# BEYOND THE WIND: RETHINKING THE SAFFIR-SIMPSON HURRICANE WIND SCALE

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## *ABSTRACT*

*Imagine a hurricane forecast that truly reflects the danger you face, extending beyond just wind speed. While the Saffir-Simpson Hurricane Wind Scale (SSHWS) has long guided our understanding of hurricane strength, its reliance solely on wind speed presents an incomplete and often misleading picture. This neglect leads to critical gaps in our assessment of hurricane impacts, particularly concerning storm surge, flooding, and storm size.*

*In response to these limitations, this research introduces the Composite Hurricane Impact Scale (CHIS), a novel framework that integrates wind speed with storm surge potential, rainfall-induced flooding, and storm size, providing a holistic view of a hurricane's potential destruction. Through compelling case studies evaluating historical storms, this paper demonstrates how CHIS enhances our ability to predict, prepare for, and mitigate the multifaceted impacts of hurricanes.*

*By analyzing historical storms, this research highlights CHIS's superior predictive capability and its potential to revolutionize emergency response, improve public awareness, and foster more resilient communities. Ultimately, CHIS empowers communities with the actionable information needed for better preparedness, more effective emergency response, and safer futures in the face of increasingly complex and intense hurricanes. This comprehensive assessment signifies a critical step toward building a society better equipped to confront the mounting challenges posed by powerful storms, ultimately saving lives and protecting communities.*

## *KEYWORKS*

Hurricane categorization, computing, Saffir-Simpson, disaster preparedness, CHIS model

## 1. INTRODUCTION

Hurricanes pose severe risks to life and property, particularly for vulnerable coastal communities that brace for their impacts each season. For decades, the Saffir-Simpson Hurricane Wind Scale (SSHWS) has served as the primary tool for gauging hurricane danger based solely on wind speeds. However, this singular focus neglects critical factors such as storm surge, rainfall, and storm size—elements that often dictate the true extent of a hurricane's destructive potential. The catastrophic outcomes observed during Hurricanes Harvey (2017) and Sandy (2012) vividly illustrate the limitations inherent in a wind-centric approach.

As climate change fuels the intensification of storms, the need for a more comprehensive understanding of these natural threats becomes increasingly urgent—not merely as an academic pursuit, but as a matter of life and death. Recognizing the detrimental consequences of existing methodologies, this research introduces the Composite Hurricane Impact Scale (CHIS), a novel framework that integrates essential variables beyond wind speed. By incorporating storm surge potential and rainfall-induced flooding into a unified assessment, CHIS offers a more nuanced,

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accurate prediction of a hurricane's multifaceted impacts.This study aims to revolutionize emergency response and public preparedness by addressing the shortcomings of the SSHWS and providing communities with actionable information necessary for better preparedness. Ultimately, our goal is to enhance disaster readiness and foster resilient communities capable of facing the challenges posed by increasingly complex hurricanes. Through this research, we lay the foundation for a future where hurricane predictions can truly encapsulate the magnitude of the danger they represent.

## 2. Overview of the Problem

Hurricanes, formidable forces of nature, pose escalating threats to coastal regions, necessitating a risk assessment that accurately reflects their multifaceted dangers. While the Saffir-Simpson Hurricane Wind Scale (SSHWS) has served as the dominant framework for hurricane categorization since the 1970s, its singular focus on wind speed creates a critical disconnect between forecasted intensity and the true scope of devastation. Storm surge, torrential rainfall, and the sheer size and duration of storms are often the key factors dictating the most catastrophic outcomes. This reality is starkly illustrated by the flood-dominated destruction caused by Hurricanes Harvey (2017) and Sandy (2012). This discrepancy is not merely a scientific oversight; it represents a growing threat to public safety. As climate change intensifies the frequency and severity of hurricanes, the limitations of the SSHWS become increasingly perilous [1][2][3].

### 2.1. The Illusion of Simplicity: A Historical Reliance on the Saffir-Simpson Scale

For decades, the SSHWS has been the primary tool for classifying hurricanes, mainly focusing on sustained wind speeds and categorizing storms into five levels. While the scale's simplicity makes it user-friendly, it neglects other significant hazards like storm surge and heavy rainfall. The limitations of the SSHWS have become particularly evident during events such as Hurricane Harvey and Hurricane Sandy, where flooding was the main cause of destruction rather than high winds. These cases highlight the need for a more comprehensive classification system that accurately reflects the diverse threats hurricanes present[4].

### 2.2. The Critical Need for Accurate Hurricane Risk Communication

Effective risk communication is the cornerstone of preparedness and resilience. The SSHWS's failure to convey the full spectrum of hurricane hazards—including storm surge and rainfall—leaves communities vulnerable to devastating outcomes. A comprehensive framework like the proposed Composite Hurricane Impact Scale (CHIS) is essential for ensuring the public receives clear, actionable information that accurately reflects the threats they face[5].

### 2.3. Objectives, Scope, and Significance: A Call for Comprehensive Assessment

This study aims to address the critical gaps in hurricane risk assessment by: (1) systematically identifying and analyzing the deficiencies of the SSHWS and (2) introducing the CHIS, a holistic framework that integrates wind speed, storm surge, rainfall, and storm size. Our scope includes a thorough evaluation of recent catastrophic hurricanes, focusing on their impacts beyond wind speed, alongside a critical analysis of the SSHWS. The significance of this research lies in its potential to transform hurricane risk communication and emergency management, ultimately improving public safety and resilience. By presenting CHIS, we provide a pathway for more nuanced and accurate hurricane risk assessment, paving the way for future research and enhanced community preparedness[3].

# 3. LITERATURE REVIEW: A CALL FOR CHIS

The SSHWS, while widely recognized, has been increasingly criticized for its singular focus on wind speed, neglecting critical factors like storm surge and rainfall that significantly contribute to hurricane-related fatalities and destruction. This literature review highlights the growing body of research advocating for a more comprehensive approach to hurricane risk assessment, demonstrating the limitations of the SSHWS and the necessity for innovative frameworks like the CHIS. Recent catastrophic hurricanes, including Katrina, Florence, and Harvey, have underscored the urgent need for a classification system that transcends wind speed, prompting a reevaluation of traditional risk assessment concepts and the development of alternative indices.

## 3.1. Reconsidering the Risk Assessment Concept: Addressing Vulnerability

Hollenstein[6]emphasizes the need for improved vulnerability assessments in natural hazard risk evaluations, advocating for standardized impact descriptions to enhance the integration of hazard and vulnerability models. This perspective is particularly relevant to hurricanes, where a focus solely on wind criteria, as evidenced in Katrina, Sandy, and Harvey, fails to capture the multifaceted nature of storm impacts. Hollenstein's work underscores the importance of moving beyond simplistic metrics to understand the complex interplay of factors that contribute to hurricane devastation.

## 3.2. Simulating Hurricane Risk: Advancing Predictive Capabilities

Vickery et al. [7]introduce a storm track modeling technique that links hurricane metrics, such as central pressure, to environmental factors like sea surface temperature. This research significantly advances hurricane risk simulation, providing foundational methodologies for coastal management and urban planning. However, the study also highlights the ongoing need for improved modeling techniques to capture the full complexity of hurricane dynamics, particularly in the context of climate change.

## 3.3. New Storm Surge Scale Proposals: Quantifying Water's Fury

Recognizing the inadequacy of the SSHWS in representing storm surge dynamics, Fitzpatrick et al. [8] propose an innovative storm surge scale that integrates maximum sustained wind, storm size, bathymetry, and translation speed. This proposal directly addresses the critical gap in current hurricane classification systems, focusing on improving predictions and public safety in vulnerable coastal areas. By advocating for an integrated framework, Fitzpatrick et al. contribute to more effective hurricane forecasting and disaster preparedness, laying the groundwork for more comprehensive risk assessments.

## 3.4. Reassessing the Saffir-Simpson Scale: Public Perception and Misunderstanding

Paxton et al. [9]examine the SSHWS's limitations in communicating hurricane risks, highlighting the scale's failure to adequately represent risks such as flooding and storm surge. This leads to public misunderstandings, particularly regarding lower-category storms. The authors advocate for re-evaluating current frameworks and developing user-friendly communication strategies that enhance public understanding and preparedness, emphasizing the need for a more nuanced approach to risk communication.

### 3.5. The Necessity of Alternatives: Toward a More Comprehensive Framework

Kantha [10]argues that the SSHWS no longer meets the challenges posed by increasing hurricane intensity and frequency, exacerbated by climate change. Kantha introduces the Hurricane Intensity Index (HII) and Hurricane Hazard Index (HHI) as continuous metrics that encapsulate maximum wind speed, size, and speed, advocating for a triad of metrics, including total rainfall potential, to enhance disaster preparedness. This research underscores the urgent need for alternatives to the SSHWS, providing a foundation for the development of comprehensive indices like CHIS.

### 3.6. Multidisciplinary Approaches: Integrating Diverse Perspectives

Camelo and Mayo [11]emphasize the critical role of storm surge in hurricane fatalities, highlighting the need for multidisciplinary approaches to risk communication. They argue that addressing storm surge risks requires integrating insights from meteorology, social science, public health, and infrastructure planning. This perspective underscores the complexity of hurricane hazards and the necessity for holistic approaches to community resilience, reinforcing the need for comprehensive frameworks like CHIS.

### 3.7. Evaluating New Hurricane Classification Indices: Validation and Application

Studies evaluating indices like the Hurricane Intensity Index (HII), Hurricane Damage Index (HDI), and Hurricane Surge Index (HSI)[12]against historical data reinforce the need for nuanced classification systems that transcend SSHWS constraints. These evaluations demonstrate the potential of integrated assessments to enhance predictive capabilities and inform emergency management, providing empirical support for the development of CHIS.

### 3.8. Foundations for the CHIS: Integrating Key Factors

The referenced studies collectively provide a robust theoretical and empirical foundation for the CHIS. By integrating wind speed, storm surge, flood potential, and storm size/duration, CHIS aims to address the limitations of the SSHWS and provide a more comprehensive assessment of hurricane impacts. This section outlines the specific methodologies and indices that inform the development of CHIS, including:

3.8.1. Saffir-Simpson Hurricane Wind Scale (SSHWS): Foundation for wind speed assessment[13].
3.8.2. Hurricane Flood Damage Potential (HFDP)[14][15]: Methodologies for assessing flood damage potential.
3.8.3. Storm Surge Analysis: Research on storm surge risk and vulnerability[16][17].
3.8.4. Storm Size and Duration[18] [19]: Studies illustrating the impact of storm size and duration.
3.8.5. Comprehensive Hurricane Impact Scales and Indices[20] [21]: [20] [21]: Foundation for integrated metrics.
3.8.6. Hurricane Risk and Damage Models [22]: Research on damage functions for tropical cyclones.
3.8.7. Alternative Indices: Hurricane Severity Index (HSI)[23]:A nuanced representation of destructive potential.
3.8.8. Alternative Indices: Integrated Kinetic Energy (IKE) Index[3]: Measuring destructive potential via wind field size and intensity.
3.8.9. SSHWS Historical Inclusion of Storm Surge and Rainfall[24]: Understanding the evolution of SSHWS and the need for new indices

# 4. METHODOLOGY

The CHIS is a multidimensional metric that combines four critical components—wind severity, storm surge potential, flood damage potential, and storm size/duration—to provide a holistic assessment of hurricane impact. Each component is derived using scientifically grounded methodologies and scaled from 1 to 5, with weights applied to reflect their relative importance. The CHIS is designed to address the limitations of traditional single-factor hurricane indices, such as the Saffir-Simpson Hurricane Wind Scale, by incorporating the full spectrum of risks posed by hurricanes.

The wind severity component is based on the SSWHS, which categorizes hurricanes by sustained wind speed. Wind remains a critical determinant of structural damage, particularly to buildings and infrastructure [25]. However, the SSWHS has been adapted to account for factors such as gust duration and the extent of the wind field, which are critical for assessing the broader wind impacts of large storms [26].

Storm surge (SS), the abnormal rise of water generated by a storm's winds, is the leading cause of hurricane-related fatalities and coastal property damage. The storm surge potential component integrates variables such as central pressure, forward speed, and bathymetry to estimate the extent of inundation [27]. This metric uses a formula derived from storm surge models validated in peer-reviewed studies, allowing for accurate predictions of coastal impacts.

The flood damage potential (HFDP) metric considers rainfall intensity, storm duration, and topography to estimate the inland flooding risk. Recent hurricanes, such as Harvey (2017), have highlighted the catastrophic damage caused by prolonged rainfall [28]. The HFDP formula combines hydrological modeling and rainfall distribution data to produce a score reflecting potential flood severity, which is critical for areas far from the coast.

The storm size/duration (SD) component accounts for the physical scale of the storm and its movement speed. Larger storms with extensive rain bands and slower forward movement often cause more prolonged and widespread damage, even if their peak winds are moderate [21]. This metric is derived by integrating satellite data, radius of maximum winds, and forward velocity, following methodologies outlined in recent meteorological research.

The CHIS combines these four components using weighted averages that prioritize the elements based on their typical contribution to hurricane impact. For example, storm surge and flood potential are weighted more heavily due to their disproportionate contribution to fatalities and economic losses [29]. By providing a composite score, the CHIS addresses critical gaps in traditional hurricane metrics and offers emergency planners, policymakers, and the public a clearer understanding of a storm's potential impacts. Hypothetical storms were also modeled to test the effectiveness of the proposed CHIS in communicating multivariate risks.

## 4.1.Proposed Supplemental Ratings

### 4.1.1. Wind Speed (SSWHS)

Wind speed is a critical component associated with the structural damage caused by hurricanes. The SSHWS classifies hurricanes based on sustained wind speeds that indicate potential damage [30]. While high winds are responsible for the destruction of buildings, trees, and power lines, relying solely on wind speed can underestimate the overall impact of a hurricane on a community. Research shows that while wind speed is a significant factor influencing damage, it does not account for other life-threatening hazards like storm surge, which can be more devastating, particularly on coastal communities [31]. Thus, a 30% weight reflects its importance without allowing it to dominate the index. Wind is a critical factor in infrastructure damage and loss of life but does not capture the full destructive potential of a storm.

The Suggested Weight is 30%. Wind speed is a traditional measure of hurricane intensity and has a significant impact on infrastructure, trees, and power lines. However, it may not fully capture the storm's total destructive potential, especially when factoring in storm surge or rainfall. Wind speed is critical, but it shouldn't dominate the index. This scale measures the maximum sustained wind speeds of a hurricane and indicates potential wind damage. Categories are 1-5, with higher categories indicating stronger winds and more destructive potential. See Table 1 for SSWHS Category Scale.

Table 1. SSWHS Category Scale[30]

| SSWHS Category | Wind Speed | Description |
|---|---|---|
| 1 | 74-95 mph | Minimal Damage, well-constructed buildings |
| 2 | 96-110 mph | Significant damage, roofs and trees blown down |
| 3 | 111-129 mph | Extensive damage, structure damage likely |
| 4 | 130-156 mph | Catastrophic damage, widespread destruction |
| 5 | 157+ mph | Catastrophic damage, most areas uninhabitable |

### 4.1.2. Storm Surge (SS)

SS is often the leading cause of fatalities and significant property damage in coastal areas during hurricanes. Research indicates that storm surge, a result of high winds pushing water toward the shore, can inundate coastal areas, leading to catastrophic flooding and loss of life [27]. Moreover, surge can disproportionately affect areas with low-lying topography. Because of its critical role in hurricane devastation, a weight of 35% appropriately reflects its severity, capturing its higher risk of fatality and damage compared to wind speed. Multiple studies have been done to more accurately predict the impact of modern storm surge. SS, the water pushed onto land as a hurricane makes landfall, can range from a few feet to over 30 feet. It is life-threatening, fast-moving, and fast-rising, capable of washing away buildings and roadways, which forms the basis of many evacuation orders. SS is not just a coastal hazard. Figure 4 shows examples of SS scenarios to illustrate how far inland storm surge can be pushed and the damages it can cause. SS impacts coastal waters first and continues to push inland. For Hurricane Ian, storm surge reached up to 15 feet at the coast on Fort Myers Beach and was pushed 15 miles inland. Along rivers and waterways, storm surge was pushed up to 24 miles inland, with a depth of up to eight feet. Evacuation orders are issued to move people out of harm's way. Run from the water. Hide from the wind.This scale measures the height of the storm surge, which is the leading cause of hurricane-related fatalities. Categories are 1-5, with higher categories indicating greater storm surge risks. The proposed formula to calculate SS can be found in Equation 1. See Table 2 for SS category scale definitions and Appendix 1 for SS sample calculations.

$$SS = (k_1 \times W \times R \times \sin\theta) + (k_2 \times P) + (k_3 \times F \times CG) \quad (1)$$

$SS$ = Storm Surge Height (feet) (Estimated height of water above normal tide levels)

$W$ = Maximum Sustained Wind Speed (mph) (The driving force behind wind-generated water movement)

$R$ = Radius of Maximum Winds (nautical miles) (Represents the size of the most intense part of the storm)

$sin\theta$=Coastal Angle Factor (accounts for angle between the storm^' s forward motion and coastline.

$P$ = Central Pressure Deficit (in millibars)

$F$ = Forward speed of the storm (mph)

$CG$ = Coastal Geometry / Bathymetry Factor (Accounts for the shape of the coastline and underwater slope

$k_1$, $k_2$, $k_3$ = Empirical Constants (0.005, 0.05, 0.02) (Constants determined through historical data and reflect the relative contributions of wind, pressure and motive to surge height)

$(k_1 \times W \times R \times sin\theta)$ = Wind and Radius Contribution: The product of wind speed, storm size and coastal angle provides the primary energy surge. Larger storms and stronger winds cause more water displacement

$(k_2 \times P)$ = Pressure Deficit Contribution: Low central pressure draws water toward the storm center, contributing to higher surge heights

$(k_3 \times F \times CG)$ = Forwards Speed and Coastal Interaction: Faster-moving storms and favorable coastal

Table 2. Storm Surge (SS) Category Scale[27]

| SS Category | Surge Height | Description |
|---|---|---|
| 1 | <5 feet | Minimal surge, limited threat to coastal areas |
| 2 | 5-7 feet | Moderate surge, some risk to low-lying areas |
| 3 | 7-10 feet | Significant surge, risk to coastal infrastructure |
| 4 | 10-15 feet | Major surge, widespread damage to coastal areas |
| 5 | >15 feet | Extreme Surge, catastrophic flooding and destruction |

$S$ = Storm surge height (feet), $R$ = Rainfall intensity (inches), $P$ = Population density (people per square mile), $I$ = Infrastructure vulnerability (scale of 1-10, where 1 = low vulnerability and 10 = high vulnerability), $F$ = Floodplain exposure factor (scale of 1-5, where 1 = low exposure and 5 = high exposure), $V$ = Value of exposed infrastructure (in million USD).

### 4.1.3. Flood Damage Potential (HFDP)

The flood damage potential (HFDP) metric considers rainfall intensity, storm duration, and topography to estimate the inland flooding risk. Recent hurricanes, such as Harvey (2017), have highlighted the catastrophic damage caused by prolonged rainfall [28]. The HFDP formula combines hydrological modeling and rainfall distribution data to produce a score reflecting potential flood severity, which is critical for areas far from the coast. Flooding contributes to damage well beyond immediate storm surge effects, especially during prolonged rainfall, which can inundate inland areas far from the coast [28]. When hurricanes stall or move slowly, the flooding can become even more severe, leading to long-lasting impacts on infrastructure and communities. Considering rainfall intensity, local population density, and infrastructure vulnerability, the HFDP effectively addresses these critical aspects and warrants a weight of 20%. The cumulative risk of flooding can often outweigh that of wind damage alone, justifying its inclusion in the assessment framework.This scale measures the potential for flooding damage from a hurricane, combining factors such as storm surge, rainfall, and local infrastructure vulnerability. Categories are 1-5, where higher scores indicate greater potential for devastating flooding. The proposed formula to calculate HFDP can be found in Equation 2. See Table 3 for the proposed HFDP category scale and Appendix 2 for variable definitions and sample calculations.

(2) $$HFDP = (S \times R \times P) + (I \times F \times V)$$

Table 3. Flood Damage Potential (HFDP) Category Scale[27]

| HFDP Category | HFDP Score | Damage Potential |
|---|---|---|
| 1 | 0-100,000 | Low Damage Potential, Minimal flooding, localized |
| 2 | 100,001-200,000 | Moderate Damage Potential Moderate flooding, some areas affected |
| 3 | 200,001-350,000 | Significant Damage Potential, Significant flooding, some destruction |
| 4 | 350,001-500,000 | High Damage Potential, Severe flooding, widespread destruction |
| 5 | >500,000 | Extreme Damage Potential Catastrophic flooding, widespread devastation |

### 4.1.4. Storm Size & Duration (SD)

The storm size/duration (SD) component accounts for the physical scale of the storm and its movement speed. Larger storms with extensive rain bands and slower forward movement often cause more prolonged and widespread damage, even if their peak winds are moderate [21]. This metric is derived by integrating satellite data, radius of maximum winds, and forward velocity, following methodologies outlined in recent meteorological research.

Suggested Weight: 15%. Larger storms with extensive wind fields or longer durations can lead to more widespread damage, even if the storm's wind speeds are lower. The size and duration are particularly important in determining how long the storm lasts and the geographic area impacted.

A large, slow-moving storm could produce extended rainfall and flooding, increasing the overall impact. This scale evaluates the size of the hurricane and the duration of its impact, accounting for the storm's wind field and time spent over a given region. Categories are 1-5, where larger and longer-lasting storms result in higher impact scores [19]. Equation 3 shows the proposed formula to calculate SD.

$$Duration(hours) = {Diameter\ of\ Storm\ Impact\ Area\ (miles)} \Big/ {Forward\ Speed\ (miles\ per\ hour)} \quad (3)$$

Table 4. Example SD Calculation

| **Example Storm Variables** |
|---|
| Hurricane Example: Radius of Winds: ~230 miles; Forward Speed at Landfall: ~15 mph |
| Equation (3): $Duration^{Example} = \frac{(2*34.5)}{15} = \frac{69}{15} = 4.6\ hours$ |

Table 5. Storm Size & Duration (SD) Category Scale[21]

| SD Category | Size (Wind Radius) | Duration (Over Area) | Description |
|---|---|---|---|
| 1 | <50 miles | <6 hours | Small & Brief: Small storm with short duration, minimal impact over a localized area |
| 2 | 50-100 miles | 6-12 hours | Moderate Size & Duration: Medium-sized storm with moderate duration, some regional impact |
| 3 | 100-200 miles | 12-24 hours | Large & Moderate: Large Storm with significant impact in a broad regional for at least one full day |
| 4 | 200-300 miles | 24-36 hours | Very Large & Long Duration: Very Large storm causing significant impact for more than one full day |
| 5 | >300 miles | >36 hours | Massive & Prolonged: Extremely large storm with prolonged duration, extension regional and local impacts |

### 4.1.5. Comprehensive Hurricane Index Score (CHIS)

The SSHWS, while effective in its simplicity, is limited in scope. Hurricanes are complex systems that inflict damage through a combination of wind, water, and persistence. By adopting alternative or supplemental ratings like those proposed here, the author attempts to provide a more accurate and actionable assessment of hurricane risks. This improved understanding would empower individuals, communities, and governments to take more informed and effective action, potentially saving lives and mitigating damage in the face of these powerful natural disasters. See Equation 4 for the proposed formula to calculate overall CHIS, with Table 6 providing an example on how to calculate.

$$CHIS = (SSWHS \times 0.3) + (SS \times 0.35) + (HFDP \times 0.2) + (SD \times 0.15) \quad (4)$$

Table 6. Example CHIS Calculation

| **Hurricane X** |
|---|
| SSWHS: Category 2 (Wind Speed: 105 mph) ‣ Score = 2; HFDP: Catastrophic flooding (375,000) ‣ Score = 4; SS: Extreme storm surge (11 feet) ‣ Score = 4; SD: Massive, prolonged storm (250 miles, 26 hrs.) ‣ Score = 4 |
| Equation (4): (SSWHS×0.3) + (SS×0.35) + (HFDP×0.2) + (SD×0.15) = (2×0.3) + (4×0.35) + (4×0.2) + (4×0.15) = 0.6+1.4+0.8+0.6 = **3.4** |

Higher scores indicate more severe hurricanes, with potential for greater loss of life, damage to infrastructure, and long-term impacts on communities. The CHIS score can inform emergency response, resource allocation, and long-term recovery planning for affected areas. For each hurricane, the individual scores for SSWHS, Storm Surge, HFDP, and Storm Size & Duration are calculated as described in earlier examples. Then, the overall CHIS score is computed by applying the weights to each component. See Tables 7 and 8 for proposed CHIS category scale and example reporting.

Table 7. CHIS Category Scale[29]

| Category | Score Range | Description |
|---|---|---|
| 1 | 1.0  1.9 | Minimal threat with limited impact |
| 2 | 2.0 - 2.9 | Moderate threat, some damage in localized areas |
| 3 | 3.0 - 3.75 | Significant impact, widespread damage in many regions |
| 4 | 3.75 - 4.50 | Severe impact with extensive damage across large areas |

Table 8. Example CHIS Reporting.

| $\boldsymbol{KATRINA^{CHIS}}$ |
|---|
| Equation (5) = CHIS \|( SSWHS \|SS \| HFDP \| SD ) = $\mathbf{4.85}^{\boldsymbol{CHIS}}$\|$5^{\mathrm{SSWHS}}$ \| $5^{\mathrm{SS}}$ \| $5^{\mathrm{HFDP}}$ \| $4^{\mathrm{SD}}$ \| |
| Thus, Hurricane Katrina would score 4.85 / 5.0 on the CHIS, indicating predicted catastrophic damage, widespread devastation and loss of life. |

#### 4.1.6. Data Sources for CHIS.

To calculate the CHIS factors accurately, reliable and robust data sources are necessary. Appendix 3 is a list of recommended data sources for each component of CHIS. By combining data from these sources, the CHIS can be calculated accurately and validated with historical events. The transparency and reliability of these datasets ensure that CHIS scores can provide actionable insights for planning and risk management.

## 5. RESULTS: VALIDATING THE CHIS FRAMEWORK

To assess the effectiveness and applicability of the Composite Hurricane Impact Scale (CHIS), experimental data was calculated using the proposed equations for a range of historical hurricanes, spanning various categories on the Saffir-Simpson Hurricane Wind Scale (SSHWS). This analysis aimed to demonstrate the CHIS's ability to provide a comprehensive and nuanced assessment of hurricane impacts, addressing the limitations of single-factor indices. By assigning weighted values to each component—wind severity, storm surge potential, flood damage potential, and storm size/duration—the CHIS formula was systematically applied to each selected hurricane. This process generated a quantifiable impact score, allowing for a consistent and comparative evaluation of each storm's overall severity.

The use of the CHIS framework not only standardizes the evaluation of hurricane impacts but also offers a clearer understanding of the relative severity and potential damage of each event. This methodology underscores the robustness and practical applicability of the CHIS in enhancing our comprehension of hurricane impacts, moving beyond the limitations of the SSHWS. The insights gained from this analysis are invaluable for future hurricane prediction and mitigation strategies. Equations 1-4 were utilized to calculate the respective component values and the final CHIS scores.

### 5.1. Storm Surge (SS) Calculations (Table 9)

Table 9 presents the calculated storm surge (SS) values for each selected hurricane, using the proposed formula and empirical constants. The table includes key parameters such as wind speed, radius of maximum winds, coastal angle, pressure deficit, forward speed, and coastal geometry. The resulting SS values, categorized from 2 (Moderate) to 5 (Extreme), demonstrate the variability in storm surge impacts across different hurricanes, highlighting the importance of considering multiple factors beyond wind speed.

Table 9. SS Calculations (Empirical Constants $k_1$=0.005, $k_2$=0.05, $k_3$=0.02)

| | Wind Speed | Radius of Max Winds | Coastal Angle | Pressure Deficit | Forward Speed | Coastal Geometry | SS | SS Category |
|---|---|---|---|---|---|---|---|---|
| Katrina (2005) | 120 mph | 30 n.m. | 90° | 50 mb | 10 mph | 1.2 (shallow shelf) | 20.74 feet | 5 (Extreme) |
| Harvey (2017) | 130 mph | 20 n.m. | 60° | 40 mb | 7 mph | 1.0 | 13.39 feet | 4 (Major) |
| Idalia (2023) | 100 mph | 25 n.m. | 50° | 45 mb | 14 mph | 1.3 (shallow shelf) | 12.189 feet | 4 (Major) |
| Sandy (2012) | 90 mph | 60 n.m. | 30° | 60 mb | 28 mph | 1.4 (shallow shelf) | 17.284 feet | 5 (Extreme) |
| Otis (2023) | 150 mph | 20 n.m. | 40° | 70 mb | 18 mph | 1.5 (shallow shelf) | 13.69 feet | 4 (Major) |
| Helene (2018) | 85 mph | 25 n.m. | 30° | 40 mb | 12 mph | 1.2 | 7.60 feet | 3 (Significant) |
| Irene (2011) | 115 mph | 20 n.m. | 40° | 50 mb | 15 mph | 1.1 | 10.22 feet | 4 (Major) |
| Agnes (1972) | 75 mph | 15 n.m. | 60° | 30 mb | 10 mph | 1.0 | 6.57 feet | 2 (Moderate) |
| Joaquin (2015) | 140 mph | 25 n.m. | 30° | 50 mb | 12 mph | 1.3 | 11.56 feet | 4 (Major) |
| Claudette (1979) | 85 mph | 20 n.m. | 40° | 35 mb | 14 mph | 1.0 | 7.50 feet | 3 (Significant) |
| Dora (1964) | 110 mph | 25 n.m. | 30° | 40 mb | 12 mph | 1.2 | 9.16 feet | 3 (Significant) |

## 5.2. Flood Damage Potential (HFDP) Calculations (Table 10)

Table 10 presents the calculated flood damage potential (HFDP) values for each hurricane, incorporating factors such as storm surge, rainfall, population density, infrastructure vulnerability, floodplain exposure, and the value of exposed infrastructure. The resulting HFDP scores, categorized from 1 (Low) to 5 (Extreme), illustrate the varying degrees of flood risk associated with each storm, emphasizing the importance of considering inland flooding in hurricane risk assessment.

Table 10. HFDP Calculations for Historical Hurricanes

| | Storm Surge, feet (S) | Rainfall, inches (R) | Population Density (P) people/ mi$^2$ | Infrastructure Vulnerability (I) | Floodplain Exposure (F) | Value of Exposed Infrastructure (V) | HFDP | HFDP Category |
|---|---|---|---|---|---|---|---|---|
| Katrina (2005) | 20.74 feet | 20 | 1,500 | 9 | 5 | $1000M | 667,200 | 5 (Extreme) |
| Harvey (2017) | 13.39 feet | 25 | 1,2000 | 7 | 5 | $800M | 427,570 | 4 (High) |
| Idalia (2023) | 12.189 feet | 18 | 1,000 | 6 | 4 | $600M | 236,202 | 2 (Moderate) |
| Sandy (2012) | 17.284 feet | 12 | 1,300 | 8 | 5 | $900M | 310,318 | 4 (High) |
| Otis (2023) | 13.69 feet | 15 | 1,000 | 8 | 4 | $500M | 221,275 | 3 (Significant) |
| Helene (2018) | 7.60 feet | 10 | 800 | 6 | 3 | $300M | 66,208 | 1 (Low) |
| Irene (2011) | 10.22 feet | 12 | 1200 | 7 | 4 | $400M | 158,354 | 2 (Moderate) |
| Agnes (1972) | 6.57 feet | 8 | 600 | 5 | 3 | $200M | 34,522 | 1 (Low) |
| Joaquin (2015) | 11.56 feet | 14 | 1100 | 9 | 5 | $450M | 199,053 | 2 (Moderate) |
| Claudette (1979) | 7.50 feet | 9 | 700 | 6 | 3 | $250M | 51,756 | 1 (Low) |
| Dora (1964) | 9.16 feet | 11 | 900 | 7 | 4 | $250M | 100,601 | 2 (Moderate) |

## 5.3. Storm Size & Duration (SD) Calculations (Table 11)

Table 11 presents the calculated storm size and duration (SD) ratings, considering the diameter of the storm and its forward speed. The resulting SD ratings, categorized from 3 (Large & Moderate) to 5 (Massive & Prolonged), highlight the impact of storm size and duration on overall hurricane severity.

Table 11. SD Calculations for Historical Hurricanes

| | Storm Size (miles) | Category | Diameter (miles) | Forward Speed (mph) | Duration | Category | SD Description | SD Rating |
|---|---|---|---|---|---|---|---|---|
| **Katrina (2005)** | 230 | 4 (Very Large) | 460 | 15 | 30.6 hours | 4 (Long Duration) | **4 (Very Large & Long)** | **4** |
| **Harvey (2017)** | 175 | 3 (Large) | 350 | 7 | 50 hours | 5 (Prolonged) | **3 (Large) + 5(Prolonged)** | (3+5)/2 = **4** |
| **Idalia (2023)** | 109 | 3 (Large) | 218 | 14 | 15.6 hours | 3 (Moderate) | **3 (Large & Moderate)** | **3** |
| **Sandy (2012)** | 404 | 5 (Massive) | 808 | 28 | 28.9 hours | 4 (Long Duration) | **5 (Massive) + 4(Long)** | (5+4)/2 = **4.5** |
| **Ian (2022)** | 140 | 3 (Large) | 280 | 9 | 31.1 hours | 4 (Long Duration) | **3(Large) & 4 (Long)** | (3+4)/2 = **3.5** |
| **Irene (2011)** | 220 | 4 (Very Large) | 440 | 20 | 22 hours | 3 (Moderate) | **4 (Very Large) +3 (Moderate)** | **(4+3)/2 = 3.5** |
| **Agnes (1972)** | 2000 | 5 (Massive) | 4000 | 15 | 266.7 | 5 (Prolonged) | **5 (Massive & Prolonged)** | **5** |
| **Joaquin (2015)** | 150 | 3 (Large) | 300 | 15 | 20 | 3 (Moderate) | **3 (Large & Moderate)** | **3** |
| **Claudette (1979)** | 200 | 3 (Large) | 400 | 15 | 26.7 | 4 (Long Duration) | **3(Large) & 4 (Long)** | (3+4)/2 = **3.5** |
| **Dora (1964)** | 150 | 3 (Large) | 300 | 15 | 20 | 3 (Moderate) | **3 (Large & Moderate)** | **3** |

## 5.4. CHIS Calculations: Demonstrating Enhanced Predictive Power (Table 12)

Table 12 presents the final CHIS scores for each hurricane, calculated by integrating the weighted component scores. The results demonstrate that CHIS provides a more nuanced and accurate assessment of hurricane severity compared to the SSHWS. Notably, hurricanes like Harvey and Sandy, which caused extensive damage due to flooding and storm surge, received CHIS scores that accurately reflected their devastating impacts, despite their lower SSHWS categories. This highlights the CHIS's ability to capture the complex interplay of factors that contribute to hurricane damage.

Table 12, CHIS Calculations for Historical Hurricanes[35][36][2][37][38][39][40]

| | SSWHS (30%) | SS (35%) | HFDP (20%) | SD (15%) | CHIS | CHIS Category |
|---|---|---|---|---|---|---|
| **Katrina (2005)** | 5 | 5 | 5 | 4 | **4.85** | **Catastrophic** |
| **Harvey (2017)** | 4 | 4 | 4 | 4.5 | **4.08** | **Severe** |
| **Idalia (2023)** | 3 | 4 | 2 | 3 | **3.15** | **Significant** |
| **Sandy (2012)** | 3 | 5 | 4 | 4.5 | **4.13** | **Severe** |
| **Irene (2011)** | 3 | 4 | 2 | 3.5 | **3.23** | **Significant** |
| **Agnes (1972)** | 1 | 2 | 1 | 5 | **1.95** | **Minimal** |
| **Joaquin (2015)** | 4 | 4 | 2 | 3 | **3.45** | **Significant** |
| **Claudette (1979)** | 1 | 3 | 1 | 3.5 | **2.08** | **Moderate** |
| **Dora (1964)** | 4 | 3 | 2 | 3 | **3.10** | **Significant** |

### 5.5. Key Observations and Implications: Validating the CHIS as a Tool for Enhanced Risk Communication and Preparedness

The results from this analysis provide compelling evidence of the CHIS's effectiveness in providing a more comprehensive and accurate assessment of hurricane impacts. By integrating multiple factors beyond wind speed, CHIS offers a more realistic representation of the threats posed by hurricanes. This is particularly evident in the case of storms like Harvey and Sandy, where the CHIS scores accurately reflect the widespread damage caused by flooding and storm surge, which the SSHWS fails to capture adequately.

The CHIS framework serves as a valuable tool for emergency planners, policymakers, and the public, enabling more informed decision-making and improved preparedness. By providing a more nuanced understanding of hurricane risks, CHIS can enhance risk communication and ultimately save lives and protect property.

This research represents a crucial step in advancing hurricane risk assessment. However, further validation and refinement are essential. Future studies will focus on gathering more real-world data from past and current hurricanes, collaborating with agencies like NOAA and FEMA. Additionally, public feedback will be collected through surveys to identify potential areas for improvement and ensure the CHIS effectively communicates hurricane risks to diverse audiences. The goal is to continuously refine and validate the CHIS, establishing it as a reliable and actionable tool for hurricane risk management and mitigation.

## 6. Discussion: CHIS as a Paradigm Shift

The CHISrepresents a paradigm shift in how we measure and communicate hurricane impacts. Unlike the SSHWS, which is limited to sustained wind speeds, CHIS integrates critical factors such as storm surge, rainfall, and storm size/duration, providing a comprehensive and nuanced understanding of a hurricane's potential devastation. This holistic approach directly addresses the shortcomings of the SSHWS, offering a more accurate and actionable assessment of hurricane risks.

The necessity for a more comprehensive assessment tool has been underscored by recent catastrophic hurricanes that have exposed the limitations of the SSHWS. Events like Hurricane Harvey (2017), with its unprecedented rainfall and flooding, and Hurricane Sandy (2012), despite its Category 1 classification, with its devastating storm surge, highlight the critical need to consider factors beyond wind speed. CHIS directly responds to these challenges by providing a multi-dimensional framework that captures the complex interplay of factors contributing to hurricane impacts.

By incorporating storm surge potential, CHIS provides a more accurate assessment of coastal inundation, which is often the leading cause of hurricane-related fatalities and property damage. The inclusion of rainfall intensity and storm duration enhances the scale's ability to predict inland flooding, as demonstrated by the prolonged rainfall and subsequent flooding during Hurricane Harvey. Furthermore, the addition of storm size/duration allows for a better understanding of the broader impacts of larger storms, which can affect a wider area and cause prolonged damage[17][15][21].

CHIS aims to improve public awareness and disaster preparedness by providing a clearer and more comprehensive picture of the multifaceted risks posed by hurricanes. Emergency response teams can leverage CHIS for more effective resource allocation and evacuation planning, while policymakers can use it to develop better-informed strategies for building resilient infrastructure and implementing mitigation measures. Additionally, CHIS serves as a valuable tool for scientific research, providing a framework for analyzing the impacts of future hurricanes and enhancing our understanding of how different factors contribute to overall hurricane damage. The scale's multidimensional nature allows for more nuanced risk communication, which is crucial in the context of climate change and increasing hurricane activity[16].

In essence, CHIS represents a significant advancement over the SSHWS by addressing its limitations and providing a more comprehensive assessment of hurricane impacts. By integrating wind severity, storm surge potential, flood damage potential, and storm size/duration, CHIS offers a holistic view of hurricane risks, enhancing emergency response, public awareness, and disaster preparedness. This research lays the groundwork for future studies to refine and validate CHIS, ultimately contributing to more effective hurricane risk management and mitigation efforts.

## 6.1. Final CHIS Ratings & Interpretations: Real-World Validation and Insights

To validate the CHIS framework, we applied it to a range of historical hurricanes, demonstrating its ability to capture the diverse impacts of these storms. Each case study provides valuable insights into the strengths and potential refinements of CHIS.

$$AGNES^{CHIS} = \mathrm{CHIS}\ |(\ \mathrm{SSWHS}\ |\mathrm{SS}\ |\ \mathrm{HFDP}\ \big|\ \mathrm{SD}\ ) = \mathbf{1.95}^{\boldsymbol{CHIS}}\big|1^{\mathrm{SSWHS}}\big|2^{\mathrm{SS}}\big|1^{\mathrm{HFDP}}\big|5^{\mathrm{SD}}\big|$$

Hurricane Agnes (1972): Despite its Category 1 status, Agnes caused widespread flooding. CHIS, with a low overall score (1.95) but a high SD rating (5), highlights the importance of considering storm size and duration, even in lower-category storms. This underscores the need for a comprehensive assessment that goes beyond wind speed[42].

$$CLAUDETTE^{CHIS} = \ \mathrm{CHIS}\big|\ = \mathbf{2.08}^{\boldsymbol{CHIS}}\big|1^{\mathrm{SSWHS}}\big|3^{\mathrm{SS}}\big|1^{\mathrm{HFDP}}\big|3.5^{\mathrm{SD}}\big|$$

Tropical Storm Claudette (1979): Claudette's record-setting rainfall and flooding, despite its tropical storm status, are accurately reflected in CHIS's higher storm surge and SD ratings. This demonstrates CHIS's ability to capture the impact of non-wind-related hazards[43].

$$DORA^{CHIS} = \ \mathrm{CHIS}\ \big| = \mathbf{3.10}^{\boldsymbol{CHIS}}\big|4^{\mathrm{SSWHS}}\big|3^{\mathrm{SS}}\big|2^{\mathrm{HFDP}}\big|3^{\mathrm{SD}}\big|$$

Hurricane Dora (1964): The CHIS rating of 3 for storm surge, coupled with the overall CHIS rating, would have provided better warning of the flooding risks, complementing the SSHWS's wind-focused warning.[44].

$$IDALIA^{CHIS} = \mathrm{CHIS}\ \big|= \mathbf{3.15}^{\boldsymbol{CHIS}}\big|3^{\mathrm{SSWHS}}\big|4^{\mathrm{SS}}\big|2^{\mathrm{HFDP}}\big|3^{\mathrm{SD}}\big|$$

Hurricane Idalia (2023): CHIS's storm surge rating of 4 accurately predicted the extensive flooding risks, highlighting the scale's effectiveness in providing timely and accurate warnings[45][46].

$$IRENE^{CHIS} = \mathrm{CHIS}\ \big|\ = \mathbf{3.23}^{\boldsymbol{CHIS}}\big|3^{\mathrm{SSWHS}}\big|4^{\mathrm{SS}}\big|2^{\mathrm{HFDP}}\big|3.5^{\mathrm{SD}}\big|$$

Hurricane Irene (2011): CHIS's multi-factor ratings, including a storm surge rating of 4 and an SD rating of 3.5, provide a more comprehensive understanding of Irene's potential impact, demonstrating the scale's ability to capture the complexities of hurricane risks.[47][48].

$$JOAQUIN^{CHIS} = \ C\mathrm{HIS}\ \big| = \mathbf{3.45}^{\boldsymbol{CHIS}}\big|4^{\mathrm{SSWHS}}\big|4^{\mathrm{SS}}\big|2^{\mathrm{HFDP}}\big|3^{\mathrm{SD}}\big|$$

Hurricane Joaquin (2015): CHIS's storm surge and SD ratings accurately predicted the severe flooding caused by prolonged rainfall, emphasizing the scale's ability to capture inland flooding risks[49].

$$HARVEY^{CHIS} = \text{CHIS}\big| = \mathbf{4.08}^{\boldsymbol{CHIS}}\big|4^{\text{SSWHS}}\big|4^{\text{SS}}\big|4^{\text{HFDP}}\big|4.5^{\text{SD}}\big|$$

Hurricane Harvey (2017): CHIS's high ratings for storm surge, HFDP, and SD, along with its overall score, accurately reflect the catastrophic flooding and widespread damage caused by Harvey, demonstrating the scale's ability to capture the multifaceted impacts of major hurricanes[40].

$$SANDY^{CHIS} = \text{CHIS}\,\big| = \mathbf{4.13}^{\boldsymbol{CHIS}}\big|3^{\text{SSWHS}}\big|5^{\text{SS}}\big|4^{\text{HFDP}}\big|4.5^{\text{SD}}\big|$$

Superstorm Sandy (2012): CHIS's high ratings for storm surge, HFDP, and SD accurately reflect Sandy's devastating impacts, highlighting the scale's ability to capture the complexities of post-tropical cyclones[50]

$$KATRINA^{CHIS} = \text{CHIS}\,\big| = \mathbf{4.85}^{\boldsymbol{CHIS}}\big|5^{\text{SSWHS}}\big|5^{\text{SS}}\big|5^{\text{HFDP}}\big|4^{\text{SD}}\big|$$

Hurricane Katrina (2005): CHIS's nearly maximum score accurately reflects the catastrophic damage caused by Katrina, demonstrating the scale's ability to capture the full spectrum of hurricane impacts[51].

## 6.2. Comparing Proposed Storm Surge Formula Against Actual Historical Data: Validating Predictive Accuracy

The validation of the proposed storm surge formula (Eq. 1) against historical data is crucial for assessing its accuracy and reliability. While weather prediction is inherently prone to inaccuracies, the performance of our formula falls within acceptable ranges, demonstrating its potential utility.

Our analysis revealed an average inaccuracy range of 8-17%, which is within the typical accuracy range for weather forecasts, especially considering the limitations of an original formula developed with limited research and resources. For example, the inaccuracy percentages for storms such as Hurricane Harvey (11.58%) and Hurricane Sandy (8.02%) fall within acceptable ranges[52][53].

However, the outlier, Hurricane Katrina, with a 25.93% inaccuracy, highlights the need for further refinement and adjustment of weights based on specific contexts and unique scenarios. Despite this anomaly, the overall performance of the formula demonstrates its potential validity and provides a solid foundation for further development.

Table 12. Comparison of calculated Storm Surge and Actual Measured Storm Surge

| | SS | SS Category | Estimated Actual | Δ | % Inaccuracy |
|---|---|---|---|---|---|
| **Katrina (2005)** | 20.74 feet | **5 (Extreme)** | **28** | ***7.26*** | 25.93% |
| **Harvey (2017)** | 13.39 feet | **4 (Major)** | **12** | ***-1.39*** | 11.58% |
| **Idalia (2023)** | 12.189 feet | **4 (Major)** | **10.75** | ***-1.439*** | 13.39% |
| **Sandy (2012)** | 17.284 feet | **5 (Extreme)** | **16** | ***-1.284*** | 8.02% |
| **Otis (2023)** | 13.69 feet | **4 (Major)** | **11.8** | ***-1.89*** | 16.02% |
| **Helene (2018)** | 7.60 feet | **3 (Significant)** | **6.5** | ***-1.1*** | 16.92% |
| **Irene (2011)** | 10.22 feet | **4 (Major)** | **9** | ***-1.22*** | 13.56% |
| **Agnes (1972)** | 6.57 feet | **2 (Moderate)** | **6** | ***-0.57*** | 9.50% |
| **Joaquin (2015)** | 11.56 feet | **4 (Major)** | **12.5** | ***0.94*** | 7.52% |
| **Claudette (1979)** | 7.50 feet | **3 (Significant)** | **8** | ***0.5*** | 6.25% |
| **Dora (1964)** | 9.16 feet | **3 (Significant)** | **8.1** | ***-1.06*** | 13.09% |

### 6.3. Supposition: CHIS as a Tool for Enhanced Disaster Resilience

The comparison of these hurricanes underscores the diverse and multifaceted impacts that wind speed, storm surge, rainfall, and coastal geography have on communities. CHIS effectively captures these varied factors, providing a comprehensive assessment of storm risks. By integrating storm surge, flood damage potential (HFDP), size, and duration, CHIS offers a more holistic understanding of hurricane impacts, which is crucial for effective disaster preparedness and mitigation efforts.

The cases of Superstorm Sandy and Hurricane Katrina, with their maximum ratings for storm surge and significant HFDP values, illustrate the potential for better forecasting and preparation that CHIS could provide. Furthermore, the ability of CHIS to account for prolonged rainfall and storm size, as seen in the evaluations of Harvey and Joaquin, further reinforces its value.

Overall, the CHIS framework demonstrates that a more detailed and multifactorial approach to hurricane assessment can significantly improve our ability to predict and mitigate the diverse dangers associated with these natural disasters. This research validates the concept and highlights the importance of further development and application of the proposed method, ultimately contributing to enhanced public safety and disaster resilience.

### 6.4. Future Directions

To further refine and validate the CHIS, future research should focus on several key activities. First, we aim to gather more real-world data from past and current hurricanes by collaborating with agencies such as NOAA and FEMA. This data will enhance the robustness of CHIS. Additionally, we will conduct sensitivity analyses to optimize the weighting of CHIS components, ensuring their contribution reflects the actual impact of hurricanes more accurately. Another important aspect of our research will be the development of user-friendly tools and visualizations that effectively communicate CHIS information to diverse audiences. To improve the system continually, we will also collect public feedback through surveys, allowing us to identify potential areas for enhancement and ensure that CHIS communicates hurricane risks effectively. Furthermore, we will investigate the integration of climate change projections into CHIS to account for future hurricane trends. Through these efforts, we aim to establish CHIS as a reliable and actionable tool for hurricane risk management and mitigation. For a detailed overview of proposed adjustments to the weights based on specific contexts, please refer to Appendix 4.

## 7. LIMITATIONS AND FUTURE RESEARCH DIRECTIONS

While the CHIS demonstrates significant promise in providing a more comprehensive assessment of hurricane impacts, it is essential to acknowledge its limitations and outline future research directions.

### 7.1. Limitations of the CHIS Framework

Weighting of Components: The CHIS relies on weighted averages to combine its four components. While these weights were determined based on typical contributions to hurricane impact, they may not be universally applicable. Future research should explore sensitivity analyses to optimize these weights and consider regional variations.

Data Availability and Accuracy: The accuracy of CHIS calculations depends on the availability and quality of input data, such as storm surge heights, rainfall amounts, and storm size. Data limitations or inaccuracies can affect the reliability of CHIS scores.

Complexity of Hurricane Dynamics: Hurricanes are complex meteorological phenomena, and CHIS, while comprehensive, may not capture all the nuances of their behavior. Future research should explore the integration of additional factors, such as vertical wind shear and atmospheric instability, to further enhance the scale's accuracy.

Subjectivity in Categorization: While the CHIS provides a quantitative score, the categorization of hurricanes into discrete levels (1-5) involves a degree of subjectivity. Future research should explore the development of continuous or probabilistic CHIS scores to provide a more nuanced representation of hurricane risks.

Public Understanding and Communication: Effectively communicating the complexities of CHIS to the public is crucial for its successful implementation. Future research should focus on developing user-friendly tools and visualizations to enhance public understanding and facilitate informed decision-making.

Climate Change Integration: While the discussion highlights the importance of climate change, the current CHIS framework does not explicitly integrate climate change projections. Future research should explore the incorporation of climate models and sea-level rise scenarios to account for future hurricane trends.

Lack of direct economic damage calculation: While the HFDP contributes to an understanding of economic damage, the CHIS does not have a direct economic damage calculation. Future research should include a method to directly estimate potential economic damages.

### 7.2. Future Research Directions

To address these limitations and further refine CHIS, future research should focus on the following areas:

Enhanced Data Gathering and Validation: Collaborate with agencies like NOAA and FEMA to gather more real-world data from past and current hurricanes, ensuring the accuracy and reliability of CHIS calculations.

Sensitivity Analyses and Weight Optimization: Conduct sensitivity analyses to optimize the weighting of CHIS components, considering regional variations and specific storm characteristics.

Integration of Additional Factors: Explore the integration of additional factors, such as vertical wind shear, atmospheric instability, and climate change projections, to further enhance the scale's accuracy.

Development of Continuous or Probabilistic CHIS Scores: Investigate the development of continuous or probabilistic CHIS scores to provide a more nuanced representation of hurricane risks.

User-Friendly Tools and Visualizations: Develop user-friendly tools and visualizations to enhance public understanding and facilitate informed decision-making.

Public Feedback and Education: Collect public feedback through surveys and educational initiatives to identify potential areas for improvement and ensure CHIS effectively communicates hurricane risks to diverse audiences.

Economic Damage Modeling: Create a method to directly calculate potential economic damages and include this calculation within the CHIS framework.

Regional Specific CHIS development: Create region specific versions of the CHIS, that would account for the different variables that impact different regions.

## 8. CONCLUSION: CHIS AS A TOOL FOR ENHANCED DISASTER RESILIENCE

The Composite Hurricane Impact Scale (CHIS) represents a significant advancement in hurricane risk assessment, offering a holistic and nuanced understanding of hurricane impacts that transcends the limitations of the Saffir-Simpson Hurricane Wind Scale (SSHWS). By integrating critical factors such as storm surge, rainfall, and storm size/duration, CHIS provides a more accurate and actionable assessment of hurricane risks, enabling improved emergency response, public awareness, and disaster preparedness.

The validation of CHIS with historical hurricanes demonstrates its ability to capture the complex interplay of factors that contribute to hurricane damage, highlighting its potential to enhance risk communication and inform decision-making. While CHIS has limitations, future research efforts will focus on refining and validating the scale, ensuring its reliability and applicability in diverse contexts.

Ultimately, CHIS serves as a valuable tool for building disaster resilience, empowering communities to better prepare for and mitigate the devastating impacts of hurricanes. By continuously refining and validating CHIS, we aim to establish it as a reliable and actionable tool for hurricane risk management and mitigation, ultimately saving lives and protecting property.

## 9. ACKNOWLEDGEMENTS

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# 11. APPENDICES

## 11.1. Appendix 1 – SS - Sample Calculations

Table 13. Sample Storm Variables.

| Example Storm Variables |
|---|
| 120 mph, Radius of Maximum Winds = 30 nautical miles, Coastal Angle = 1 (direct hit), Pressure Deficit = 50 mb, Forward Speed = 10 mph, Coastal Geometry = 1.2 (shallow shelf), Empirical Constants ($k_1$=0.005, $k_2$=0.05, $k_3$=0.02) |

Table 14. Example SS Calculation.

| Utilizing Equation (1) |
|---|
| $SS^{Example} = (0.005 \times 120 \times 30 \times 1) + (0.05 \times 50) + (0.02 \times 10 \times 1.2) = 18 + 2.5 + 0.24 = 20.74\ feet$ |

## 11.2. Appendix 2 – HFDP - Equation 1 Variables Definitions and Sample Calculations

Table 15. Sample Storm Data

| Example Storms |
|---|
| Example 1: Hurricane A (Category 3 Storm) - Storm Surge (S): 10 feet; Rainfall (R): 12 inches; Population Density (P): 2,500 people per square mile; Infrastructure Vulnerability (I): 7 (high vulnerability, older buildings); Floodplain Exposure (F): 4 (significant exposure in coastal flood zones). Value of Exposed Infrastructure (V): 500 million USD |
| Example 2: Hurricane B (Category 1 Storm) - Storm Surge (S): 5 feet; Rainfall (R): 6 inches; Population Density (P): 1,200 people per square mile; Infrastructure Vulnerability (I): 5 (moderate vulnerability, newer infrastructure); Floodplain Exposure (F): 2 (moderate exposure). Value of Exposed Infrastructure (V): 100 million USD |

Table 16. Example HFDP Calculations

| Utilizing Equation (2) |
|---|
| $HFDP^{Hurricane\ A} = (S\times R\times P) + (I\times F\times V) = (10*12*2500) + (7*4*500) = 314{,}000$ |
| $HFDP^{Hurricane\ B} = (S\times R\times P) + (I\times F\times V) = (5*6*1200) + (5*2*100) = 37{,}000$ |

Interpretation of Results: The HFDP values represent the relative potential damage to an area from flooding during a hurricane. Higher values indicate more severe damage, which can guide emergency response, resource allocation, and long-term recovery planning. Hurricane A has a higher damage potential (314,000 points) due to its stronger storm surge, greater rainfall, and higher population and infrastructure vulnerability. Hurricane B has a lower damage potential (37,000 points) but could still lead to significant localized damage depending on its impact on infrastructure and flood-prone areas [15].

## 11.3. Appendix 3 – Data Sources

| | |
|---|---|
| Wind Severity (Saffir-Simpson Hurricane Wind Scale - SSWHS) | • National Hurricane Center (NHC): Provides real-time and historical data on sustained winds, gust speeds, and wind field size for hurricanes. Website: https://www.nhc.noaa.gov<br>• Hurricane Research Division (HRD): Offers detailed hurricane wind analyses using H*Wind products. Website: https://www.aoml.noaa.gov/hrd<br>• NOAA Historical Hurricane Tracks Database: Contains historical wind speed data for Atlantic and Eastern Pacific hurricanes. Website: https://coast.noaa.gov/hurricanes |
| Storm Surge Potential | NOAA Storm Surge Database: Includes real-time storm surge observations, forecasts, and historical data. Website: https://www.nhc.noaa.gov/surge<br>• SLOSH (Sea, Lake, and Overland Surges from Hurricanes) Model: Provides storm surge estimates using storm parameters (pressure, size, speed, etc.).<br>Website: https://www.nhc.noaa.gov/surge/slosh.php<br>• USGS Coastal and Marine Hazards and Resources Program: Provides coastal inundation data for specific hurricanes.<br>Website: https://www.usgs.gov/centers/coastal-and-marine-hazards-and-resources-program |
| Flood Damage Potential (HFDP) | National Weather Service (NWS) Advanced Hydrologic Prediction Service: Offers rainfall accumulation data during storms. Website: https://water.weather.gov/precip<br>• NOAA Precipitation Frequency Data Server (PFDS): Includes rainfall return period statistics. Website: https://hdsc.nws.noaa.gov/hdsc/pfds<br>• USGS Flood Event Viewer: Real-time and historical flood stage data. Website: https://stn.wim.usgs.gov/FEV/<br>• NASA Global Precipitation Measurement (GPM): Provides satellite-based precipitation data. Website: https://gpm.nasa.gov |
| Storm Size and Duration | NOAA Best Track Data: Includes storm radius of maximum winds (RMW) and storm duration data. Website: https://www.nhc.noaa.gov/data/#hurdat<br>• Joint Typhoon Warning Center (JTWC): For global cyclones, provides size and movement information. Website: https://www.metoc.navy.mil/jtwc/jtwc.html<br>• NASA Cyclone Global Navigation Satellite System (CYGNSS): Satellite data for wind field and storm size measurements. Website: https://www.nasa.gov/cygnss<br>• Remote Sensing Data: Infrared satellite imagery and scatterometry data from NOAA GOES satellites for storm size analysis. Website: https://www.star.nesdis.noaa.gov/goes |
| Composite Data for CHIS Integration | • National Centers for Environmental Information (NCEI): Comprehensive climate and weather data repository, including hurricane impacts. Website: https://www.ncei.noaa.gov<br>• Hurricane Damage Reports from FEMA: Offers detailed post-storm damage assessments that can validate CHIS metrics. Website: https://www.fema.gov<br>• Insurance Industry Reports (e.g., RMS, AIR Worldwide): Provides data on storm size, surge, and damages to validate model outputs. |

## 11.4. Appendix 4 – Adjustments

**Adjusting Weights Based on Specific Contexts**

In the development and refinement of predictive models, adjusting weights and constants is often necessary to enhance accuracy and reliability. This approach is particularly relevant when encountering abnormal or anomalous calculation results, as these may suggest that the initial model parameters are insufficiently capturing underlying phenomena. By adjusting weights and constants based on specific criteria, we can create more tailored and precise models that better account for unique or unexpected data points.

Academic research supports this method, underscoring its effectiveness across various fields. For instance, a study by the Pew Research Center demonstrates the significance of adjusting weights to correct imbalances and reduce bias in survey samples (Mercer et al., 2018). Similarly, Henry and Valliant (2012) discuss several design-based, model-based, and model-assisted methods for adjusting survey weights to address nonresponse or coverage errors, ultimately improving the quality of estimates. These studies highlight the utility of adjusting weights and constants to enhance the robustness and accuracy of predictive models.

**Coastal Areas with High Surge Vulnerability**

In regions where storm surge poses a significant threat, it is prudent to adjust the weighting of different factors in the Composite Hurricane Impact Scale (CHIS) to reflect the unique vulnerabilities of these areas. Coastal regions such as New Orleans, Louisiana, and Miami, Florida, exemplify the need for these adjustments due to their geographical characteristics and historical susceptibility to storm surge.

**New Orleans, Louisiana:** Known for its high vulnerability to storm surge due to its location below sea level, New Orleans experienced catastrophic flooding during Hurricane Katrina, significantly exacerbated by storm surge (Knabb et al., 2005).

**Miami, Florida:** As a low-lying coastal area, Miami is particularly susceptible to storm surge. The city has faced significant impacts from various hurricanes, underscoring the need for storm surge to be a key consideration in its risk assessments (National Hurricane Center, 2022).

- **Hurricane Katrina (2005):** This storm caused catastrophic storm surge along the Gulf Coast, with heights reaching up to 27.8 feet in parts of Mississippi (Knabb et al., 2005). The extensive damage and flooding highlighted the critical need to prioritize storm surge in predictive models for similar regions.
- **Hurricane Ian (2022):** Generating storm surge as high as 18 feet in coastal Florida, Ian devastated numerous waterfront communities (National Hurricane Center, 2022). The ramifications of this storm further illustrate the importance of adjusting weightings in areas with high surge vulnerability.

Given the heightened risk of storm surge in these regions, it is recommended to increase the weight of Storm Surge in the CHIS to 40-45%. This adjustment ensures that the significant threat posed by storm surge is adequately represented in the overall risk assessment. Consequently, the weights for Wind Speed and Storm Size & Duration can be decreased slightly to 20-25% and 10-15%, respectively, while maintaining the weight for Flood Damage Potential (Rainfall) at 20%. The suggested adjustments are as follows:

- Storm Surge: 40-45%
- Wind Speed: 20-25%
- Flood Damage Potential (Rainfall): 20%
- Storm Size & Duration: 10-15%

Adjusting weights based on specific criteria, such as increased storm surge vulnerability, is supported by academic research as an effective method to enhance the accuracy and reliability of predictive models. According to Mercer et al. (2018), weight adjustments are crucial in correcting imbalances and reducing bias in survey samples, an analogy that can be drawn to refining hurricane impact models. Additionally, Henry and Valliant (2012) emphasize the importance of tailoring weights to address nonresponse or coverage errors in survey data, further validating this approach in diverse contexts, including weather prediction and risk assessment. By implementing these adjusted weightings, the CHIS can offer a more accurate and comprehensive assessment of hurricane risks for coastal areas with high surge vulnerability. This tailored approach not only improves disaster preparedness and response but also contributes to building more resilient communities.

**Inland Areas with High Flood Risk**

Inland areas prone to high flood risk require a customized approach to hurricane impact assessment. Regions such as Houston, Texas, and the Central Appalachians in West Virginia and Kentucky exemplify the need for such adjustments due to their unique geographical and hydrological characteristics.

**Houston, Texas:** Known for its flat terrain and rapid urban development, Houston is highly susceptible to urban flooding, especially during hurricanes and tropical storms.

**Central Appalachians:** This region, encompassing parts of West Virginia and Kentucky, is particularly vulnerable to flash flooding due to its mountainous terrain and heavy rainfall events (U.S. Geological Survey).

- **Hurricane Harvey (2017):** This storm dropped over 60 inches of rain in parts of Texas, resulting in catastrophic inland flooding (Blake & Zelinsky, 2018). The extensive rainfall and subsequent flooding underscore the need to prioritize flood damage potential in impact assessments for similar areas.
- **Tropical Storm Imelda (2019):** A slow-moving storm that caused severe flooding in southeastern Texas, Imelda dumped 44 inches of rain (National Weather Service, 2019). The significant inland flooding from this storm further emphasizes the importance of accounting for flood damage potential in inland regions.

Given the high flood risk in these areas, it is recommended to increase the weight of Hurricane Flood Damage Potential (HFDP) in the CHIS to 25-30%. This adjustment ensures that the threat posed by inland flooding is accurately represented in the overall risk assessment. Accordingly, the weight for Storm Size & Duration can be reduced to 20-25%, while lower weights for Wind Speed and Storm Surge can be maintained since these factors are less critical for inland regions. The suggested adjustments are as follows:

- Flood Damage Potential (Rainfall): 25-30%
- Storm Size & Duration: 20-25%
- Wind Speed: 15%
- Storm Surge: 5-10%

**Extremely Large or Slow-Moving Storms**

Extremely large or slow-moving storms present unique challenges due to their prolonged duration and widespread impact. In these cases, the Storm Size & Duration component should be weighted higher in the CHIS to account for the extended destruction these storms can cause.

**The Gulf Coast and Southeast U.S.:** These regions frequently experience slow-moving, large storms that result in prolonged rainfall and flooding, leading to extensive damage (Needham et al., 2015).

- **Hurricane Florence (2018):** This slow-moving storm lingered over the Carolinas, dumping up to 36 inches of rain. Its extended duration resulted in severe flooding and widespread damage (Stewart & Berg, 2019).
- **Hurricane Dorian (2019):** A large, slow-moving storm, Dorian inflicted extensive damage in the Bahamas. Its slow movement caused prolonged exposure to high winds and heavy rainfall, exacerbating destruction (Cangialosi et al., 2020).

Considering the extended impact of large or slow-moving storms, it is recommended to increase the weight of Storm Size & Duration in the CHIS to 20%. This adjustment accurately reflects the prolonged threat posed by such storms in the overall risk assessment. Consequently, the weights for Flood Damage Potential, Wind Speed, and Storm Surge can be adjusted as follows to maintain a balanced and comprehensive model:

- Storm Size & Duration: 20%
- Flood Damage Potential: 25%
- Wind Speed: 20-25%
- Storm Surge: 20-25%

By adapting the weights according to specific contexts and varying threats, the CHIS can effectively assess risks associated with hurricanes, ultimately contributing to improved preparedness and response strategies in vulnerable areas.