Overall, there was less agreement among respondents for linear assets, as observed by the generally higher standard deviations as compared to transit facilities. Tunnel structure damage estimates were a partial exception, with comparatively high agreement among respondents at lower flood depths, decreasing thereafter (i.e., increasing standard deviation with depth).

Several respondents noted that structural damage to tunnel walls would be highly dependent on age and construction type, suggesting that a correlation between flood depth and structural damage would be highly variable. This aligns with prior assessments, which indicate tunnel design, material quality, and construction quality influence the susceptibility of tunnel structure to water-related damage (Chen & Lalas, 2012; FHWA, 2005; Nazarchuk, 2008). Further, there exists an increased potential for damage at locations of mixed-face geologic conditions (HNTB, 2014), construction joints (particularly for cut-and-cover tunnel sections), and preexisting cracks (FHWA, 2005; Nazarchuk, 2008; Chen & Lalas, 2012), particularly under prolonged exposure to water. While saltwater exposure has the potential to uniformly accelerate corrosion and spalling, preexisting cracks in the tunnel structure can allow for a deeper penetration of sulfates into the tunnel lining, which is likely to accelerate deterioration (HNTB, 2014; Nazarchuk, 2008) and contribute to spatial variability in structural damage to the tunnel.

FIGURE 5 Depth damage curves for linear transit assets constructed by equal weighting of survey responses
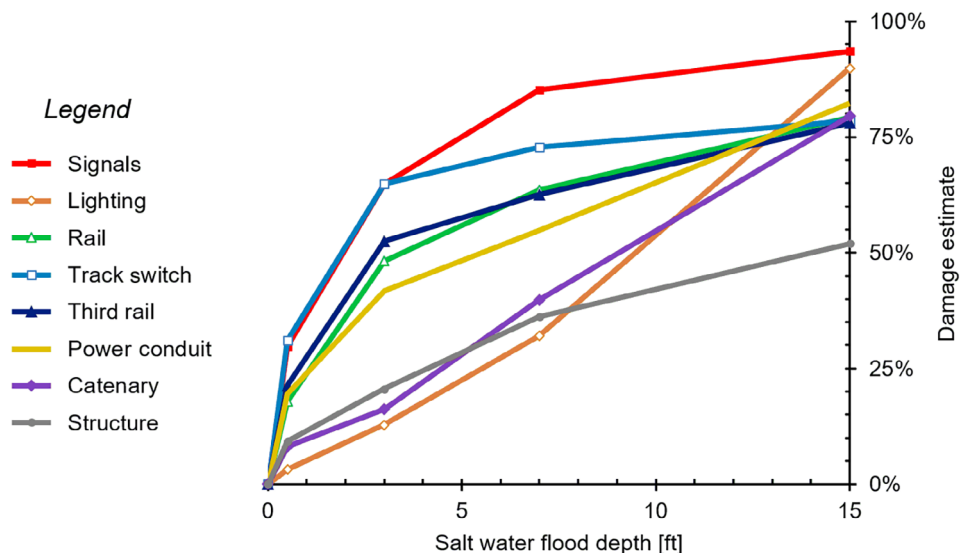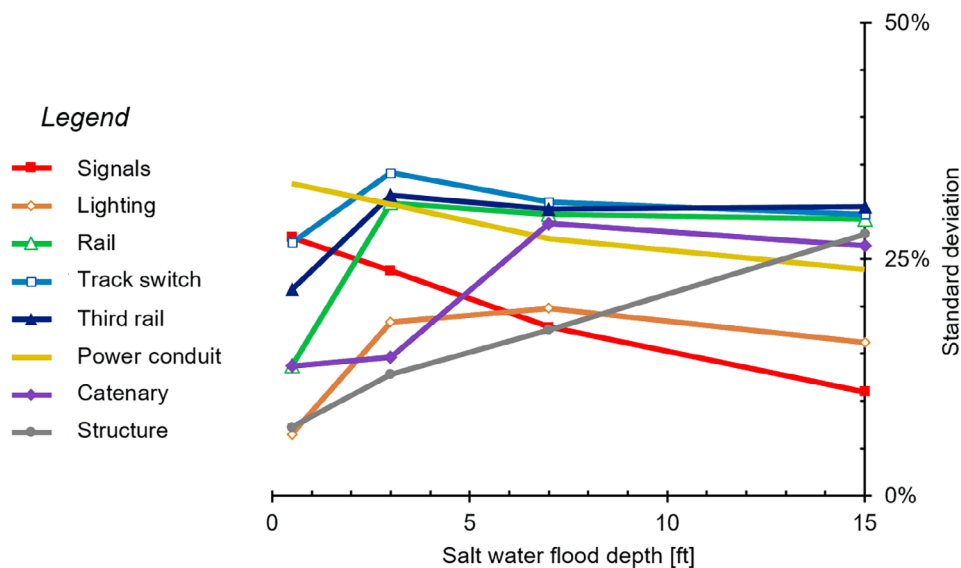

FIGURE 6 Standard deviation of survey responses for linear transit assets

Respondents noted that the specific location and elevation of linear assets relative to the tunnel invert and/or along the right of way greatly informs damage estimates. This was especially noted for duct banks and DC power cables, which are typically 0–3 ft off the ground in the MTA system, and can be located below grade, as is sometimes the case for catenary feeder cables in the MBTA system. MBTA respondents noted that most operational components in tunnels are typically at-grade and are also sensitive to saltwater corrosion.

In the particular case of signal systems, respondents noted that signal bungalows are critical facilities: Any replacement of signal bungalows would also trigger replacement of a significant portion of the affected signaling system, requiring a difficult repair and replacement process. One MBTA respondent noted a historic flood on the Green Line (October 1996) resulted in significant flooding at Kenmore Station and led to the replacement of a signal bungalow and all associated signals. The subsequent inspection, de-watering, and repairs efforts after the flood event required 7 days of full tunnel closure and 1.5 months before complete service restoration (Moore & Chiasson, 1996). Respondents also mentioned that the condition of equipment, particularly for electrical systems would also inform damage estimates.

6.3 | Damage variability

Respondents expected a significant degree of variability in damage associated with a given flood depth across all asset classes, as shown in Figure 7a. Averaging across all respondents, the anticipated lower bound of damages was found to be 50% of the damage estimate, though
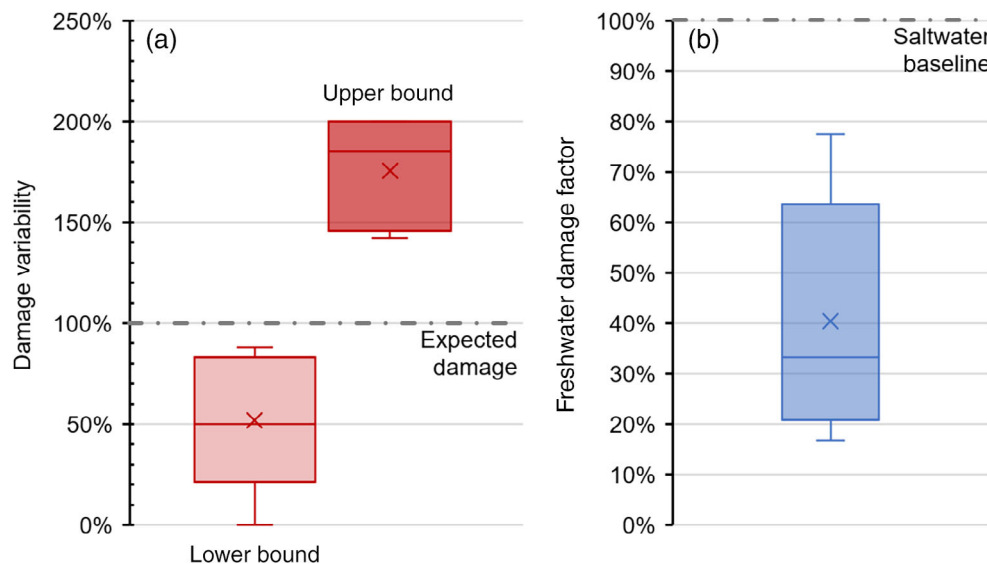
FIGURE 7 Damage variability estimates (a) across all assets for a given flood depth (lower and upper bound estimates); (b) for freshwater flood exposure as compared to an equivalent saltwater flood exposure

several respondents provided a lower bound of 0% (i.e., no damage). Conversely, the anticipated upper bound of damages was found to be 176% of the damage estimate, with several respondents suggesting this could be as high as 200% (i.e., twice the damage estimate). These results are broadly consistent with respondent comments and damage variability observations from prior studies (e.g., Dottori et al., 2016; Franco et al., 2020; Pistrika et al., 2014; USACE, 1992a, 2015), suggesting other factors also inform damage magnitude and contribute to damage model uncertainty. While these general expectations of damage variability can be used to inform models that scale damage uncertainty proportional to flood damage (e.g., Saint-Geours et al., 2015), damage variability is also likely to vary with flood depth (Egorova et al., 2008; Lehman & Hasanzadeh Nafari, 2016; USACE, 2015). As such, these results can also be used to inform alternative damage uncertainty models that capture such variability with flood depth, such as Egorova et al. (2008) which requires the calibration of an uncertainty parameter, k, that remains constant with respect to flood depth.

Water salinity is an important additional factor influencing the severity of flood damage, particularly for electronic components. While we provide damage estimates for saltwater flood exposure, we also investigated general expectations of the relative severity of saltwater versus freshwater flooding. On average, survey respondents estimated that relative to an equivalent depth of saltwater, a fresh water flood event would result in less than one third (31%) the damage, though there was significant variability across respondents (Figure 7b). Freshwater damage factor estimates exhibited significant variability and ranged as low as 17% and as high as 80% of the expected saltwater damage

for an equivalent flood depth. This variability and lack of consensus among respondents suggests such a general freshwater damage factor has limited predictive power. Future collection of transit asset-specific freshwater damage factors or freshwater damage curves is likely needed to further elucidate the relation between freshwater flood exposure and transit asset damage estimates.

6.4 | Validation via benchmarking

Validation of depth-damage curves (i.e., determining whether a depth-damage curve accurately reflects the fragility of an asset) is an important but challenging exercise requiring some degree of engineering judgment, as there is generally insufficient empirical data available for more conventional validation efforts. This holds true for comparatively more common residential and commercial structures; as such, benchmarking (i.e., comparisons with existing depth-damage curves) is typically the only practical, available, and reliable method of depth-damage curve validation (Gerl et al., 2016). In the context of transit system assets, there are very few potentially relevant depth-damage functions currently available in literature (Habermann & Hedel, 2018) which further complicates validation efforts. At present, the most relevant depth-damage functions available are those for general infrastructure, electrical and communication systems, and railways (de Moel & Aerts, 2011; Kok et al., 2004; Vanneuville et al., 2003).[3] The construction methods for these damage curves remains unclear (i.e., whether they are empirically derived from observations, or synthetically constructed from expert judgment), though absent this information or other potentially credible sources, we
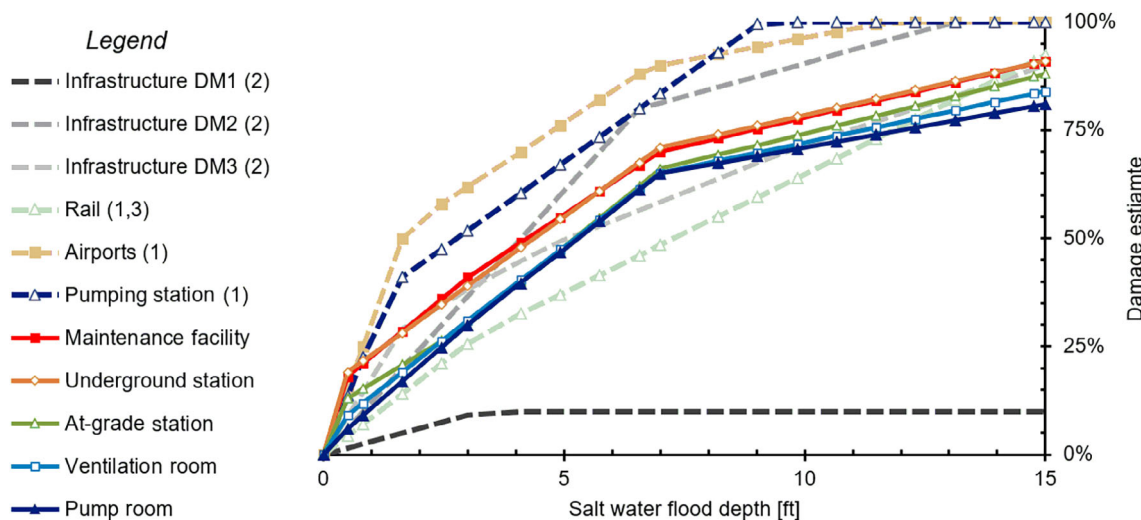
FIGURE 8 Comparison of transit facility depth-damage curves (this study) to previously published curves from (1) Kok et al. (2004), (2) de Moel and Aerts (2011), and (3) Vanneuville et al. (2003). DM, damage model

FIGURE 9 Comparison of linear transit asset depth-damage curves (this study) to previously published curves from (1) Kok et al. (2004), (2) de Moel and Aerts (2011), and (3) Vanneuville et al. (2003). DM, damage model
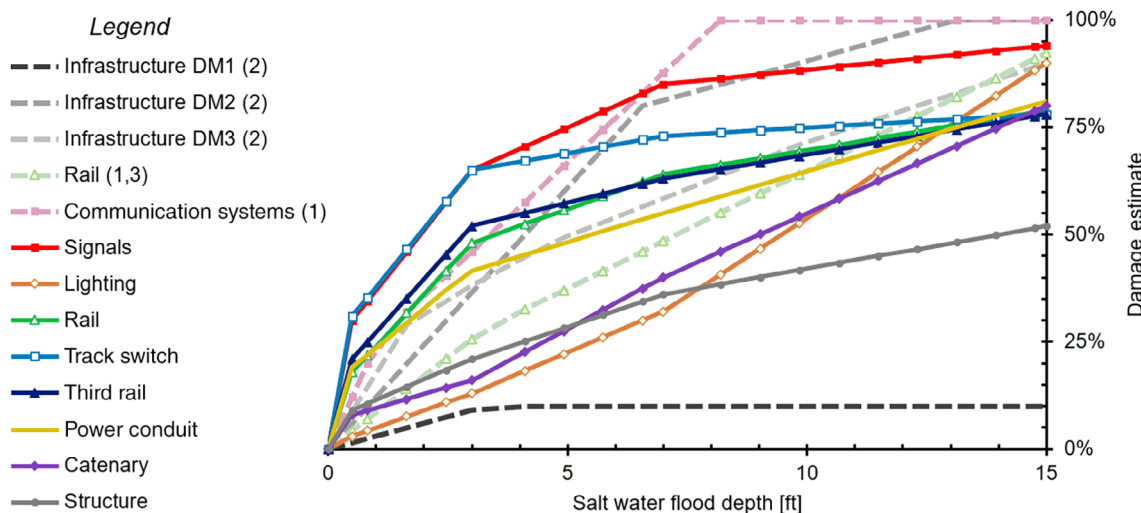
assume these curves adequately characterize asset fragilities to flooding.

Figures 7 and 8 compare the relevant depth-damage curves found in the literature with results from the current study for rail facilities and linear assets, respectively. The general infrastructure curve from de Moel and Aerts (2011), Damage Model 2 (DM2), most closely matches the current survey results for rail facilities. The published results for communications systems (Kok et al., 2004), Figure 9, underestimates the expected damage for signal and track switch assets from our study for smaller flood events (<5 ft) but overestimates for the larger events. Similarly, relative to the rail curve produced by this study, the previously published curve (Kok et al., 2004;

Vanneuville et al., 2003) underestimates damage for most of the flood depths shown (<10 ft) and overestimates thereafter. The first general infrastructure curve (DM1) is a clear lower bound of the published studies and is only comparable to the curves for catenary power and tunnel lighting at low flood depths (<3 ft), while the third general infrastructure curve (DM3) comes closest to approximating the curves produced for rail, third-rail, and power conduits. Overall, while the variance in the depth-damage curves relative to previously published curves is notable, these variances largely fall within the ranges of previously published curves for related assets. Based on these comparisons and exercising some degree of engineering judgment, we can conclude only the first general

infrastructure curve (DM1; de Moel & Aerts, 2011) fails this benchmarking validation exercise, as it differs significantly from all other curves presented.

While this comparison focuses on the depth-damage curves synthesized for saltwater flooding, a similar evaluation can also be conducted for freshwater damage curves. Application of the expected freshwater damage factor presented above (31%) significantly changes these comparisons, and instead results in freshwater depth damage curves incongruent with all but the first general infrastructure curve (DM1) presented in de Moel and Aerts (2011). While the DM1 curve, derived from the Rhine Atlas, is likely representative of freshwater flooding, given the potential applicability of the remaining curves to freshwater flooding, the validity of freshwater factor adjusted curves remains unclear. These results could suggest the DM1 curve is most indicative of freshwater flooding, though further research is needed to further investigate freshwater depth-damage relationships.

7 | DISCUSSION

Overall, the relatively consistent agreement across all asset classes coupled with the thoughtful and detailed commentary of respondents suggests a high-quality set of survey responses. While the benchmarking validation presented above validates the depth-damage curves presented in this study, future validation using empirical data would provide stronger support for the predictive accuracy of the depth-damage curves presented. Future work collecting such data for empirical validation would likely require a rapid response collection effort following in the wake of a significant flood event. Absent such efforts or other comparable depth-damage curves, given the quality of responses and the benchmarking validation, the results presented represent the best available estimate of transit asset fragility to saltwater flooding.

7.1 | Limitations

While this study attempts to characterize the effect of water salinity on damage estimates, further investigation is needed to better characterize the impact of other factors, such as wave action, flood duration, sediment load, water quality, flood timing, asset age, and construction typology on flood damage to transit assets. In particular, further consideration of the relationship between saltwater flood duration and damage could help to quantify the potential benefits of mitigation projects (e.g., by increasing pump resiliency and capacity in tunnels and underground stations, such as in recent MTA capital projects;

USACE, 2019). Based on survey responses, such flood duration reduction efforts would be particularly beneficial for more sensitive assets with electrical and electronic components (power, signal systems, etc.), though additional research is needed to further explore the relation between flood duration and damage severity. In the absence of an understanding of how these additional factors inform flood damage estimates, it is important to recognize their potential to introduce variability in projected flood damages. The flood damage variability estimates presented can be used to characterize damage uncertainty distributions (e.g., Egorova et al., 2008) to recognize the potential influence of these additional factors. Though informative and useful, these variability estimates should be interpreted with caution, as these results are likely subject to an overconfidence bias (Hanea et al., 2018; Moret & Einstein, 2012) where aggregate expert judgment estimates a narrower range of variability as compared to actual outcomes (e.g., USACE, 2015).

These other factors outstanding, in order to operationalize the proposed depth-damage curves, it is necessary to estimate the replacement cost of the relevant transit assets. While a catalog of these costs can be compiled based on historic pricing of completed projects and internal cost estimates, macroeconomic forces also have the potential to increase overall flood damage costs. Respondents noted that in the wake of Hurricane Katrina in 2005 and Hurricane Sandy in 2012, the recovery efforts of RTA and the MTA respectively were severely limited by supply chains, with lasting component supply shortages noted by respondents not directly affected by either event. While such post-disaster macroeconomic shocks are difficult to forecast and understand with accuracy ex ante, parallel research investigating vaccine supply chain resilience in the context of the COVID-19 pandemic suggests a tradeoff exists between supply chain efficiency and resilience (Golan et al., 2021). Further research investigating the resilience of transit component supply chains could elucidate potential macroeconomic complications that are likely to impinge transit system recovery to flood events and increase the overall costs of flood events.

8 | CONCLUSION

The synthetic depth-damage curves presented in this paper represent the first extensive attempt to systematically characterize the fragility of transit assets to saltwater flood exposure and represent a significant step toward a greater understanding of present flood risk exposure and the increasing threat climate change poses to transit systems. The expert elicitation methods presented can be

readily extended to create similar depth-damage curves for other types of infrastructure assets for which such information is presently lacking. Future work collecting relevant empirical data for transit systems would further improve collective understanding of the fragility of transit system assets to saltwater flooding and allow for further validation of the depth-damage curves presented. The construction of depth-damage curves for rail rapid transit infrastructure assets also represents a significant step toward quantifying the true costs of flood damage in coastal cities and enabling improved valuation of the direct benefits of climate change adaptation projects.

ACKNOWLEDGEMENTS

DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are available from the corresponding author upon reasonable request.

ORCID

Michael V. Martello ⓘ https://orcid.org/0000-0002-6977-7657
Andrew J. Whittle ⓘ https://orcid.org/0000-0001-5358-4140
Hannah R. Lyons-Galante ⓘ https://orcid.org/0000-0002-9615-8712

ENDNOTES

[1] During Hurricane Sandy, infrastructure systems in the greater NY–NJ area sustained an estimated \$17.1B in direct damages, 23% of the \$62.3B total estimated direct damages reported by Aerts et al. (2013).

[2] More recent precipitation-based flood events in London, Zhengzhou, and New York City have received media coverage (Barry & McGloin, 2021) though have not yielded substantive relevant documentation for the research community as of the time of writing.

[3] None of these functions explicitly consider saltwater flooding. Kok et al. (2004) assert that their functions are valid for fresh or salt water, while the other references neglect to mention the type of flooding, though DM1, derived from the Rhine Atlas (de Moel & Aerts, 2011) is likely representative of freshwater flooding.

REFERENCES

Aerts, J. C. J. H., Botzen, W. J. W., de Moel, H., & Bowman, M. (2013). Cost estimates for flood resilience and protection strategies in New York City: Flood management strategies for New York City. *Annals of the New York Academy of Sciences*, *1294*(1), 1–104. https://doi.org/10.1111/nyas.12200

Aspinall, W. P., & Cooke, R. M. (2013). Quantifying scientific uncertainty from expert judgement elicitation. In J. Rougier, S. Sparks, & L. Hill (Eds.), *Risk and uncertainty assessment for natural hazards* (pp. 64–99). Cambridge University Press. https://doi.org/10.1017/CBO9781139047562.005

Ayyub, B. M. (2001). *A practical guide on conducting expert-opinion elicitation of probabilities and consequences for corps facilities*. Report prepared for the U.S. Army Corps of Engineers (USACE) Institute for Water Resources, Alexandria, VA. https://www.iwr.usace.army.mil/Portals/70/docs/iwrreports/01-R-01.pdf

Barry, E., & McGloin, C. (2021, August 22). In low-lying Boston, storms bring fears of flooded subways. *The New York Times*. https://www.nytimes.com/live/2021/08/22/us/hurricane-henri-updates#in-low-lying-boston-storms-bring-fears-of-flooded-subways

Buchanan, M. K., Kopp, R. E., Oppenheimer, M., & Tebaldi, C. (2016). Allowances for evolving coastal flood risk under uncertain local sea-level rise. *Climatic Change*, *137*(3–4), 347–362. https://doi.org/10.1007/s10584-016-1664-7

Budiyono, Y., Aerts, J., Brinkman, J., Marfai, M. A., & Ward, P. (2015). Flood risk assessment for delta mega-cities: A case study of Jakarta. *Natural Hazards*, *75*(1), 389–413. https://doi.org/10.1007/s11069-014-1327-9

Chen, W., & Lalas, P. (2012). *Leakage repairs for transit tunnels*. North American Tunneling 2012 Proceedings, Indianapolis, IN (pp. 371–381).

Clemen, R. T. (2008). Comment on Cooke's classical method. *Reliability Engineering & System Safety*, *93*(5), 760–765. https://doi.org/10.1016/j.ress.2008.02.003

Compton, K. L. (Ed.). (2009). *Uncertainty and disaster risk management: Modeling the flash flood risk to Vienna and its subway system*. IIASA.

Cooke, R. M. (1991). *Experts in uncertainty: Opinion and subjective probability in science*. Oxford University Press.

de Moel, H. (2012). *Uncertainty in flood risk* (PhD thesis). Amsterdam, Netherlands: VU University Amsterdam. https://research.vu.nl/ws/portalfiles/portal/42215325/complete+dissertation.pdf

de Moel, H., & Aerts, J. C. J. H. (2011). Effect of uncertainty in land use, damage models and inundation depth on flood damage estimates. *Natural Hazards*, *58*(1), 407–425. https://doi.org/10.1007/s11069-010-9675-6

Dombrowski, T., Ratnadiwakara, D., & Slawson, V. C. (2020). The FIMA NFIP's redacted policies and redacted claims datasets. *Journal of Real Estate Literature*, *28*(2), 190–212. https://doi.org/10.1080/09277544.2021.1876435

Dottori, F., Figueiredo, R., Martina, M. L. V., Molinari, D., & Scorzini, A. R. (2016). INSYDE: A synthetic, probabilistic flood damage model based on explicit cost analysis. *Natural Hazards and Earth System Sciences*, *16*(12), 2577–2591. https://doi.org/10.5194/nhess-16-2577-2016

Egorova, R., van Noortwijk, J. M., & Holterman, S. R. (2008). Uncertainty in flood damage estimation. *International Journal of River Basin Management*, *6*(2), 139–148. https://doi.org/10.1080/15715124.2008.9635343

Evans, S. (2020, April). New York MTA to renew MetroCat re parametric cat bond. Launches $100m deal. *Artemis.Bm*. https://www.artemis.bm/news/new-york-mta-to-renew-metrocat-re-parametric-cat-bond-launches-100m-deal/

Federal Highway Administration (FHWA). (2005, March). *FHWA tunnel leak assessment* (Boston Central Artery Interim Report).

Franco, G., Becker, J. F., & Arguimbau, N. (2020). Evaluation methods of flood risk models in the (re)insurance industry. *Water Security*, *11*, 100069. https://doi.org/10.1016/j.wasec.2020.100069

Gerl, T., Kreibich, H., Franco, G., Marechal, D., & Schröter, K. (2016). A review of flood loss models as basis for harmonization and benchmarking. *PLoS One*, *11*(7), e0159791. https://doi.org/10.1371/journal.pone.0159791

Golan, M. S., Trump, B. D., Cegan, J. C., & Linkov, I. (2021). Supply chain resilience for vaccines: Review of modeling approaches in the context of the COVID-19 pandemic. *Industrial Management & Data Systems*, *121*(7), 1723–1748. https://doi.org/10.1108/IMDS-01-2021-0022

Habermann, N., & Hedel, R. (2018). Damage functions for transport infrastructure. *International Journal of Disaster Resilience in the Built Environment*, *9*(4/5), 420–434. https://doi.org/10.1108/IJDRBE-09-2017-0052

Hallegatte, S., Green, C., Nicholls, R. J., & Corfee-Morlot, J. (2013). Future flood losses in major coastal cities. *Nature Climate Change*, *3*(9), 802–806. https://doi.org/10.1038/nclimate1979

Hallegatte, S., Ranger, N., Mestre, O., Dumas, P., Corfee-Morlot, J., Herweijer, C., & Wood, R. M. (2011). Assessing climate change impacts, sea level rise and storm surge risk in port cities: A case study on Copenhagen. *Climatic Change*, *104*(1), 113–137. https://doi.org/10.1007/s10584-010-9978-3

Hanea, A. M., McBride, M. F., Burgman, M. A., & Wintle, B. C. (2018). The value of performance weights and discussion in aggregated expert judgments: The value of performance weights and discussion. *Risk Analysis*, *38*(9), 1781–1794. https://doi.org/10.1111/risa.12992

Hanea, A. M., Nane, G. F., Bedford, T., & French, S. (Eds.). (2021). *Expert judgement in risk and decision analysis* (Vol. 293). Springer International Publishing. https://doi.org/10.1007/978-3-030-46474-5

Hemming, V., Hanea, A. M., & Burgman, M. A. (2021). What is a good calibration question? *Risk Analysis*, *42*(2), 264–278. https://doi.org/10.1111/risa.13725

HNTB. (2014). *Structural assessment of the Amtrak under river tunnels in NYC inundated by Super Storm Sandy*. Amtrak. https://ded2pkq5zsyd4.cloudfront.net/images/article-0105/NYC-HNTB-tunnels-assessment-report.pdf?v=a502f3f167b6719a21025e61ccec80822b910c72

Keenan, J. M. (2019). *Climate adaptation finance and investment in California*. Taylor & Francis Group.

Kirshen, P., Thurson, K., McMann, B., Foster, C., Sprague, H., Roberts, H., Borrelli, M., Byrnes, J., Chen, R., Lockwood, L., Watson, C., Starbuck, K., Wiggin, J., Novelly, A., Uiterwyk, K., Bosma, K., Holmes, E., Stromer, Z., Famely, J., ..., Turner, R. L. (2018) *Feasibility of harbor-wide barrier systems—Preliminary analysis for Boston Harbor*. Sustainable Solutions Lab, University of Massachusetts Boston. https://www.greenribboncommission.org/document/feasibility-of-harbor-wide-barrier/

Kok, M., Huizinga, H. J., Vrouwenvelder, A. C. W. M., & Barendregt, A. (2004). *Standard method 2004 damage and casualties caused by flooding* (Report no. DWW-2006-009). Rijkswaterstaat, Netherlands. http://publicaties.miniem.nl/download-bijlage/58008/dww-2005-009-standard-method-2004-damage-and-casualties-ca.pdf

Kopp, R. E., Horton, R. M., Little, C. M., Mitrovica, J. X., Oppenheimer, M., Rasmussen, D. J., Strauss, B. H., & Tebaldi, C. (2014). Probabilistic 21st and 22nd century sea-level projections at a global network of tide-gauge sites. *Earth's Future*, *2*(8), 383–406. https://doi.org/10.1002/2014ef000239

Lehman, W., & Hasanzadeh Nafari, R. (2016). An empirical, functional approach to depth damages. *E3S Web of Conferences*, *7*, 05002. https://doi.org/10.1051/e3sconf/20160705002

Martello, M. V., Whittle, A. J., Keenan, J. M., & Salvucci, F. P. (2021). Evaluation of climate change resilience for Boston's rail rapid transit network. *Transportation Research Part D: Transport and Environment*, *97*, 102908. https://doi.org/10.1016/j.trd.2021.102908

Massachusetts Bay Transportation Authority (MBTA). (2018). *Massachusetts Bay Transportation Authority: Orient Heights maintenance and storage facilities current and future vulnerabilities to climate stressors*. Prepared by AECOM. Boston, MA.

Massachusetts Bay Transportation Authority (MBTA). (2019). *Final memorandum: MBTA climate resilience decision-making tool*. Prepared by Botros, R., Diaz, N., Rambert, R., and Shah, A. Cambridge, MA.

Miao, Q., Feeney, M. K., Zhang, F., Welch, E. W., & Sriraj, P. S. (2018). Through the storm: Transit agency management in response to climate change. *Transportation Research Part D: Transport and Environment*, *63*, 421–432. https://doi.org/10.1016/j.trd.2018.06.005

Moore, S., & Chiasson, G. (1996). The Green Line Flood of 1996. *NE Transit*. https://web.archive.org/web/20080725075644/http://members.aol.com/netransit8/flood/flood.html

Moret, Y., & Einstein, H. H. (2012). Experience in expert estimation of probabilities and correlations for rail line construction. *Journal of Construction Engineering and Management*, *138*(9), 1103–1106. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000505

Morgan, M. G. (2014). Use (and abuse) of expert elicitation in support of decision making for public policy. *Proceedings of the National Academy of Sciences*, *111*(20), 7176–7184. https://doi.org/10.1073/pnas.1319946111

National Academies of Sciences, Engineering, and Medicine (NASEM). (2017). *Improving the resilience of transit systems threatened by natural disasters, volume 2: Research overview*. The National Academies Press. https://doi.org/10.17226/24974

National Academies of Sciences, Engineering, and Medicine (NASEM). (2021). *Mainstreaming system resilience concepts into transportation agencies: A guide*. The National Academies Press. https://doi.org/10.17226/26125

Nazarchuk, A. (2008). *Water intrusion in underground structures* (MEng thesis). Department of Civil & Environmental Engineering, Massachusetts Institute of Technology, Cambridge, MA. http://hdl.handle.net/1721.1/43880

Oddo, P. C., Lee, B. S., Garner, G. G., Srikrishnan, V., Reed, P. M., Forest, C. E., & Keller, K. (2020). Deep uncertainties in sea-level rise and storm surge projections: Implications for coastal flood risk management. *Risk Analysis*, 40(1), 153–168. https://doi.org/10.1111/risa.12888

Pistrika, A., Tsakiris, G., & Nalbantis, I. (2014). Flood depth-damage functions for built environment. *Environmental Processes*, 1(4), 553–572. https://doi.org/10.1007/s40710-014-0038-2

Prahl, B. F., Rybski, D., Boettle, M., & Kropp, J. P. (2016). Damage functions for climate-related hazards: Unification and uncertainty analysis. *Natural Hazards and Earth System Sciences*, 16(5), 1189–1203. https://doi.org/10.5194/nhess-16-1189-2016

Rasmussen, D. J., Buchanan, M. K., Kopp, R. E., & Oppenheimer, M. (2020). A flood damage allowance framework for coastal protection with deep uncertainty in sea level rise. *Earth's Futures*, 8(3), 1–16. https://doi.org/10.1029/2019EF001340

Rosenzweig, C., Solecki, W., DeGaetano, A., O'Grady, M., Hassol, S., & Grabhorn, P. (Eds.). (2011). *Responding to climate change in New York state: The ClimAID integrated assessment for effective climate change adaptation* (Technical report). New York State Energy Research and Development Authority (NYSERDA) http://www.nyserda.ny.gov

Saint-Geours, N., Grelot, F., Bailly, J.-S., & Lavergne, C. (2015). Ranking sources of uncertainty in flood damage modelling: A case study on the cost-benefit analysis of a flood mitigation project in the Orb Delta, France: Ranking sources of uncertainty in flood damage modelling. *Journal of Flood Risk Management*, 8(2), 161–176. https://doi.org/10.1111/jfr3.12068

Transportation Research Board (TRB), & National Academies of Sciences, Engineering, and Medicine (NASEM). (2021). *Analysis of Green Bond financing in the public transportation industry*. Transportation Research Board. https://doi.org/10.17226/26066

Transportation Research Board (TRB) & National Academies of Sciences, Engineering, and Medicine. (NASEM). (2007). *Guidance for cost estimation and management for highway projects during planning, programming, and preconstruction*. Transportation Research Board. https://doi.org/10.17226/14014

United States Army Corps of Engineers (USACE). (1992a). *Guidelines for risk and uncertainty analysis in water resources planning: Volume I*. https://www.iwr.usace.army.mil/portals/70/docs/iwrreports/92r1.pdf

United States Army Corps of Engineers (USACE). (1992b). *Catalog of residential depth-damage functions used by the Army Corps of Engineers in flood damage estimation* (IWR Report 92-R-3). https://www.iwr.usace.army.mil/Portals/70/docs/iwrreports/92-R-3.pdf

United States Army Corps of Engineers (USACE). (2006). *Depth-damage relationships for structures, contents, and vehicles and content-to-structure value rations (CSVR) in support of the Donaldsonville to the Gulf, Louisiana, feasibility study*. https://www.mvn.usace.army.mil/Portals/56/docs/PD/Donaldsv-Gulf.pdf

United States Army Corps of Engineers (USACE). (2015). *North Atlantic Coast comprehensive study: Resilient adaptation to increasing risk—Physical depth damage function summary report*. https://www.nad.usace.army.mil/Portals/40/docs/NACCS/10A_PhysicalDepthDmgFxSummary_26Jan2015.pdf

United States Army Corps of Engineers (USACE). (2019). *New York–New Jersey Harbor and Tributaries New York District: Interim Report Plan Formulation Appendix*. https://www.nan.usace.army.mil/Portals/37/docs/civilworks/projects/ny/coast/NYNJHAT/NYNJHAT%20Interim%20Report%20PLF%20Appendix%20-%20Existing%20and%20Assumed%20Projects%2022Feb2019.pdf?ver=2019-02-22-104229-043

Vanneuville, W., De Maeyer, P., Maeghe, K., & Mostaert, F. (2003). Model the effects of a flood in the Dender catchment, based on a risk methodology. *Bulletin of the Society of Cartography*, 37(2), 59–64.

Wagenaar, D. J., de Bruijn, K. M., Bouwer, L. M., & de Moel, H. (2016). Uncertainty in flood damage estimates and its potential effect on investment decisions. *Natural Hazards and Earth System Sciences*, 16(1), 1–14. https://doi.org/10.5194/nhess-16-1-2016