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Economic Impact Modeling of Flood-Related Airport Disruptions: A Prototype for Integrated Resilience

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Summary

As a part of NASA's Convergent Aeronautics Solutions (CAS) project, this memorandum provides a brief methodology to calculate the economic damages of lengthy airport disruptions related to flooding and storm surge events in the United States. Using three benchmark events (Hurricane Harvey, Hurricane Ian, and Superstorm Sandy), we extract the timeline and extent of aviation disruption. To simulate a hypothetical shutdown, we calculate the daily revenue losses from both the airport and the airlines, and multiply these by daily cancellation rates to obtain a first-cut estimate of potential damages to U.S. airports and aviation. A Harvey-like event would result in losses in the order of $104.8 million for SFO (San Francisco) and $84.9 million for EWR (Newark) without accounting for international revenue and local spillovers. These results motivate flood-related infrastructure investments to improve aviation resilience in the long-term.

Nomenclature

ARMD	=	NASA Aeronautics Research Mission Directorate
BEARS	=	Building Enhanced Aviation Resilience Systems
CAS	=	Convergent Aeronautics Solutions project
NAS	=	National Airspace System
RIA	=	Resilience in Aviation
WHDA	=	Weather hazard and disaster adaptation
SLR	=	Sea Level Rise
IRROPS	=	Irregular Operations
ATM	=	Air Traffic Management

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Introduction

Modern aviation networks form the backbone of global and domestic connectivity, enabling the swift movement of passengers, goods, and critical services. Yet, this system is increasingly vulnerable to hydrological stressors. Disruptive events such as coastal flooding, storm surge, and recurring inundation now pose material risks to airport operations, particularly at low-lying facilities that anchor high-volume air traffic corridors and economic throughput. These disruptions are no longer isolated anomalies; they are becoming embedded features of the operational landscape for many key nodes in the air transportation system.

More than 1,200 airports worldwide are situated within the Low Elevation Coastal Zone (LECZ), with 995 of those operating five or fewer routes, often serving as lifeline infrastructure for island and rural communities. In the United States, many commercial airports—including major hubs such as San Francisco/Oakland (SFO, OAK), New York (EWR, LGA, JFK), and Miami (MIA)—face increasing exposure to storm surge and flood risk. These at-risk airports cumulatively handle hundreds of millions of passengers and billions of dollars in cargo annually.

Economic costs associated with flooding-related disruptions are substantial. A comprehensive analysis by the U.S. Department of Transportation found that flight delays alone cost passengers and airlines over $28 billion in a single year, with ripple effects on GDP and lost productivity exceeding $4 billion annually (DOT, 2010). However, these figures do not account for increasingly frequent interruptions driven by hydrological extremes or the capital losses tied to infrastructure degradation, evacuation, rerouting, or emergency mitigation. The financial burden of maintaining current risk levels through flood protection infrastructure at vulnerable airports could reach $57 billion globally by 2100 (Hinkel et al., 2014).

Recent modeling tools developed under NASA's Building Enhanced Aviation Resilience Systems (BEARS) initiative underscore the need to quantify not only direct physical damage but also the broader operational and economic disruptions resulting from natural hazard events such as storm surge and flooding. Tools like the Vulnerability Assessment for Aviation Systems Tool (VAAST), currently under development in the BEARS project, integrate airport-level flooding exposure, delay metrics, infrastructure vulnerability, and cost analytics to support decision-making and resilience planning. Users include airline stakeholders (especially in network planning, strategy, operations and recovery, capital investment, and sustainability), airport planners, as well as federal and local government agencies. The tool can able these users to quickly identify vulnerable infrastructure, select high return-to-investment areas, forecast risks and recovery costs, and plan for insurance, budgeting, and resource allocation.

Given the strategic significance of the aviation sector to the economy, a rigorous, system-level assessment of the economic costs of flood-related disruptions is important for aviation resilience. Doing so enables informed prioritization of infrastructure investment, targeted adaptation strategies, and enhanced continuity planning across the National Airspace System. To quantify the potential economic costs associated with flood-related disruptions at U.S. coastal airports, this memo outlines a first-cut estimation framework grounded in historical precedent and operational data. The approach focuses on both airport-level and airline-level economic impacts, using three benchmark flood events that previously inundated major airports as empirical anchors. For each case, cancellation and delay timelines were extracted and aligned with airport-specific operational statistics such as daily departures, enplanements, and estimated revenue from domestic tickets. These figures were then scaled to simulate hypothetical disruptions at other vulnerable U.S. airports, generating scenario-driven loss projections. While this method offers a simplified first-order approximation, it provides a valuable baseline for understanding the magnitude of potential losses. The approach can be directly incorporated into the VAAST environment to support scenario planning, visualize operational exposure, and inform investment decisions related to airport resilience against rising coastal and inland flood risks.

Flooding and Sea Level Changes as Threats to Aviation

Flooding presents multifaceted risks to the aviation industry, impacting infrastructure, operational efficiency, safety, and economic stability. This includes flooding from sea level rise, precipitation events/weather, and drainage/water management infrastructure factors. Impacts range from flooding of runways, terminals, and critical infrastructure through to secondary impacts such as a need to relocate or reconfigure airports to maintain them as operational.

Our assessment of the published literature as well as gray literature (conference papers, industry reports) found that some geographic risk assessments exist and that many airports have some degree of planning in place around flood risk and water management. However, comprehensive economic assessments characterizing the risks of flooding on the entire aviation system, or to metro areas that airports serve, are lacking.

Given the downstream impacts to logistics, business, and human safety that can occur when parts of the aviation system go offline, whether temporarily or longer term (in the case of prolonged floods or permanent sea level rise), we have identified translational economic modeling as a gap to be filled through additional research.

Reach and Impact of the Hazard

Flooding presents a formidable challenge to the aviation sector, which is a vital component of the global transportation network. The interconnected nature of the global aviation system means that flooding hazards in one region can cascade, disrupting air traffic and economic activities worldwide (Markolf et al. 2019). The growing risks from extreme weather and flooding necessitate a comprehensive understanding and proactive management of these impacts across all regions that support aviation operations (Yesudian and Dawson, 2021).

The aviation industry's logistical challenges are amplified by flooding, risking both passenger safety and economic stability. Being a systemic hazard, vulnerabilities in one aviation network segment inevitably affect the broader system, demanding globally coordinated responses and investments in infrastructure resilience (Lindbergh et al. 2022; Hsu et al. 2024).

Regional Analysis of Most Vulnerable Areas Globally and in the United States

1. **Coastal Airports and Low-lying Regions**

- Airports in Southeast Asia and along the U.S. Gulf Coast face significant risks from sea level rise and storm surges, as illustrated by Lindbergh et al. (2022). These coastal airports deal with increased inundation risks, threatening long-term structural integrity and operational functionality.
- The geographical characteristics of these regions make them especially susceptible to flooding, aligning with IPCC (2023) findings on the global impact on low-lying coastal areas.

2. **Delta and River Basin Regions**
   - Airports situated in major river deltas like the Mississippi are prone to riverine flooding, highlighted by complex drainage systems that are often overwhelmed during extreme weather.
   - Peng et al. (2022) discuss innovative drainage solutions, necessary for mitigating flooding impacts, demonstrating their critical application in these vulnerable regions.

3. **Islands and Archipelagic States**
   - Island nations and the Caribbean face rising sea levels and intense storms, placing critical aviation lifelines at risk of operational disruptions.
   - The limited geographical terrain of these islands means even slight increases in sea levels can have severe impacts, necessitating robust infrastructure defenses (Camastral 2014).

4. **Urbanized Coastal Metropolises**
   - Major urban centers such as those in New York face considerable risks from sea-level rise, exacerbated by high population densities that complicate flood management efforts (Yesudian and Dawson 2021).
   - The challenge of integrating effective drainage is compounded by the built-up environment, emphasizing the necessity of comprehensive flood adaptation strategies.

5. **Arid and Semi-Arid Regions with Flash Flood Risks**
   - Airports in arid regions like the Southwestern U.S. are increasingly exposed to flash flooding, as noted by Davies (2016), where sporadic intense rainfalls can lead to sudden floods.
   - Hardened, impermeable surfaces in these areas can exacerbate runoff, stressing the need for tailored flood management tactics.

By recognizing these geographically distinct vulnerabilities, the aviation industry can better understand, prepare for, and mitigate flooding's adverse impacts. Targeted infrastructure investments, strategic adaptations, and enhanced operational protocols are essential to maintaining a resilient global air transportation system in the face of flooding threats.

Analysis of Impact Dimensions

As a critical component of the global transportation network, the resilience of the aviation industry relies on understanding and addressing the multifaceted impacts of flooding across various dimensions. These dimensions encompass infrastructure, operations, aircraft design, economics, health and safety. An understanding of the impacts in each dimension and its relevance to the economic model is explored in this section.

Each dimension represents unique challenges and opportunities, calling for a coordinated, multi-pronged approach to ensure continuity in service while minimizing disruptions. The complexity of these hazards requires strategic solutions and adaptations to and safeguard the aviation industry's future. By exploring these impact dimensions, stakeholders can develop a thorough understanding of the economic effects and develop targeted interventions that align with broader strategic and economic goals.

Infrastructure

Flooding poses significant risks to airport infrastructure, impacting everything from physical structures to essential services. This dimension of impact is multifaceted and contributes several factors to be modeled:

- **Drainage System Overload**: Airports frequently face challenges with overloaded drainage systems during heavy rainfall or storm surges, leading to widespread flooding of runways and terminals. This affects the operational ability of airports, leading to flight cancellations and delays.
- **Infrastructure Damage**: Flooding can cause severe damage to airport infrastructure, including runways, terminals, and critical ground equipment. This can require significant repairs to return to normal operations. The work of Lindbergh et al. (2022), Poo et al. (2018), and Hsu et al. (2024) underscores these vulnerabilities. (Lindbergh et al. 2022; Poo et al. 2018; Hsu et al. 2024).
- **Chronic Flooding Effects**: Medium-term impacts involve chronic flooding in low-lying areas, leading to structural degradation, frequent airport closures, and increased maintenance costs.
- **Cargo Airports**: The United States has 12 predominantly cargo airports that face unique flooding challenges. Disruptions here can ripple through supply chains, affecting timely deliveries and economic operations across various sectors.
- **System Disruptions**: Besides structural damage, flooding disrupts essential airport services such as refueling, passenger, and cargo loading. This can lead to flight delays or longer turnaround times for passengers.
- **Access and Mobility Challenges**: Continuous flooding can make ground transportation to and from airports unreliable, affecting passenger and cargo mobility and requiring enhanced infrastructure planning.
- **Permanent Infrastructure Loss**: In the medium to long term, airports, particularly those in coastal regions with large US cities like JFK/EWR/LGA (New York City), MIA (Miami), and SFO/OAK (San Francisco), face risks of permanent structural loss. Strategic investments are crucial to avoid long-term operational cessations.
- **Subsurface Erosion**: Floodwaters can wash away the ground beneath runways, roads, and buildings, destabilizing structures and requiring costly foundational reinforcement to prevent such washouts.

- **Material Durability and Investment**: Materials must withstand exposure to saltwater without degrading. Given the high costs, infrastructure investments must be strategically planned and adequately budgeted.
- **Comprehensive Infrastructure Consideration**: Beyond airports, other aviation infrastructures, such as FAA radar facilities, are equally vulnerable, as demonstrated by outages in Puerto Rico during hurricanes. This can lead to widespread operational disruptions.

Operations

Flooding poses substantial challenges to aviation operations. The unpredictability of weather patterns and flood events can affect the reliability and efficiency of air travel:

- **Service Disruptions**: Flooding leads to frequent service interruptions, including flight delays and cancellations, due to adverse weather and localized conditions (Markolf et al., 2019; Zhou and Chen, 2020; Malandri, 2020). Some flooding events can result in multi-day partial or full airport closures. Such disruptions challenge the operational consistency that both passengers and airlines depend on.
- **Impact on Supply Chains**: Short-term flooding can significantly disrupt supply chains, leading to delays in airport access and affecting broader transit systems (Glass et al., 2022; Gu et al., 2024; Çevik, 2024). This highlights the interconnectedness of aviation operations with other economic sectors.
- **Medium-term Implications**: Persistent disruptions may force revisions to flight routes and schedules, reducing the predictability and reliability of air travel, especially in frequently flood affected.
- **Cargo Handling Challenges**: The efficiency of cargo operations is compromised during floods, with difficulties in loading and delays impacting logistics and economic activities.
- **Maintenance and Refueling Complexities**: Flood conditions complicate routine maintenance and refueling, with potential hazards from flooded ground power units requiring careful management to ensure safety.
- **Infrastructure Accessibility**: Runways and taxiways may become unusable due to flooding, necessitating urgent assessments and closures that disrupt flight operations and increase delays.
- **Passenger Compensations**: Flood-induced operational disruptions may result in passenger compensations by airlines including rebooking, food, and hotel accommodations.
- **Ground Crew Safety and Effectiveness**: Severe weather conditions can hinder ground crew operations, affecting their ability to carry out essential services and maintain operational safety, leading to flight delays.
- **Vulnerability of Critical Facilities**: Floods threaten vital operational facilities like radar and repair centers, which, if compromised, can disrupt network-wide aviation operations.

Aircraft Design

Flooding poses distinctive challenges to aircraft design, particularly concerning the durability and functionality of components in adverse weather conditions. The effects of flooding on aircrafts may lead to significant maintenance and repair costs:

- **Corrosion Risks from Saltwater**: Storm surges introduce saltwater that can lead to corrosion in aircraft components (Blanc-Brude et al. 2022). This may lead to more frequent aircraft repair and maintenance.
- **Vulnerability to Flood Water**: Smaller aircraft are particularly susceptible to flood waters, as standing water can penetrate and compromise critical components (Hsu et al. 2024).
- **Challenges of Electrification**: As aircraft electrification advances, the interaction with saltwater presents significant risks, potentially compromising electric systems (Yesudian and Dawson, 2021).
- **Ventilation System Integrity**: Flood conditions can introduce humidity and mold into aircraft ventilation systems. Aircraft inspections are needed to ensure the safety of aircrafts for passengers and crew.

Health and Safety

Flooding presents a multitude of health and safety challenges for the aviation industry, impacting passengers, employees, and surrounding communities. The multifaceted risks necessitate comprehensive strategies to protect human health and enhance safety protocols:

- **Toxic and Hazardous Conditions**: Floodwaters can carry harmful contaminants, posing significant risks to both humans and wildlife. Chemicals, fuel residuals, de-icing agents, and sewage can be picked up by floodwaters and dispersed into surrounding neighborhoods and ecosystems, leading to large-scale environmental contamination and health hazards. Aircraft and infrastructure inspections are needed for early detection of these effects.
- **Injury Risks**: Passengers and workers face increased risks of injury during flood conditions. Hazards such as slips, falls, and potential electrocution from waterlogged facilities may result in injury compensations in extreme scenarios.
- **Waterborne Diseases**: Flood conditions can exacerbate the spread of waterborne diseases, posing serious health risks to those exposed to contaminated water. Ensuring rapid response for clean water supplies and effective sanitation measures is critical in flooding scenarios.
- **Mold and Mildew Hazards**: Post-flood environments often breed issues like mold and mildew, leading to respiratory issues and other long-term health problems for those who frequent indoor airport facilities. Proactive inspections and remediation efforts are necessary to mitigate these effects.
- **Contaminated Water Supplies**: Flooding can lead to the contamination of drinking water supplies, necessitating robust filtration and testing systems to ensure safety.
- **Emergency Response Challenges**: Flood-induced evacuations and response efforts can often be delayed by difficult conditions, exacerbating health and injury issues. On-site capabilities to respond effectively to crises could be enhanced to provide immediate care and safety assurance.
- **Pest and Wildlife Concerns**: Increased wildlife and pests, such as mosquitoes, may seek refuge at airports during floods, necessitating integrated pest management measures to protect public health.
- **Stress and Mental Health Impacts**: Flooding events contribute to heightened stress and mental health challenges for both passengers and workers, requiring supportive measures

and mental health resources to alleviate the psychological burden associated with such crises.

- **Medical Supply Chain Disruptions**: Flooding can disrupt medical supply chains, impacting the availability of essential health supplies. Ensuring these supply chains remain robust and well-prepared for emergencies is crucial.

Benchmark Events: Hurricane Harvey, Hurricane Ian, and Superstorm Sandy

Hurricane Harvey

Hurricane Harvey struck the Texas coast on August 25, 2017 as a category 4 hurricane. The storm brought record breaking rainfall, windgusts, and storm surge leading to widespread flooding lasting several days. Hurricane Harvey affected operations in Texas airports George Bush Intercontinental Airport (IAH) and William P. Hobby Airport (HOU), which experienced full airport closures for five days. Damages from Hurricane Harvey are an estimated $125 billion as reported by NOAA. A reported 4539 flights were cancelled and 7547 flights were delayed in the first weekend (Flightaware via LA Times). Several smaller regional airports were also affected including Houston Executive, which experienced water covering runways and taxiways, West Houston Airport, which saw 8 inches of water in the terminal and 2–3 feet in some hangars, and other regional airports that also closed such as Jack Brooks Regional (Beaumont), Conroe-North Houston Regional, Ellington Field (Houston), Mustang Beach Airport (Port Aransas), Sugar Land Regional, Houston Executive, and Lackland AFB. IATA estimated that around 110,000 passengers per day were affected due to the storm's effects. Over 500 people remained at Hobby Airport until Spirit Airlines evacuated them. Flooding caused airport access roads and runways to be submerged. Additionally, 20% of U.S. refining capacity went offline, leading to jet fuel shortages and a price spike that added an estimated $350–400 million to airlines' fuel costs in the following month. IATA reported airline losses to be $32 million per day, which includes a $266 million loss for United Airlines, $77 million for Southwest Airlines, and $11 million for Spirit (A Cowen & Co. analysis reported in LA Times).

Super Storm Sandy

Super Storm Sandy struck the New York and New Jersey area as a powerful tropical storm on October 29, 2012, bringing $65 billion in total damages as reported by NOAA. The storm brought with it high storm surge and flooding that affected operations in Newark International Airport (EWR), Laguardia International Airport (LGA), and John F. Kennedy International Airport (JFK) between October 29th and November 1st. Effects were also seen in airports across the north east including PHL, BOS, Teterboro Airport, ACY, Long Island MacArthur (ISP), Westchester County Airport (HPN). Airport closures lasted 3 days, leading to 17,000–20,000 cancelled flights (NPR). Airlines lost a reported $100 million in revenue (NPR). Port Authority of NY/NJ, which operates the major NYC-area airports, reported approximately $2 billion in damages.

Hurricane Ian

Hurricane Ian made landfall in Florida on September 28 2022 and continued to travel through Georgia, South Carolina and North Carolina. The storm affected airport operations for two days in Orlando International Airport (MCO), Tampa International Airport (TPA), Southwest Florida International Airport (RSW), Miami International Airport (MIA), Jacksonville International Airport (JAX), Fort Lauderdale-Hollywood International Airport (FLL), and Charleston International Airport (CHS). There were a reported 4100 flight cancellations and 3000 flight delays nationwide (CNN Travel). Some airports had 3 days of closures, while RSW remained closed for 14 days, allowing only military and humanitarian flights. MCO saw 130,000 passengers impacted per day (CNN Travel), while TPA had 100,000 passengers affected by the closures (TPA). Economic losses due to the storm include a $3.5 million loss to Allegiant Air (FlightGlobal), while TPA reported $2 million in costs for closing the airport for 2.5 days (TPA).

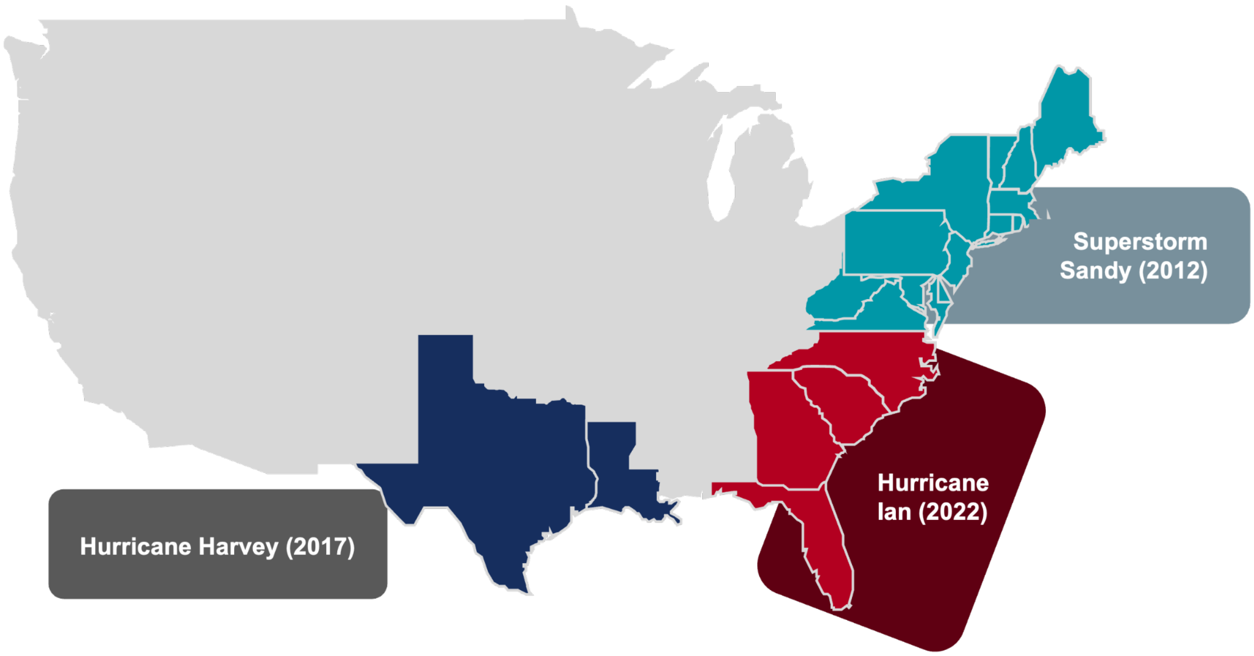

Fig. 1 Map of the key regions disrupted by Hurricane Harvey, Ian, and Sandy

Extracting Disruption Timelines

To quantify the operational impact of severe coastal flooding on major airports, three benchmark storm events—Hurricane Harvey (2017), Hurricane Ian (2022), and Hurricane Sandy (2012)—were selected as case studies. These events were chosen for their significant and well-documented disruption to airport operations in different U.S. regions. Operational performance data were obtained from the U.S. Department of Transportation's Bureau of Transportation Statistics (BTS) On-Time Performance database.[1] This database provides daily flight-level records for major U.S. carriers, including departure and arrival times, delay durations, and cancellation status.

For each hurricane, the official dates of regional impact were identified using news and National Weather Service reports. The major airports most affected by each event were then selected: Hurricane Harvey impacted William P. Hobby Airport (HOU) and George Bush Intercontinental Airport (IAH) in Houston, Texas; Hurricane Ian affected Southwest Florida International (RSW), Orlando International (MCO), and Tampa International (TPA) in Florida; and Hurricane Sandy disrupted Newark Liberty International (EWR), LaGuardia (LGA), and John F. Kennedy International (JFK) in the New York metropolitan area.

The BTS On-Time Performance data is recorded at the level of individual flights and includes the scheduled date, carrier, origin, destination, and operational outcome for each. For this analysis, all

[1] Accessible here: https://www.transtats.bts.gov/DatabaseInfo.asp?QO_VQ=EFD%20&Yv0x=D

flights either originating from or arriving at the affected airports during a 12-day analysis window—covering the storm's onset, peak disruption, and recovery phase—were extracted. The flight-level data was then aggregated by date and airport to calculate total scheduled operations, the number and proportion of cancellations, the number and proportion of delayed arrivals, and the cumulative delay minutes for arriving flights. This required summing operations for all relevant flights at the airport on a given day and concatenating results across all affected carriers. Cancellation and delay rates were then computed as the fraction of impacted flights relative to the total daily scheduled operations.

The resulting event-specific tables revealed distinct disruption patterns for each hurricane. Hurricane Harvey produced the most severe operational collapse, with both HOU and IAH experiencing a multi-day complete shutdown due to extensive flooding and restricted airport access. Hurricane Ian caused widespread cancellations at Florida's Gulf Coast airports and disrupted central Florida operations. Hurricane Sandy brought near-total suspension of activity across New York's three major airports, followed by a slower recovery as infrastructure and power restoration efforts progressed. The delay and cancellation rates calculated for the three benchmark events are shown in Appendix A.

These empirically derived disruption timelines serve as operational impact scenarios for simulating hypothetical flooding events at other coastal U.S. airports. By pairing these patterns with airport-specific daily traffic and revenue data, the model generates potential economic loss estimates under analogous multi-day runway inundation and operational disruption conditions.

Estimating Damages: Overall Approach

Economic damages to aviation because of a flood event can come in many different forms. Below we outline some of the damages that can be experienced over the short versus medium to long term.

- **Immediate Economic Costs**: Flooding leads directly to financial losses due to necessary repairs, increased insurance premium costs, and lost revenue from disrupted operations. The financial burden also includes higher maintenance costs over time (Blanc-Brude et al., 2022; De León-Alejandro, 2007; Davies, 2016; Assab, 2023; Yesudian & Dawson, 2021).
- **Adaptation and Renovation Expenses**: Construction of flood protection measures, renovations of existing infrastructure, or relocation of critical facilities incurs substantial costs. Airports and other aviation decision-makers must balance these investments against the benefits of risk reduction.
- **Operational Delays and Reduced Consumer Confidence**: Flooding causes operational delays, leading to financial losses from disrupted service and diminishing consumer confidence in aviation reliability (Camastral, 2014). These disruptions can result in reputational damage, affecting passenger loyalty and future revenues long-term.
- **Regional Economic Disruptions**: Flooding events cause downstream economic losses to local and regional economies, impacting supply chains and services, causing increased cargo and supply chain costs, and resulting in lost income for vendors and service providers (Joint Economic Committee, 2020).

- **Insurance and Risk Management**: Airports require comprehensive insurance strategies to manage flooding risks. Information asymmetries between airports and insurers regarding flood risk assessments can complicate negotiations and raise insurance costs.
- **Fuel and Resource Costs**: Flood-related disruptions escalate fuel and resource costs for airlines, impacting operational expenses and profitability.

Flood-related airport disruptions impact multiple stakeholder groups in distinct ways, requiring tailored estimation approaches for each. This analysis considers three primary categories of affected stakeholders: airports, airlines, and passengers. While the eventual goal is to capture the full spectrum of losses across all three, the current implementation focuses on first-cut estimates for airports and airlines, with passenger-level costs to be incorporated in later work.

For airports, the loss calculation draws on financial data from FAA Form 127 Airport Financial Reports, which contain annual revenue line items relevant to periods of operational shutdown. These include landing and take-off fees, fuel sales, ground handling services, labor, concessions, parking, and related ancillary income streams. The process begins by converting annual reported revenues to daily averages, producing an "average daily airport revenue" metric that represents exposure for each day of complete or partial closure. This metric is then paired with disruption timelines derived from benchmark flood events—Hurricanes Harvey, Ian, and Sandy—to estimate lost revenue over the modeled shutdown period. In the section below, we detail the decision criteria as to which line items to include and exclude for the damage calculations based on airport financials.

For airlines, the estimation approach focuses on revenue loss from canceled itineraries originating or terminating at the affected airport. While there are multiple possible modeling pathways—including cost-based estimates of fuel, crew time, and maintenance—the current version uses the U.S. DOT DB1B 10% domestic ticket revenue sample as a proxy for daily origin-destination ticket revenues. This approach provides a reasonable approximation for extended, multi-day cancellations, where ticket revenue losses dominate over incremental delay-related costs. A more detailed modeling approach could incorporate delay and tarmac time effects, which increase airline fuel burn and labor costs, using Form 41 operating expense data to capture these additional impacts. However, in this version, such costs are not explicitly calculated; the DB1B proxy is retained for simplicity, representing the economic value of disrupted air travel as O–D tickets that did not reach their destinations.

Passenger-level losses, including the economic value of lost time, rebooking inconvenience, and ancillary costs (e.g., accommodations, missed connections), are not calculated in this memo. However, they are a significant component of total system impact, as documented in the U.S. DOT Total Delay Impact Study, and are intended to be integrated in future iterations of this model to provide a more complete picture of flood-related disruption costs.

The combined damage estimate for a given scenario is generated by summing the daily losses across the event period for both airport-level and airline-level impacts. The event period is based on the benchmark storm disruption profiles, allowing users to simulate the financial implications of a Harvey-scale, Ian-scale, or Sandy-scale flood event at any coastal U.S. airport. While simplified, this approach provides an actionable first order estimate that can be incorporated into the VAAST tool, enabling scenario-driven assessments of how rising coastal flood risks translate into operational and economic consequences for aviation.

Estimating Damages: Airport Level

To quantify the financial impact of weather-related disruptions such as flooding at the airport level, we use the FAA's Form 5100-127 ("Form 127", Operating and Financial Summary) airport financial data as a standardized source. Form 127 provides a detailed breakdown of an airport's annual operating revenues across aeronautical and non-aeronautical categories. Not all of these revenue streams are equally sensitive to short-term operational disruptions. Some are contract-based or fixed over time, while others are directly tied to the number of flights, passengers, and associated airport activity.

FAA Form 127 is the official annual financial reporting instrument for U.S. commercial service airports. The Federal Aviation Administration requires filing from obligated commercial service airports (≥2,500 enplanements) that provided commercial service in the preceding year. Form 127 is filed online in CATS (Certification Activity Tracking System) and is publicly viewable. It carries OMB Control No. 2120-0569. AC 150/5100-19D is the controlling guidance for how sponsors file Forms 126/127. Reporting is mandated by Title 49 of the U.S. Code and corresponding FAA grant assurances, ensuring that every publicly owned, federally obligated airport meeting the threshold submits a consistent set of data each fiscal year. Airports typically submit Form 127 via the FAA's online reporting system within 120 days of their fiscal year-end. The data is prepared by the airport's finance department and often comes directly from audited financial statements, ensuring that the figures match formal financial records.

FAA Form 127 breaks out annual revenues at the airport level into detailed categories. Many of these revenues, such as fixed land leases, long-term contracts, or federal reimbursements would remain stable during short-term closures due to flooding or other weather or operational impacts. For the purposes of this analysis, we identified the airport revenue categories most directly linked to aircraft movements, passenger throughput, or on-site spending, as these categories would see an immediate impact during operational disruptions or significant closures.

Form 127 covers Aeronautical revenues (e.g., airline landing fees, terminal rents, apron charges, fuel flowage fees, cargo-related fees), Non-aeronautical revenues (e.g., concessions, parking, rental cars, hotels, advertising, land leases), Operating expenses and non-operating revenues (e.g., Passenger Facility Charges, Customer Facility Charges, grants), and Operating statistics (e.g., enplanements, landed weight, aircraft operations). Each revenue category is itemized with a numerical code (e.g., 1.1 for passenger airline landing fees) to standardize reporting across all airports.

Form 127 is widely regarded as a reliable source for airport financial data because it is mandatory for eligible airports. This creates a standardized, nationally comparable source for airport revenue analysis. FAA provides a standardized chart of accounts and definitions, minimizing variation in how categories are interpreted. Because Form 127 disaggregates revenue by activity type, it allows us to identify and isolate the categories directly linked to passenger throughput and aircraft operations. This granularity is critical when modeling the immediate financial effect of weather-related disruptions. The reporting standards and consistency across U.S. airports make it possible to apply the same methodology nationally, while retaining airport-specific accuracy. For a detailed analysis of the included and excluded categories of Form 127, see Table 1 and Table 2 in Appendix B.

The FAA 127 categories included in our model are:

Aeronautical Revenues

Passenger airline landing fees (1.1)
Terminal arrival fees, rents, and utilities (1.2)
Terminal area apron charges/tie downs (1.3)
Other passenger aeronautical fees (1.5)
Landing fees from cargo operations (2.1)
Fuel flowage fees (2.6)

Non-Aeronautical Revenues

Terminal food & beverage concessions (4.2)
Terminal retail & duty-free concessions (4.3)
Terminal services & other (4.4)
Rental cars (excluding facility charges) (4.5)
Parking and ground transportation (4.6)
Hotel revenue (4.7)

Other Revenue

Passenger Facility Charges (8.4)

These categories are included because they scale directly with flights and passengers, both of which decline sharply during closures. Using the reported annual revenues for each selected category, we calculate an average daily revenue from these categories, establishing the baseline daily value at risk for each revenue stream. More detail on rationale for each category included is provided in Appendix B, Table 1.

This method produces airport-specific loss estimates, considering each facility's actual revenue mix from Form 127. It can be scaled across multiple airports and applied to different weather events by changing the event-specific disruption pattern (duration and severity) and the annual revenue inputs for the airport in question.

Revenues such as federal inspection fees, land leases, grant receipts, and interest income are excluded because they are generally fixed, contractual, or allocated independently of daily passenger volumes or aircraft movements. Including these would inflate impact estimates without reflecting true short-term revenue vulnerability. More detail on these excluded revenues are included in Appendix B, Table 2.

$$AirportDamage_i = AirportDaily_i \times \sum_{d=1}^{12} CancelPerc_d$$

The total revenue loss or damage for an airport *i* is estimated using the above equation. For each of the 12 days of disruption based on the three benchmark events (in Appendix A), each day's (*d*) cancellation rate is multiplied by the daily-level airport revenue as described above from Form 127. Each 12 days of revenue loss is calculated and summed to yield the expected damage to airport revenue for the corresponding benchmark event scenario.

Estimating Damages: Airline Level

The airline-level loss estimates in this prototype model are based on the U.S. Department of Transportation's DB1B Origin-Destination Survey, a 10% sample of domestic airline tickets. For this version, we focus on 2019 as the baseline year, though the method can be extended to other years to assess changes in exposure. The dataset contains itinerary-level ticket sales information, including origin and destination airports, passenger counts (which are scaled by a factor of 10 to represent the full market), and fares paid.

For this prototype, we extract origin-destination (O-D) ticket data for the summer quarter (Q3: July-September) of 2019, the period most prone to flood- and storm surge–related disruptions. The analysis is limited to 12 U.S. airports, 10 identified by Wong et al. (2025) as among the most vulnerable to sea level rise or with documented histories of severe flood disruptions. These are: San Francisco International (SFO), Oakland International (OAK), Key West International (EYW), Tweed New Haven Airport (HVN), Miami International (MIA), St. Pete-Clearwater International (PIE), Newark Liberty International (EWR), LaGuardia Airport (LGA), John F. Kennedy International (JFK), Philadelphia International (PHL), George Bush Intercontinental Airport (IAH), and William P. Hobby Airport (HOU). The last two are included specifically due to the extensive storm surge impacts from Hurricane Harvey in 2017.

For each airport, all tickets for itineraries departing from or arriving at the airport are extracted. Passenger counts are scaled up from the DB1B 10% sample to represent the full passenger volume. Fares are then summed to yield the total revenue associated with travel through each airport during the summer season. Dividing this by the number of days in the quarter produces an estimate of average daily airline revenue attributable to the airport.

The disruption loss calculation applies the same method used for airport-level damages. For each of the three benchmark hurricane events—Harvey, Ian, and Sandy—the daily cancellation rate from the 12-day event profile is multiplied by the estimated daily airline revenue for the airport. Summing across the 12 days yields the estimated total revenue loss for that event scenario at that airport.

$$AirlineDamage_i = ODDaily_i \times \sum_{d=1}^{12} CancelPerc_d$$

The total revenue loss or damage for an airline located for airport *i* is estimated using the above equation. For each of the 12 days of disruption based on the three benchmark events (in Appendix A), each day's (*d*) cancellation rate is multiplied by the daily-level airline origin-destination (OD) revenue as derived from DB1B. Each 12 days of revenue loss is calculated and summed to yield the expected damage to airline revenue for the corresponding benchmark event scenario.

It is important to note that this method produces a lower-bound estimate. The approach currently excludes multi-stop itineraries, connecting passenger revenue, and freight shipments. It only accounts for domestic ticket revenue, which means that airports with substantial international operations (e.g., SFO, MIA, JFK) will have significantly higher true losses than estimated here. Furthermore, the calculation implicitly assumes that a cancelled flight results in a total revenue loss—either through refunds or through rescheduling costs and delay compensation exceeding the ticket value. While this simplification omits some airline operational adjustments and revenue recovery strategies, it provides a transparent first-cut approximation of potential airline-level losses under severe flood disruptions.

Results: Prototype Dashboard Implementation

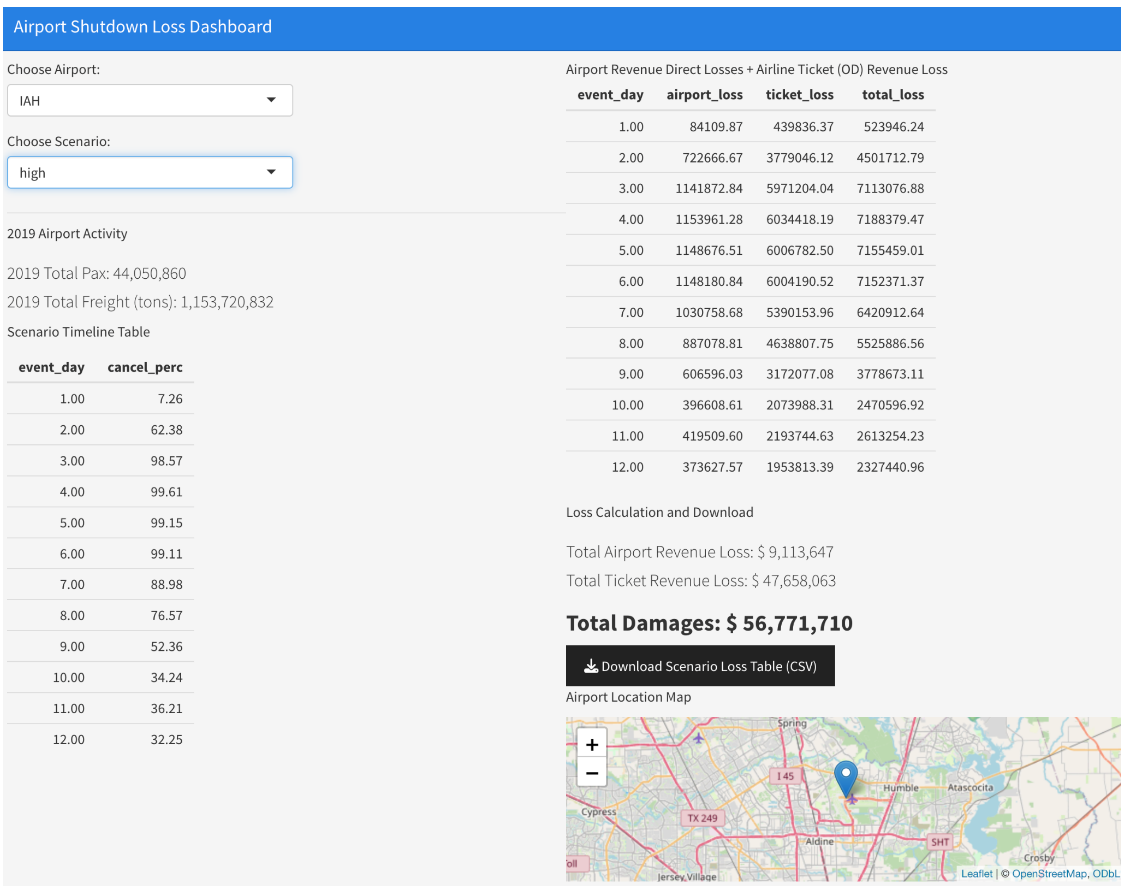

Fig. 2 Prototype Economic Damages Dashboard

We applied the airport- and airline-level loss estimation methods outlined above to construct a prototype interactive dashboard. The dashboard is designed to operationalize the calculations and allow users to quickly visualize potential economic impacts under different disruption scenarios. The current version serves as a functional module for eventual integration into the Vulnerability Assessment for Aviation Systems Tool (VAAST).

The interface (see Fig. 2) begins with an airport selection panel, populated with the vulnerable facilities identified for this study. Upon selection, the map display confirms the airport's location, providing immediate geographic context. Users then select one of the three benchmark disruption scenarios—Harvey-scale, Ian-scale, or Sandy-scale—each corresponding to a 12-day cancellation timeline derived from historical On-Time Performance records.

With these inputs, the dashboard retrieves the pre-calculated baseline daily airport and airline revenue exposures for the selected facility and applies the chosen scenario's daily cancellation rates. The calculations are executed in the background using the same formulas described in the preceding sections. The results are presented as daily loss curves and cumulative totals, with separate reporting for airport-level and airline-level impacts.

The interface is designed to allow rapid iteration, enabling users to switch between airports and disruption scenarios to see how estimated damages vary across facilities and event intensities. This capability supports side-by-side comparisons and sensitivity testing, making it possible to quickly identify airports with the highest economic exposure under different benchmark storm profiles. The visual presentation of daily and cumulative losses also helps convey the shape and duration of potential disruptions, highlighting how even short-lived events can result in significant financial impacts when applied to large, high-traffic airports. Appendix C provides further details of the prototype dashboard.

While the current version of the dashboard focuses on airport-level and airline-level revenue losses, it does not yet incorporate passenger time-value impacts, freight disruptions, or international ticket revenues. These omissions mean that the current outputs should be treated as lower-bound estimates. The underlying framework, however, has been built to accommodate additional loss categories and higher-fidelity disruption models. In future VAAST deployments, these enhancements will allow for more comprehensive scenario-driven assessments to inform resilience planning, guide investment prioritization, and support cost–benefit evaluations of adaptation measures at both the airport and system level.

Results: Airports with the Highest Economic Damages

Across the benchmark disruption scenarios, the largest estimated damages are concentrated at major hub airports with high passenger throughput and revenue density. On the East Coast, Newark Liberty International Airport (EWR) exhibited the single highest combined estimated loss, totaling approximately $84.9 million under a Harvey-like event. This consists of $19.5 million in airport revenue losses and $65.3 million in domestic ticket revenue losses. Under the Sandy scenario, Newark's combined damages fall to $36.1 million, comprising $8.3 million in airport-side revenue losses and $27.8 million in ticket revenue losses, while the Ian scenario produces the lowest losses. John F. Kennedy International Airport (JFK) follows closely, with damages on the order of $77.4 million, and LaGuardia Airport (LGA) with $65.6 million. Miami International Airport (MIA) shows a total estimated damage of $46 million.

On the West Coast, San Francisco International Airport (SFO) registers the single largest domestic-only damage estimate at $104.8 million, reflecting its role as a major hub with significant transcontinental and domestic flows. Oakland International Airport (OAK), by contrast, shows a much smaller loss at $19.8 million.

However, it is important to note that these are likely underestimating the impact of these disruption scenarios, as the calculation currently excludes international revenue losses—which make up many major hub's operations and revenue. Inclusion of international ticket revenue would raise MIA, SFO, JFK, and EWR's losses substantially.

Results: Implementation in VAAST

The Vulnerability Assessment for Aviation Systems Tool (VAAST) is being developed as an interactive, geospatial platform to support decision-making on aviation resilience under future flood and sea-level rise (SLR) scenarios. The tool integrates high-resolution geospatial data, facility-specific elevation models, and hazard projections to visualize inundation patterns for both present-day and future conditions. VAAST allows users to explore coastal flooding and SLR impacts through an interactive interface that links hazard projections with critical infrastructure footprints, enabling targeted risk assessment at the airport level.

The work detailed in this memo contributes to VAAST's capabilities by adding a first-cut economic damage estimation module. This new component builds on the methods described above to calculate scenario-driven airport and airline revenue losses under modeled flood events. The core advantage is that these estimates can be generated for any airport in the database, not just those with a documented history of flooding. This is essential because most individual airports have experienced only a small number of historical flood events, limiting the ability to infer risk from past data alone.

In the current prototype, calculations rely on static 2019 operational and financial data for the selected airport. Within VAAST, this framework can be expanded to incorporate a timeline toggle. When set to a past year, the module would draw on historical flight, passenger, and revenue records—like the datasets used in this work—to estimate damages for that year's operational baseline. When set to a future year, the system could link to a built airline demand model to be implemented in VAAST, which would project operations and revenues forward using baseline financial data, traffic forecasts, and demand growth scenarios.

By combining VAAST's high-resolution inundation visualizations with this economic modeling capability, users will be able to select any airport, choose a hazard scenario, and instantly view estimated damages for airport operations, airline revenues, and, once incorporated, passenger-level losses. This integration will transform VAAST from a primarily hazard visualization tool into a multi-dimensional risk assessment platform that connects projected physical impacts directly to economic consequences. Such a linkage will support prioritization of adaptation investments and provide relevant stakeholders and decision-makers with a clear, quantitative basis for evaluating resilience strategies.

Discussion: Future Work

The economic loss estimation approach presented here represents a first-cut methodology and, as such, contains several important limitations that will require refinement before full operational use in VAAST.

At the airport level, financial data from FAA Form 127 is available only at the annual aggregate level, which masks seasonal fluctuations in revenue. This limitation is significant for hazards with pronounced seasonal timing, such as hurricanes. Also, there is no publicly available dataset detailing actual operational and revenue impacts experienced by airports during disruption periods, making it necessary to infer losses indirectly from financial averages. Cargo and freight revenues, which can be substantial at some airports, are currently excluded, as are impacts on airport personnel costs, such as overtime wages or altered staffing schedules during recovery periods.

On the airline side, the current model does not account for irregular operations (IRROPS) costs, which include customer service labor, passenger accommodations, meal vouchers, rebooking, interlining charges, and compensation payouts. In many cases, these costs can exceed ticket revenue losses for severely disrupted itineraries. International operations are also absent from the current dataset, which means that losses for large hub airports with significant international traffic (e.g., JFK, MIA, SFO) are underestimated. While FAA Form 41 contains some relevant airline cost data (e.g., fuel, crew, and maintenance), it is not reported at the flight level, limiting its direct application. Additional operational costs, such as fuel burn from extended taxi or tarmac time, crew deadheading, rerouting, or overnighting, are similarly unaccounted for. The model also excludes losses tied to mishandled baggage and service breakdowns, which have been prominent in recent industry events (e.g., the Southwest Airlines operational disruption).

Passenger-level losses are also not yet integrated. Future work will incorporate nuisance and delay costs, including lost time and lost economic output, drawing on the U.S. DOT Value of Time Survey. These estimates can be paired with On Time Performance data for cancellations and delay minutes to produce more complete passenger impact valuations. Developing a cost model for delays is a natural extension of this work, and would allow the framework to address hazards beyond flooding, such as severe convective weather. Thunderstorms, while often producing shorter-duration disruptions, tend to result in high delay rates with fewer outright cancellations, presenting a different disruption profile. Implementation of this hazard class in VAAST will require leveraging historical operational data and machine learning methods to account for the complexity of network effects and the interplay of weather conditions at both origin and destination airports.

The methods demonstrated in this technical memorandum build directly on BEARS' original objectives by offering a scenario-based approach to estimating airport and airline losses from hazard-driven disruptions. The current focus is on coastal flooding and storm surge, but the framework is translatable to other natural hazards, such as severe convective storms, that can cause significant operational and financial impacts. By translating hazard scenarios into tangible, decision-ready economic metrics, the approach creates a bridge between physical event modeling and actionable planning.

On July 30, 2025, Delta Air Lines Flight DL56, an Airbus A330-900 operating from Salt Lake City to Amsterdam, encountered severe clear air turbulence over southwestern Wyoming. The turbulence caused significant cabin movement, injured 25 people and forced an emergency diversion to Minneapolis–Saint Paul International Airport. Passengers and crew described the event as unprecedented in severity, and the NTSB has classified it as an accident. Beyond the safety dimension, the incident demonstrates how a single hazard can cascade into medical emergencies, diversion costs, congestion at diversion airports, and broader schedule disruptions, triggering operational recovery challenges and reputational effects that extend well beyond the flight itself. This incident is an example of the economic, operational, and safety impacts a weather hazard can have on aviation systems. Other weather hazards, such as hurricanes or severe flooding can have extensive, multi day impacts that propagate to systems across the country. Research carried out by the BEARS project developed a thorough understanding of the varying weather hazards, the types and severity of their impacts, and their presence across the United States and its territories. The methodology here can be extended to study other types of hazards that could have significant impacts on aviation operations in the future.

Discussion: The Future of Aviation Resilience

The Building Economic Adaptation and Resilience in Aviation Systems (BEARS) project, initiated under the Convergent Aeronautics Solutions (CAS) program, was conceived to quantify and mitigate the economic consequences of disruptive hazards on the aviation system. From its outset, the BEARS team emphasized that while hazard identification and adaptation concepts are critical, decision-making is incomplete without understanding the financial magnitude of those impacts. Without credible estimates of weather disruptions and the potential return on investment (ROI) from adaptation measures, stakeholders risk underestimating vulnerabilities and underpreparing for future events. The efforts presented in this paper explored the cost of weather disruptions, and future work can delve into the economics of adaptation and their ROI from their incorporation into aviation systems.

To develop a model for adaptations, a deeper understanding of aviation resilience should be established. In general, resilience in aviation is the ability to achieve the minimum practical cost (in USD or time lost) or operational disruption—to the traveling public, consumers relying on air freight, or other aviation stakeholders—in response to one or more disrupters/hazards. Resilience could be characterized as the number of hours (after an event/disruption) to rebound to pre-event number of enroute air traffic flights. It could also be characterized in terms of the number of hours to rebound to pre-event levels of flight delays or cancellations (averaged over a year without hazard events).

If the focus is specifically on modeling network and operations resilience, then there has in recent years been a developing body of research on that focus area, including the proposal and use of specific metrics. In defining aviation network and operations resilience consider three capacities (Francis and Bekera, 2014):

1) absorptive capacity: “the degree to which a system can absorb the impacts of system disruptions and minimize consequences with little effort” (proactive measures);
2) adaptive capacity: “the ability of a system to adjust to undesirable situations by undergoing some changes”;
3) restorative capacity: “ability to recover or bounce back from a disruptive event and quickly return to normal or improved operating conditions”.

Additionally, in the context of aviation network and operations, a consideration of the following terminology may be relevant for future modeling efforts: resilience – i.e., ability of network to neutralize impacts of disruptive events (Janić, 2015); and friability – i.e., “reducing the network’s existing resilience due to removing particular nodes/airports and/or links/air routes” (Janić, 2015).

Further, consider three layers within the aviation network (Janić, 2015): physical – i.e., impact on infrastructure- airports, airspace/air routes, ATC/ATM facilities and equipment; service – i.e., impact on the air transport services-airline flights; cognitive – i.e., air passengers' confidence in the affected and subsequently recovered flights. Modeling the potential ROI from adaptations to enhance resilience in aviation can explore solutions through the lens of resilience and friability across the physical ATC/ATM facilities and aviation networks.

Finally, for aviation networks and operations, following a disruptive event, there are five phases of response (Arabi, et. al, 2021): staging – i.e., involves proactive responses to increase its capacity beyond their maximum expected performance; reduction – i.e., operation level decreases below its minimum performance level; peak – i.e., level of operation reaches the lowest performance because of the event; restoration – i.e., operation regains its functionality and recovers to the normal state; overloading – i.e., involves reactive responses of operations that address backloads of demands. Future modeling efforts towards adaptations can parallel these response stage, uncovering stages with the highest ROI to motivate investment for solutions at those stages to enhance resilience.

Developing cost-effective adaptation strategies to future natural disasters, especially severe weather events, will require the collective input and efforts of a broad spectrum of stakeholders. These stakeholders range from municipal/regional authorities, airport operators, airlines, aircraft manufacturers, aviation and transportation researchers/academics, and the public.

The BEARS project initiated an early dialog through interviews and subsequent discussion with a small pool of stakeholders. The BEARS project also engaged at a few research forums. The biggest near-term engagement with stakeholders is anticipated to be kick-started by the development of economic modeling tools that focus on the impact of weather-related natural disasters on aviation systems. Initial focus has been on airport flooding, but the hope is to extend the tools to account for the economic impacts of severe storms, extreme temperatures, and clear air turbulence. Engagement with stakeholders will provide expert advice in the ideation and feasibility of potential adaptations to enhance resilience, provide critical feedback for features and usability of the software tool, and guide the outputs of the project to maximize its benefit to aviation systems.

Future economic modeling efforts must not only estimate hazard costs, but also consider probability of occurrence, and their likelihood of occurring in specific regions/geographic locations. Additionally, ultimately, such tools must also have the utility to consider the return-on-investment of various adaptation/mitigation approaches to minimizing the adverse impact of future weather hazards. For instance, automating ground operations may allow flight operations to continue during thunderstorm threats, minimizing flight cancellations and delays that could cascade to other airport operations and reducing the economic impact of such a weather disruption. The BEARS project would investigate the feasibility of such adaptations, model the potential economic savings of implementing the technology, and predict the operational capacity of airports that adopt the technology.

Looking ahead, there is an opportunity to sustain and expand this work in ways that complement broader efforts to modernize the National Airspace System. As future air traffic management concepts increasingly emphasize rapid operational recovery, adaptive traffic flow strategies, and minimization of network congestion during disruptions, tools such as the one demonstrated here could provide valuable inputs. Embedding hazard-driven economic modeling into integrated decision-support environments would allow stakeholders to evaluate not only the scale of potential impacts but also the relative benefits of different adaptation and recovery strategies. By linking physical hazard scenarios to operational consequences and financial outcomes, the approach can help ensure that both infrastructure planning and operational strategies are informed by consistent, scenario-based analysis, supporting a more resilient and adaptable aviation system.

Conclusions

The modeling framework presented here demonstrates how hazard-driven disruptions, such as coastal flooding, storm surge, and sea level rise, can be translated into quantifiable economic impacts at both the airport and airline levels. These outputs can be used to inform decision-making on defensive expenditures, including physical infrastructure investments such as sea walls, drainage improvements, and flood barriers, as well as operational strategies that can mitigate losses. By providing a repeatable method for estimating potential damages, the framework supports airport operators, airlines, and policymakers in evaluating the trade-offs between capital investment, operational preparedness, and anticipated hazard exposure.

Beyond infrastructure considerations, the results underscore the importance of planning for irregular operations (IRROPS) and recovery. Disruption scenarios of the type modeled here are not only costly in terms of direct revenue losses but also drive network-wide effects, including gate compression, diversion airport congestion, and increased delay propagation. Integrating this modeling into forward-looking operational planning can help stakeholders test the value of technologies, procedures, and infrastructure enhancements aimed at shortening recovery times and restoring network performance after major events.

Looking ahead, the framework can be extended to assess future operational contexts in which demand growth, evolving fleet mixes, and changing hazard profiles interact with next-generation air traffic management concepts. Alignment with emerging decision-support environments—such as those being explored for advanced traffic flow management, network optimization, and system-level resilience—would enable these economic impact assessments to complement broader NAS performance objectives. This integration would not only support hazard adaptation planning but also provide an economic lens on operational recovery strategies in the context of the evolving ATM ecosystem.

By coupling hazard visualization, economic damage modeling, and operational recovery analysis, this work offers a foundation for a more resilient, adaptive, and economically robust aviation system. In doing so, it complements ongoing efforts in the future of air traffic management, providing stakeholders with a unified framework for anticipating impacts, prioritizing adaptation measures, and aligning resilience investments with long-term NAS performance goals.

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Appendix A: Disruption Timelines for Benchmark Events

We use historical disruption data from prior weather events (e.g., Hurricanes Harvey and Ian) to model daily activity reductions. These scenarios are expressed as percentage reductions in scheduled flights and applied to daily airport and airline revenue.

- Red: ≥80% cancellations equates to "Severe disruption; nearly all flights and associated revenues suspended."
- Orange: 30–80% cancellations equates to "Significant disruption; reduced but nonzero passenger and cargo operations."
- Yellow: 10–30% cancellations equates to "Partial disruption; moderate loss of passenger and cargo throughput."

Table A1. Delay and Cancellation Rates at IAH and HOU (Hurricane Harvey), 2017

event_day	scheduled	cancel_perc	delay_perc	totaldelaymin
1	1033	7.260406	15.29526	7893
2	840	62.38095	18.57143	12371
3	977	98.56704	1.023541	1881
4	1027	99.61052	.2921129	2428
5	946	99.15434	0	0
6	1013	99.11155	.5923001	601
7	1025	88.97561	2.146342	1076
8	1033	76.57309	3.000968	1625
9	741	52.36168	5.128205	2209
10	739	34.23545	3.38295	2005
11	961	36.21228	4.266389	2204
12	1017	32.25172	9.734513	7707

Table A2. Delay and Cancellation Rates at RSW, TPA, MCO (Hurricane Ian), 2022

event_day	**scheduled**	**cancel_perc**	**delay_perc**	**totaldelaymin**
1	1293	.6960557	20.10827	18586
2	1233	.405515	18.32928	13861
3	1176	17.43197	15.47619	13692
4	1180	93.72881	2.372881	2260
5	1255	99.92032	0	0
6	1262	55.38827	18.30428	17387
7	1331	17.35537	19.45905	19057
8	1328	13.78012	14.00602	12697
9	1258	10.96979	10.73132	7882
10	1190	11.17647	14.20168	10727
11	1192	6.459732	14.84899	11945
12	1287	7.070707	10.02331	7158

Table A3. Delay and Cancellation Rates at LGA, EWR, JFK (Hurricane Sandy), 2012

event_day	scheduled	cancel_perc	delay_perc	totaldelaymin
1	1892	.6871036	17.2833	19712
2	1884	.477707	11.30573	12367
3	1397	.3579098	8.37509	7455
4	1751	26.8418	26.55625	26430
5	1883	100	0	0
6	1792	99.60938	.3348214	948
7	1779	88.36425	1.854975	2102
8	1891	31.5706	11.95135	17698
9	1888	5.29661	22.82839	23683
10	1419	.422833	10.14799	8196
11	1743	.5163511	17.32645	15494
12	1878	1.011715	15.28222	16926

Appendix B: Airport Financials Inclusion Criteria

Table B1: Revenue Items from FAA 127 and Rationale for Inclusion as Variable Revenue Elements in Instances of Flooding / Weather-Related Operational Disruption and Closure

Item	Revenue Element	Rationale for Inclusion
1.1	**Passenger airline landing fees**	Directly impacted by cancellations or diverted flights, reducing the number of aircraft landings and takeoffs.
1.2	**Terminal arrival fees, rents, utilities**	Closures cause reduced airline operations, lower passenger volume also reduces utility consumption.
1.3	**Terminal area apron charges/tie downs**	Reduced aircraft operations lower apron usage
1.5	**Other passenger aeronautical fees**	Ancillary passenger-related charges tied to passenger volumes and airline operations decline during closures
2.1	**Landing fees from cargo**	Severe weather events disrupt cargo flight schedules, impacting cargo associated landing revenues.
2.6	**Fuel flowage fees**	Reduced operations lower fuel sales at airports, directly cutting fuel related revenue.
4.2	**Terminal food and beverage**	Airport closures and reduced passenger volumes directly impact terminal food and beverage sales (fewer customers)
4.3	**Terminal retail and duty-free**	Airport closures and reduced passenger volumes directly impact retail and duty free sales (fewer customers)
4.4	**Terminal services and other**	Closures and reduced passengers lead to lower demand for terminal services.
4.5	**Rental cars excluding facility charges**	Passenger cancellations and fewer incoming travelers significantly decrease demand for rental cars, reducing concession revenues.

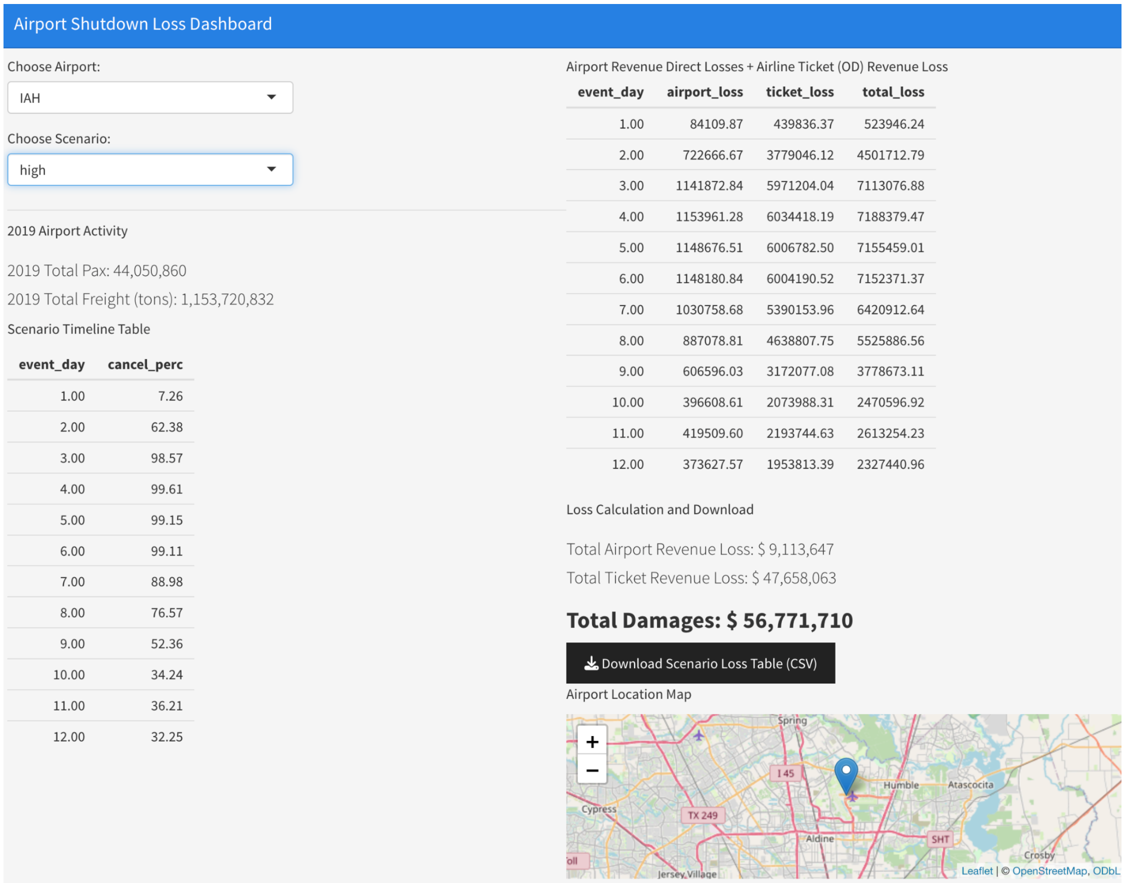
4.6	**Parking and ground transportation**	Fewer passengers lead to substantial reductions in parking, taxi, rideshare, and shuttle usage.
4.7	**Hotel**	Airport-associated hotels experience reduced occupancy when air travel is severely disrupted.
8.4	**Passenger facility charges (PFC)**	Directly linked to the number of enplaned passengers; fewer passengers leads to losses.

Table B2: Revenue Items from FAA 127 and Rationale for Exclusion

Item	Revenue Element	Rationale for Exclusion
1.4	**Federal Inspection Fees**	Typically annual fixed-rate agreements or contracts, unaffected by closures
2.2	**Landing fees from General Aviation (GA) and military**	Minimal GA at larger airports; military fees contractual, long-term.
2.3	**FBO revenue (Fixed Base Operators)**	Typically fixed contracts.
2.4	**Cargo and hangar rentals**	Monthly or annual contracts.
2.5	**Aviation fuel tax retained for airport use**	Typically state or local taxes retained by airports on a periodic or annualized basis.
2.7	**Security reimbursement from Federal Government**	Typically based on annual agreements or fixed schedules
2.8	**Other non-passenger aeronautical revenue**	Long-term contracts or fixed revenue streams
4.1	**Land and non-terminal facility leases and revenues**	Typically stable leases paid monthly or annually r

4.8	**Other miscellaneous revenues (service charges, recoveries, permits)**	Primarily driven by administrative or permit fees
8.1	**Interest Income**	Independent of airport operational status.
8.2	**Interest expense**	Independent of daily operations or passenger volumes.
8.3	**Grant receipts**	Allocated based on federal or state budgeting cycles.
8.5	**Capital contributions**	Unaffected by short-term closures.
8.6	**Special items (loss)**	One-time accounting adjustments or special circumstances.
8.7	**Other non-operating revenues (customer facility charges, loss on asset sales)**	Typically annualized or predetermined

Appendix C: Prototype Guide



Airport Shutdown Loss Dashboard

Choose Airport: IAH

Choose Scenario: high

2019 Airport Activity

2019 Total Pax: 44,050,860

2019 Total Freight (tons): 1,153,720,832

Scenario Timeline Table

event_day	cancel_perc
1.00	7.26
2.00	62.38
3.00	98.57
4.00	99.61
5.00	99.15
6.00	99.11
7.00	88.98
8.00	76.57
9.00	52.36
10.00	34.24
11.00	36.21
12.00	32.25

Airport Revenue Direct Losses + Airline Ticket (OD) Revenue Loss

event_day	airport_loss	ticket_loss	total_loss
1.00	84109.87	439836.37	523946.24
2.00	722666.67	3779046.12	4501712.79
3.00	1141872.84	5971204.04	7113076.88
4.00	1153961.28	6034418.19	7188379.47
5.00	1148676.51	6006782.50	7155459.01
6.00	1148180.84	6004190.52	7152371.37
7.00	1030758.68	5390153.96	6420912.64
8.00	887078.81	4638807.75	5525886.56
9.00	606596.03	3172077.08	3778673.11
10.00	396608.61	2073988.31	2470596.92
11.00	419509.60	2193744.63	2613254.23
12.00	373627.57	1953813.39	2327440.96

Loss Calculation and Download

Total Airport Revenue Loss: $ 9,113,647

Total Ticket Revenue Loss: $ 47,658,063

Total Damages: $ 56,771,710

Download Scenario Loss Table (CSV)

Airport Location Map

Fig. C1 Dashboard Guide

The user first selects an airport from a list, currently focusing on the 12 most vulnerable airports to sea level rise and storm surges. Once selected, the interface displays financial loss estimates for that airport under various scenarios, drawing from historic event data. The lower portion includes a map pinpointing the selected airport for geographic context.

Next, users choose a disruption scenario (High, Medium, Low) modeled after actual hurricane events—Harvey (2007, High), Ian (2022, Medium), and Sandy (2012, Low). The selected scenario determines the assumed operational disruption timeline.

The dashboard shows how the chosen scenario directly applies its cancellation timeline, taken from DOT Airline On Time Performance and hurricane event data, to estimate disruption impacts. The scenario's day-by-day cancellation profile is visible in a side table, highlighting the intensity and duration of operational shutdowns.

On the top right hand table of the dashboard, we see the airport-level revenue losses in column 2, calculated from FAA Form 127 financial reports. Relevant line items tied to flood-related disruption are annualized and converted into daily averages, representing non-airline revenue streams at risk (e.g., concessions, parking, ground services).

In column 3, we have the airline ticket revenue losses, using DB1B's 10% sample of domestic markets. The model estimates revenue foregone for itineraries originating or terminating at the disrupted airport. It does not account for connecting traffic, rebooking, or international itineraries. The sum total for each disrupted day is reported in column 4.

The model aggregates the airport-level and airline-level losses over the entire event period for the chosen scenario. The output provides a total estimated economic impact in bold for the simulated disruption. The slide notes that passenger time loss, rebooking, baggage delays, and other indirect costs are excluded, making this a first-cut proxy estimate.

As a suggestion for implementation in VAAST, users can download aggregated datasets and view an airport location map. The framework is designed to be scalable to all coastal airports, with user-defined scenario triggers or automated hazard inputs (e.g., flood or sea-level toggles). Future demand can be incorporated with a back-end demand model to simulate future revenue (and thus losses).